National Cooperative Research Program

NCHRP Synthesis 199

Recycling and Use of Waste Materials and By-Products in Highway Construction

A Synthesis of Highway Practice

Transportation Research Board
National Research Council

National Cooperative Highway Research Program

Synthesis of Highway Practice 199

Recycling and Use Of Waste Materials and By-Products in Highway Construction

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The Transportation Research Board evolved in 1974 from the Highway Research Board, which was established in 1920. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society.

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis on recycling and use of waste materials and by-products in highway construction will be of interest to administrators and policy makers; pavements, materials, geotechnical, and environmental engineers; and other professionals involved with highway design, construction, and maintenance. Information is provided on the technical, economic, and environmental aspects (including legislative and regulatory considerations) of recycling and on the specific applications of waste materials and by-products. Information is also provided on the quantities, characteristics, possible uses, current and past research activities, and actual highway construction use of each waste material or by-product. This information is classified into four broad categories based on source: agricultural, domestic, industrial, and mineral wastes.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

This synthesis of information describes the use of recycled waste materials and by-products in highway construction based on a review of nearly 1,000 references and on responses to a 1991 survey of practice by state highway and environmental agencies. Updates are included for as much of the state practice information as possible through 1993. The synthesis also identifies current research in the topic area, critical research needs, and legislative issues that affect application and use of recycled waste materials and by-products. A Technical Appendix to this document, containing an extensive bibliography by subject, supporting information, and details regarding the use of selected waste materials or by-products is available separately from the Transportation Research Board. The use of recycled waste materials and by-products for highway applications is a dynamic situation; therefore, the reader should keep in mind that the information presented in this report of the Transportation Research Board reflects the best available data at the time of publication.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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The Principal Investigators responsible for the conduct of this synthesis were Sally D. Liff, Manager, Synthesis Studies; Stephen F. Maher, Senior Program Officer; and Scott A. Sabol, Program Officer. This synthesis was edited by Linda S. Mason.

Valuable assistance also was provided by Frank R. McCullagh, Senior Program Officer, National Cooperative Highway Research Program, Transportation Research Board.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

RECYCLING AND USE OF WASTE MATERIALS AND BY-PRODUCTS IN HIGHWAY CONSTRUCTION

SUMMARY

This synthesis discusses the recycling and use of various waste materials and by-products in highway construction and maintenance operations. Waste materials and by-products are classified into four broad categories based on their source: agricultural, domestic, industrial, and mineral. More than 30 different sources of waste materials and by-products were surveyed. The quantities, characteristics, possible uses, current and past research activites, and actual highway construction use of each waste material or by-product is discussed. A volume of additional information and details regarding the use of selected waste materials and by-products and an extensive bibliography are provided in the Technical Appendix, which is available from the Transportation Research Board publications office.

Historically, state highway agencies have been proactive in their efforts to evaluate usable materials and to recycle or incorporate such materials into the highway system wherever possible. Recently, environmental concerns, declining disposal capacity, legislative mandates, economics, and conservation efforts have also influenced agencies' policies on research into and construction use of various waste materials and by-products.

Specific information is given on waste materials in the four main waste classifications. Roughly 4.6 billion tons of non-hazardous solid waste materials are produced annually in the United States. Domestic and industrial wastes constitute almost 600 million tons of this total. The remaining 4.0 billion tons are divided about equally between agricultural and mineral waste sources, a large percentage of which are located in remote areas. Many state highway agencies have long-term experience in the research and use of slags, coal ash, reclaimed paving materials, mine tailings, and concrete rubble. Some states are also familiar with the use of coal refuse, waste rock, quarry waste, wood wastes, foundry sands, or silica fume. Most states also have some experience in the evaluation and use of scrap tires. Wastes such as plastics, glass, paper, and compost are receiving increased attention.

Questionnaires were sent to state highway agencies to obtain information on the research and use of waste materials and by-products. Detailed information concerning the use of reclaimed asphalt pavement, scrap tires in asphalt, and fly ash in concrete was also requested. Responses were received from all 50 states. A status report is given on research and uses for waste materials, based on the responses from the questionnaires, as well as a review of the literature.

Questionnaires were also sent to all state environmental regulatory agencies regarding the status of recycling legislation, beneficial reuse provisions, legislative mandates for selected waste materials, and the availability of landfill space. Ninety percent of these agencies responded. Legislative and regulatory influences that affect the research and use of waste materials and by-products in highway construction are discussed. There is increased legislative activity concerning waste materials, especially at the state level, ranging from banning landfill disposal of certain wastes (scrap tires, yard waste) to mandating that state highway agencies investigate or use certain waste materials within their highway systems.

Technical, economic, and environmental aspects of recycling and using waste materials and by-products are discussed. To be considered suitable for highway construction use, such materials must be of consistent quality and must meet specification requirements. A given waste material or by-product should be economically competitive with the product or material it replaces. Although the initial cost of using a waste material may be incrementally higher, the life-cycle cost attributed to the waste material should be comparable with that of conventional materials. Consideration should be given to the societal benefits of avoided disposal costs for certain waste materials.

The environmental consequences of recycling and using waste materials and by-products in highway construction are of increasing concern. The inclusion of a recycled waste or by-product in a highway application should not threaten environmental quality or endanger the safety of workers or the general public. The highway industry has a long history of using non-hazardous solid wastes prudently; many of them are incorporated into products in which their environmental impact, if any, is minimal. The use of recycled scrap steel in bridge beams, guide rails, and reinforcing bars is an excellent example. State highway and environmental regulatory agency personnel must increase communications so that recycling and beneficial use of suitable waste materials and by-products are encouraged, not discouraged.

Overall findings and conclusions are presented and general recommendations are offered for waste recycling and use in highway construction. Recommendations are given regarding research needs and applications for specific waste materials. Tabulations are made of proven applications for frequently used waste materials and possible applications for occasionally used waste materials.

CHAPTER ONE

INTRODUCTION

STATEMENT OF THE PROBLEM

The generation, handling, and safe disposal of solid wastes has become a major concern in the United States. While the volume of wastes continues to grow, approval of facilities for waste processing and proper disposal is becoming more difficult to obtain. Many existing disposal facilities are approaching capacity. Furthermore, environmental regulations have become increasingly wide-spread and restrictive. As a consequence, the cost of waste handling and disposal has escalated significantly in recent years.

Many municipalities and industries are devoting an increasing proportion of their budgets to waste management expenditures. Stricter waste regulations have resulted in a commitment of substantially greater resources to waste management at all levels of society. Increasing waste volumes and escalating disposal costs have forced a reassessment of public attitudes regarding the way society handles its wastes. Furthermore, there is a growing public awareness of the importance of conserving and preserving our valuable natural resources.

This expanding awareness has given rise to a definite trend toward recycling or use of a wide variety of solid waste materials. Waste recycling in the 1990s has advanced from simple newspaper drives, motivated by a recognition of the resource value in high volumes of formerly discarded materials such as scrap tires, paving rubble, combustion by-products, and mining wastes. Reusing such materials reduces disposal volumes and costs, conserves natural resources, and may even generate revenue. Because highways require huge volumes of construction materials, highway agencies have become frequent participants in efforts to recycle or reuse diverse waste materials.

Solid waste materials differ vastly in their types and characteristics as well as in the applications for which they may be suited. Experiences with using waste materials in highways can vary considerably, depending on climatic differences, compositional fluctuations, material handling techniques, and construction procedures. Some waste materials and by-products (such as reclaimed paving materials, slags, and fly ash) have been used beneficially in the highway system for many years. Other materials have very little performance history from which to evaluate their potential for sustained use in highway construction. A number of waste materials may be suitable for use in constructing highways, but may have other, more economical or productive uses.

Besides these considerations, the level of practice and knowledge of waste material use in highway construction varies from state to state. Engineers and decision makers at all levels (federal, state, and local) need to be aware of the various types of waste materials, how or if they can be used in highway construction, experiences of others with using such materials, and their technical, economic, and environmental considerations.

Objectives

The objectives of this synthesis of highway practice are to

- Include a survey of the waste materials and by-products that have been used successfully, or may be used, as materials for highway construction or maintenance work.
- Determine the state of practice concerning the evaluation, field use, and degree of acceptance of waste materials and by-products in highway construction applications by state highway agencies.
- Report on the status of current or proposed regulations, state or federal legislation, procurement guidelines, and environmental mandates related to the reuse of specific waste materials or by-products in highway construction.
- Identify the technical, economic, and environmental factors that recommend or preclude the use of specific waste materials or by-products in certain highway construction applications.

Scope and Research Approach

The scope of this investigation includes a broad spectrum of non-hazardous solid waste materials generated from domestic, industrial, mineral, and agricultural sources. Hazardous chemical wastes and industrial sludges are not included. Also, wastes from state highway maintenance operations, some of which are hazardous, were excluded from consideration. The Transportation Research Board has sponsored separate synthesis projects on current practices for the collection and disposal of highway litter (*1*) and the use of recycled rubber from scrap tires in highway construction (*2*).

The research approach involved a thorough review of published literature pertaining to the generation of waste materials and by-products and the use of these materials in highway construction or maintenance operations. Contacts were made with representatives of state highway agencies throughout the United States to ascertain their experiences with such uses. In many instances, these contacts resulted in the review of additional published and unpublished literature. Contacts were also established with state environmental agencies to ascertain the status of regulations and legislative mandates pertaining to the recycling of waste materials. Appendix A provides a glossary of some of the terms or phrases most frequently used in solid waste management.

It is important to recognize that the recovery and reuse of waste materials is constantly changing and expanding, especially for construction purposes. Technology continues to advance and new ways are being found to process and make use of discarded materials that were formerly part of the waste stream. More and more attention is being focused on this topic and new publications in this area are appearing with increasing frequency. Not all developments in this field that are now in progress are addressed specifically or included in this synthesis.

CLASSIFICATION OF WASTES AND BY-PRODUCTS

Non-hazardous solid wastes and by-products can be classified according to source in one of four general categories:

- Agricultural,
- Domestic,
- Industrial, or
- Mineral.

The following chapters discuss these waste categories and provide a tabulation of the principal types of wastes or by-products in a particular category, the estimated quantities generated annually, and the various uses made of them by highway agencies. The tables are augmented by a brief description of each waste or by-product, how it is produced, and how it has been used as a highway construction material. Additional details concerning material characteristics, locations, and the extent of research and use in highway construction are provided in the Technical Appendix.

SOURCES OF INFORMATION

A keyword search of published literature on the use of wastes and by-products in highway construction was conducted using the Transportation Research Information Service (TRIS) computerized information file. To supplement the abstracts from the TRIS search, numerous technical publications, journals, periodicals, and articles were reviewed. Published information was also obtained from organizations such as the Transportation Research Board (TRB), federal agencies, trade associations, and engineering and professional societies.

Many unpublished reports were reviewed, as well as technical brochures on products containing recycled materials such as coal ash, slag, scrap tires, reclaimed plastic, kiln dust, and waste glass.

State Highway Agency Questionnaires

Questionnaires were sent to the highway agencies in all 50 states and the District of Columbia to obtain information on the state of practice relative to the use of waste materials and by-products in highway construction and maintenance (see Appendix B). It requested basic information from each state concerning

- The extent of current research on waste material use,
- The acceptability of certain waste materials in highways,
- The actual use of specific waste materials in construction,
- Any waste materials considered unacceptable for construction, and
- Federal or state laws or mandates related to waste use.

The highway agencies in all 50 states and the District of Columbia responded to this questionnaire. Chapter Five presents the information provided in these responses. A more detailed discussion of the findings from these questionnaires is provided in the Technical Appendix, a separate document available from the TRB Publications Office.

Thirteen agencies also forwarded reports discussing their research on or use of waste materials, including 10 which provided reports surveying the generation and utilization potential for waste materials in their states. Follow-up questionnaires were also sent to state agencies concerning specifications for various waste materials, as well as further information on state highway use of fly ash, reclaimed asphalt pavement, and scrap tires. Appendix B contains copies of the follow-up questionnaires.

State Environmental Agency Questionnaires

Questionnaires were also sent to the environmental regulatory agencies in all 50 states, to obtain information on the state of practice relative to waste management regulations and waste reuse activities (see Appendix B). The questionnaire requested basic information concerning

- State laws or legislative mandates for wastes,
- Beneficial reuse provisions in waste regulations,
- Mandatory recycling laws,
- Reuse of out-of-state waste, and
- Availability of landfill space.

Forty-five states responded to the environmental agency questionnaire. Chapter Six presents an overview of the questionnaire responses and a discussion of the various state laws and/or legislative mandates aimed at stimulating recycling of specific waste materials or by-products by state highway agencies.

FACTORS AFFECTING WASTE MATERIAL USE

The long-standing and increased interest in the recycling and use of waste materials has been motivated by a number of factors, including

- Environmental issues,
- Legislative activity,

- Economic comparisons,
- Engineering properties,
- Construction material shortages, and
- Alternative resource availability.

Each of these factors has helped stimulate waste reuse, particularly in highway construction.

Environmental Issues

Solid waste disposal regulations for non-hazardous wastes have become increasingly strict. Recently released statistics show that at least 32 states now require double liner systems in sanitary landfills operating in these states (*3*). These regulations have increased the cost of landfilling and are accelerating the closure of noncomplying disposal sites. The overall impact of stricter waste disposal regulations is a gradual reduction of available landfill space while larger quantities of solid wastes are being generated. As existing landfills reach capacity and are forced to close, new disposal facilities are not being approved quickly enough to meet demand. Because of declining disposal capacity, landfill tipping fees have soared in many parts of the country and are expected to continue to increase in the future (*4*). Alternatives to landfilling such as incineration are being implemented in order to manage growing volumes of solid waste adequately.

Legislative Activity

Federal and state lawmakers, aware of this declining capacity, have enacted legislation aimed at stimulating or even mandating waste separation and recycling and encouraging the beneficial reuse of selected waste materials. A section in the Resource Conservation and Recovery Act (RCRA) authorizes the establishment of guidelines for governmental procurement of items containing a significant percentage of recovered material (*5*). A provision in the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 requires the use of crumb rubber from scrap tires in asphalt paving mixes beginning in 1994 (*6*). A proposed amendment before Congress would modify crumb rubber use under ISTEA to include all civil engineering uses in highway construction, not just hot-mix asphalt.

Approximately 50 percent of all states have now adopted legislation aimed at recycling selected components of the solid waste stream. Mandatory recycling laws have thus far been enacted in approximately 40 percent of all states (*7*). Special provisions have been incorporated into some state solid waste laws, stipulating the use of specific waste materials. Legislation in many states has directed highway agencies to investigate the potential for use of certain waste materials in highway construction and report the results to the state legislature. In a number of instances, the use of certain waste materials—including some applications in highways—is mandated by state laws or regulations.

Economic Comparisons

Economics, perhaps more than any other factor, has been the impetus for recovery and recycling of waste materials. The substantial increase in waste disposal costs in some areas means that it may now be less expensive for many cities, counties, and towns to recover and process usable waste materials than to send their waste to a landfill. State and local highway agencies must also contend with increasing costs and decreasing budgets, both of which result in fewer miles of roads constructed or maintained for the dollar. In some cases, use of waste materials and by-products may be more economical than conventional construction materials, resulting in reduced construction costs. If a waste material or by-product contributes to improved performance or extended service life, its life-cycle costs may be comparatively less than those of conventional construction materials, providing an additional incentive for use.

Engineering Properties

Some waste materials and by-products have been used for highway construction purposes for many years. These materials often provide unique or improved engineering properties when used in certain applications. For example, silica fume as an admixture in portland cement concrete results in a denser, more impermeable mix that attains significantly higher compressive strength and is much more resistant to corrosion of reinforcing steel from deicing salts. Class F fly ash used as a partial replacement for portland cement in concrete mixes increases workability and sulfate resistance, while reducing alkali-silica reactivity and heat of hydration.

Construction Material Shortages

The construction industry uses enormous quantities of raw materials, as well as finished products. Approximately 2 billion tons of construction aggregate (crushed stone, sand, and gravel) are produced and sold each year in the United States (*8*). A significant percentage of this production is used for highway and bridge construction. This continuing demand for raw materials is gradually depleting natural resources.

Restrictive zoning laws, urbanization, competing land uses, and community opposition are restricting the expansion of or even forcing the closure of existing quarry and gravel pit operations. This has created localized shortages of construction aggregates and borrow materials in many areas. Stricter environmental regulations in many states make it more difficult to open new quarries or gravel pits. The expense of transporting materials over greater distances to offset localized shortages increases construction costs. Acceptable alternatives are needed to alleviate such shortages and conserve natural resources.

Alternative Resources

By-products or waste materials continue to be used as alternative resources for highway construction and improve-

ments. Some by-products are produced and stockpiled in relatively large quantities and have been used for many years. In many cases, such materials are used in areas where conventional resources may not be readily available. Some examples include iron blast-furnace and steel-making slags, waste rock and mine tailings, reclaimed asphalt pavement, and concrete rubble, all of which have been used successfully as aggregates for highway construction. Most state highway agencies have been using such alternative resources for many years and have also been recycling materials like guide rails and sign blanks routinely. One of the most widely recycled construction materials is steel, a principal component of highways. Reinforcing bars consist of 100 percent recycled steel scrap and bridge beams contain 25 percent scrap.

Summary

Each year, approximately 4.6 billion tons of non-hazardous solid wastes are produced in the United States. Table 1 provides a summary of the estimated quantities and components of the four major solid waste categories. Although there are greater opportunities for reclaiming and recycling domestic and industrial wastes and by-products, significantly larger volumes of agricultural and mineral wastes are produced. Table 1 also provides a breakdown of estimated annual quantities of domestic and industrial waste materials. The Technical Appendix contains a series of national maps that indicate locations or concentrations of major types of waste materials or by-products.

TABLE 1
CLASSIFICATION AND ANNUAL QUANTITIES OF SOLID WASTE MATERIALS AND BY-PRODUCTS

CATEGORY	DESCRIPTION	ANNUAL QUANTITY (Millions of tons per year)	TOTAL ANNUAL QUANTITY (Millions of tons per year)
Agricultural	Animal Manure	1,600	2,100
	Crop Wastes	400	
	Logging and Wood Waste	70	
	Miscellaneous Organics	30	
Domestic	Household and Commercial Refuse	185	200
	-Paper and Paperboard (71.8)		
	-Yard Waste (31.6)		
	-Plastics (14.4)		
	-Incinerator Ash (8.6)		
	Sewage Sludge		
	Scrap Tires	8	
	Compost	2.5	
	Used Oil	2.5	
		2	
Industrial	Coal Ash	72	400
	Demolition Debris	25	
	Blast-Furnace Slag	16	
	Steel Mill Slag	8	
	Non-Ferrous Slags	10	
	Cement and Lime Kiln Dust	24	
	Reclaimed Asphalt Pavement	100	
	Reclaimed Concrete Pavement	3	
	Foundry Wastes	10	
	Silica Fume*	0.05	
	Roofing Shingle Waste	9	
	Sulfate Waste	18	
	Lime Waste	2	
	Ceramic Wastes	3	
	Paper Mill Sludge	N.A.	
	Contaminated Soils	N.A.	
Mineral	Waste Rock	1,020	1,800
	Mill Tailings	520	
	Coal Refuse	120	
	Washery Rejects	105	
	Phosphogypsum	35	
		TOTAL	4,500

N.A. indicates that an estimate of the annual quantity is not available. Combined estimate is 100 million tons per year.
*Estimated

CHAPTER TWO

PRODUCTION AND USE OF AGRICULTURAL AND DOMESTIC WASTES

AGRICULTURAL WASTES

According to a U.S. Bureau of Mines study on the energy potential of organic wastes *(9)*, more than 2 billion tons of agricultural wastes are generated annually in the United States. Although this publication is nearly 20 years old, the basic types and quantities of agricultural wastes are not likely to have changed significantly. The principal types of agricultural wastes are

- Animal manure,
- Crop wastes,
- Lumber and wood wastes, and
- Miscellaneous organic wastes.

Animal Manure

Manure production from cattle, hogs, sheep, and poultry amounts to approximately 1.6 billion tons annually, based on wet weight. The moisture content of manure is highly variable. Much of it is produced from animals raised in confined conditions, such as feedlots, dairies, or hen houses. Most collected manure is not transported over great distances because of the expense involved. Some may be processed for fertilizer or refeeding. Some may also be converted into compost or thermally processed to yield oil *(9)*. An example of the use of animal manure in a highway-related application is in the state of North Carolina, where poultry manure has been used as fertilizer on highway rights of way *(C.L. Jones, North Carolina DOT. Private Communication)*.

Crop Wastes

Crop wastes range from field wastes from harvests to milling wastes from grain processing. More than 20 years ago, the total amount of annual crop waste generation was estimated at 550 million tons *(9)*. Improved crop harvesting methods and increased deposition of waste to prevent erosion have likely resulted in some reduction of this number. It is conservatively estimated that approximately 400 million tons of crop wastes are produced annually, much of it probably being used as animal feed.

There are two known examples of research into the use of crop wastes for highway purposes. One is an investigation conducted at the University of California at Berkeley on the potential use of rice husk ash as a supplementary cementing material. Replacement of 10 to 20 percent cement with rice husk ash contributed to increased early (1 to 3 days) compressive strength and resulted in reduced expansion due to alkali-aggregate reactivity *(10)*. The other example involved a Federal Highway Administration (FHWA) research contract during the late 1970s to investigate the possibility of converting cellulosic wastes (including crop residues, animal manure, and wood wastes) into road binder materials. This study found that cellulosic wastes could be converted to an oil that may be suitable as an extender of asphalt *(11)*.

Lumber And Wood Wastes

Approximately one third of the wood harvested in the United States is unused, wasted in the form of logging residues, wood and bark chips, and sawdust generated primarily at sawmills. Approximately 20 years ago, logging and wood processing residues amounted to 55 million tons per year *(9)*. Annual production of such wastes today may be in the range of 70 million tons per year, with a large proportion being generated in the Pacific Coast states. Where available, some of these wastes have been used as mulch or lightweight fill for the construction or repair of embankments. In all likelihood, some quantities of wood chips and sawdust are already being used commercially as mulching materials and in particle board production and other industry related applications.

Wood chips or fibers have been investigated or used experimentally as a mulching material by at least four states (Maryland, New Hampshire, New York, and North Carolina) and are well suited for that purpose. At least six states have used wood chips or fibers as mulch on a more routine basis.

Some form of wood waste has been used in at least six states (Alaska, Idaho, North Carolina, Washington, Wisconsin, and Wyoming) to construct or repair embankments. It is likely that there are also some other states, in which logging and lumber processing are vital industries, that have at one time or another used some type of wood waste as a lightweight fill material in embankments or for landslide repair.

In Alaska, more than 20,000 cubic yards of greenwood chips 6 in. or smaller were used to rebuild a section of roadway embankment that had settled more than 10 ft *(12)*. In Idaho, lightweight wood fiber fill was placed below and above the water table during the reconstruction of a 3200-ft-long airport runway that was built over highly compressible peaty floodplain deposits *(13)*. In North Carolina, live plant cuttings have been used as slope reinforcement in a demonstration of soil bioengineering systems *(14)*.

Since 1972, the Washington Department of Transportation has used sawdust and wood chips in at least 14 embankment projects. Their overall performance in these applications has been very successful *(15)*. During 1991, the Washington Department of Transportation evaluated their condition and performance by obtaining wood fiber samples from each project site. The Department concluded that embankments constructed from sawdust or wood fibers have an expected service life of at least 50 years *(16)*.

In Wisconsin, wood chunks were used successfully to build two thin sections of embankment on a 650-ft section of

forest service road across a muskeg bog *(17)*. Wyoming has used wood chips as a lightweight fill material in repairing landslide areas.

Miscellaneous Organic Wastes

There are no uses for these wastes, which consist of animal carcasses, fermentation residues, and organic wastes from federal installations.

Table 2 presents a summary of the production and uses of agricultural wastes, with highway construction uses highlighted in bold type.

DOMESTIC WASTES

Approximately 200 million tons of domestic wastes are generated annually in the United States. Most of this waste is household or commercial trash and garbage, which is presently estimated at 185 million tons per year *(18)*, or approximately 4 lb per person per day. Currently, about 75 percent of trash or garbage is deposited in landfills, while 11 percent is recycled and 14 percent is burned *(18)*.

The following domestic wastes have potential or actual usefulness as highway construction materials:

- Incinerator ash,
- Sewage sludge,
- Scrap tires,
- Compost,
- Glass and ceramics,
- Plastics,
- Used motor oil, and
- Waste paper.

For each material, basic information is provided on the sources and approximate quantities of the material, its possible uses (highway as well as non-highway), current and past research activities related to highway uses,and an overview of highway related applications. Table 3 presents a summary of the production and uses of domestic wastes.

Chapter Five gives a breakdown of the research into and uses of all waste materials according to state and type of end use.

Incinerator Ash

Approximately 140 thermal reduction facilities in the United States have the capacity to burn at least 50 tons of solid waste per day. These facilities operate in 32 states and the District of Columbia. It is estimated that these facilities burn approximately 28.6 million tons per year of municipal solid waste (MSW), resulting in the generation of 8.6 million tons of incinerator ash or residue *(19)*. Approximately 90 percent of this ash is bottom ash and the remainder is fly ash. At present, most operating facilities combine the fly ash and bottom ash for disposal. Leachate analysis of selected incinerator ash grab samples indicates that most incinerator fly ash samples exceed regulatory limits for lead and cadmium, while the

TABLE 2
PRODUCTION AND USE OF AGRICULTURAL WASTES

Waste Type	Amount Generated Annually	Uses **(By Highway Agencies)**
Animal manure	1.58 billion tons	Fertilizer, Refeeding, Compost, Oil production by thermal processing
Crop wastes	400 million tons	Animal feed, **Rice husks as supplementary cementing material, Cellulosic waste as asphalt extender**
Lumber and wood wastes	70 million tons	**Mulch, fill for embankments,** Particle board production
Greenwood chips		**Rebuilding roadway embankment**
Wood fiber fill		**Layered above and below water table in runway reconstruction**
Sawdust and woodchips		**Embankment projects**
Live plant cuttings		**Slope reinforcements**
Wood chunks		**Embankment projects.**

TABLE 3
PRODUCTION AND USE OF DOMESTIC WASTES

Waste Type	Amount Generated Annually	Uses (by highway agencies)
Incinerator ash	8.6 million tons	**Asphalt paving aggregate** **Cement-stabilized base** **Vitrified aggregate** **Pelletized aggregate** Reef blocks Masonry block
Sewage sludge	8 million dry tons	Land application Compost Stabilized dike material
Sewage sludge ash	0.5-1 million tons	**Asphalt mineral filler** **Concrete coarse aggregate**
Scrap tires	2.5 million tons	Tire-derived fuel **Asphalt-rubber binder** **Asphalt fine aggregate** **Stress-absorbing membranes** **Rubberized crack sealant** **Lightweight fill material**
Compost	2.5 million tons	**Mulching material**
Glass and ceramics	12.5 million tons	Glass cullet **Unbound base course** **Pipe bedding material** **Asphalt fine aggregate**
Plastic waste	14.4 million tons	**Fence and sign posts** Plastic lumber **Delineators** **Asphalt-cement modifier** **Geotextile manufacture** **Composite pipe pilings**
Used motor oil	2 million tons	Recycled as lubricant **Fuel in asphalt plants**
Paper and paperboard	71.8 million tons	Recycled paper or cardboard **Mulching material**
Recycled refuse from sanitary landfills	N/A	**Core material in medians Embankment construction (mixed with natural soil)**

majority of combined ash samples do not exceed such limits *(20)*.

Much of the early research on finding potential highway uses for incinerator ash, or incinerator residue as it was referred to then, was initiated some 20 years ago by the FHWA. Under FHWA sponsorship, considerable laboratory testing and small-scale field installations incorporating incinerator residue were successfully conducted. These installations included the use of processed residue as

- Lime-stabilized base course in the Chicago area;
- Coarse aggregate in asphalt base course mixes in Houston, Texas, and Washington, D.C.;
- Aggregate in three asphalt wearing surface mixes in southeastern Pennsylvania; and
- Fused aggregate in an asphalt wearing surface mix north of Harrisburg, Pennsylvania.

Although much valuable technical information was obtained from this work and has been published by FHWA, very little in the way of environmental monitoring was conducted in conjunction with this work. A jointly sponsored research program is now being implemented in New Jersey to evaluate the technical and environmental behavior of incinerator ash in asphalt paving. The program will monitor asphalt plant emissions, examine runoff and leachate characteristics, and evaluate engineering performance *(W. Chesner, Consultant, Private Communication)*.

Current research on highway uses for processed MSW incinerator ash is being performed at the University of Connecticut and the University of New Hampshire. This research involves studying the engineering and environmental characteristics of incinerator ash in asphalt mixes.

Processed incinerator ash has been used successfully in the field as a partial replacement for coarse aggregate in asphalt paving mixes. Perhaps the most outstanding example of ash

use in asphalt paving is a 1-mi test section of wearing surface on Route 129 in Lynn, Massachusetts *(21)*. Recent work by the University of Connecticut involved the monitoring of an incinerator ash roadway fill *(22)*. Incinerator ash has been stabilized with portland cement for base course construction. Synthetic aggregate has been produced from incinerator ash by fusion or vitrification.

Current regulatory concerns about the leaching of heavy metals have virtually eliminated any near-term possibility for the use of incinerator ash as a construction material. The EPA is now considering an option to require that if incinerator ash fails a toxicity test, it must be managed as a hazardous waste *(23)*.

Sewage Sludge

There are more than 15,000 municipal wastewater treatment plants throughout the country. These plants produce an estimated annual total of 8 million tons of dry solids of sewage sludge *(24)*, much of it discharged as a slurry with low solids content (3 to 6 percent). Following dewatering, sludge cake normally has a solids content ranging from 18 to 24 percent. Sewage sludge consists mainly of organics such as nitrogen and phosphorus, but may also contain contaminants from the wastewater. About 40 percent of municipal sewage sludge is land applied or composted and marketed. Another 40 percent is disposed of with MSW in sanitary landfills, while roughly 20 percent is incinerated *(25)*. Stabilized sewage sludge may be used as a soil amendment or nutrient on highway rights of way and also has potential for use as an embankment material.

Approximately 282 sewage sludge incinerators operate at more than 150 wastewater treatment plants in the United States, producing 0.5 million to 1 million tons of sludge ash annually *(26)*. Both dewatered sewage sludge and sludge ash have potential for beneficial reuse in highway construction, although the principal uses for sewage sludge are agricultural (as soil amendment, compost, or fertilizer). Sludge ash has potential for use as an asphalt filler and is also being used in California in brick manufacturing.

The Mineral Resources Center at the University of Minnesota recently investigated the potential for using sintered sludge ash pellets as a substitute for coarse aggregate in concrete. Sludge ash pellets were sintered at approximately 1050°C. Concrete made with 35 percent replacement of coarse aggregate by lightweight sludge ash pellets had 28-day strengths of 5810 psi, more than 15 percent higher than regular concrete *(27)*.

Sewage sludge has been used as a top soil amendment in New York. Sewage sludge ash has been used experimentally as a mineral filler in asphalt paving in at least two states (Minnesota and New Jersey). In addition to potential environmental concerns associated with the use of sewage sludge, the health and safety of workers handling the sludge must be considered. Sludge is more of a health and safety concern than sludge ash.

Scrap Tires

Approximately 235 million tires are discarded annually, generating about 2 million tons of scrap rubber *(28)*. More than 80 percent of discarded tires are landfilled. Nearly 10 percent are recovered and used as tire-derived fuel. About 2 percent of scrap tires are ground into crumb rubber and used in asphalt rubber. Scrap tires have also been shredded into chips and used as lightweight fill material to construct fills and embankments. It is estimated that as many as 2 to 3 billion scrap tires are stockpiled around the country. At least 30 states have enacted legislation regulating the disposal of scrap tires, including 22 states where tires are not permitted in landfills *(28)*.

At least 40 state highway agencies, as well as the FHWA, have conducted research on one or more ways of reusing scrap tires in highway construction, mainly as an additive to asphalt mixes. At least five states are evaluating tire chips as lightweight fill material. *Synthesis of Highway Practice 198* on the uses of recycled scrap tires in highway construction was recently published *(2)*. This document and the survey of state highway agencies indicate that rubber from scrap tires has been used in one or more of the following highway applications:

- Crumb rubber in asphalt-rubber binder for hot-mix asphalt wearing surface, binder, and base courses, seal coats, stress-absorbing membranes, joint and crack sealing, or bridge sealants (wet process);
- Crumb rubber as aggregate in gap-graded friction courses and dense-graded hot mix (dry process);
- Shredded chips as lightweight fill or insulation;
- Sidewalls as reinforcement material for embankments;
- Whole tires as crash cushions and rock protection; and
- Crumb rubber in paver blocks and grade crossings.

For many states, the use of scrap tires is still considered experimental, despite the many field projects in which scrap tires have been used for a number of years. This is especially the case for asphalt-rubber projects, which often have higher first costs than conventional asphalt pavements and require many years of monitoring to ascertain whether there is any long-term advantage in terms of reduced maintenance and lower life-cycle costs.

A follow-up questionnaire on the use of scrap tire rubber in asphalt was distributed to those 40 state highway agencies that had originally indicated some use of scrap tires (see Appendix B). All 40 states returned this questionnaire. Information was sought on the number and types of projects using scrap tires, the success and cost-effectiveness of these projects, and the attitude in each state toward increased use of scrap tire rubber.

Thirty-two states (80 percent of respondents) still consider their use of scrap tires in asphalt to be experimental. At least 35 states have used scrap tires in the wet process, while 20 states have used them in the dry process; 15 states have experience with both processes. Approximately 200 asphalt-rubber (wet process) and approximately 80 rubberized asphalt (dry process) projects have been placed by these state agencies.

Of the 35 states using the wet process, 15 consider its performance successful, 7 do not, and 13 are still undecided; 24 states consider it uneconomical, only 4 consider it economical, and 7 are still undecided. Of the 20 states using the dry process, 5 consider its performance successful, 9 do not, and 6 are still undecided; 12 states consider it uneconomical, only 2

consider it economical, and 6 are still undecided. If there were no mandate to use scrap tire rubber, only 5 states would use it routinely, 8 states would not use it at all, and the remaining 27 states would use scrap tires only experimentally.

Compost

Compost refers to the biological decomposition of organic wastes under controlled conditions. Composting is an aerobic process that occurs at elevated temperatures. It yields a relatively stable end product that can be applied to the soil. Compost can be produced from sewage sludge, yard wastes, MSW, paper mill sludge, and other organic wastes, such as agricultural and food processing wastes. Compost produced from two or more sources is referred to as co-compost.

After compost has been produced it is screened or sized to comply with market requirements. EPA criteria for compost materials involve pathogen control, pH, heavy metal content, carbon to nitrogen (C/N) ratio, and water-holding capacity *(29)*. Other criteria include maturity, particle size, and nutrient content *(30)*.

The amount of compost produced annually is growing at a steady rate. There are approximately 1400 yard waste composting operations in the United States *(31)*, as well as 133 sewage sludge compost facilities *(32)* and 18 MSW compost operations *(33)*. Seventeen states have passed legislation prohibiting the disposal of yard waste in landfills *(34)*. Compost and co-compost materials can be and are used for mulching, soil amendment, fertilizers, and erosion control, mostly on agricultural and park land.

In 1987, the California Department of Transportation (Caltrans) conducted an evaluation of compost and co-compost materials for use in highway construction as soil amendment, fertilizer, and erosion control material and in the construction of safety barriers or sound berms. The concerns associated with compost use were leaching potential, odors, worker health and safety, long-term exposure, and public acceptance. The report recommended further standards and guidelines for handling, curing, and monitoring these materials *(35)*.

At least five state highway agencies (Connecticut, Maine, Maryland, New Hampshire and New York) have indicated that they are now conducting research on the possible use of compost as a mulch. Eight states (California, Connecticut, Maine, Maryland, New Hampshire, New Jersey, North Carolina, and Oregon) have indicated that their highway agencies have used compost materials. In Maryland, New Hampshire, and New Jersey, the compost is derived from sewage sludge. California and North Carolina still consider their use of compost to be experimental. It has also been reported that composted sewage sludge from the City of Fort Worth has been given to the Texas Highway Department for more than 10 years for use in landscaping highway medians and rights of way *(36)*.

Glass And Ceramics

Approximately 12.5 million tons of glass are included in the 185 million tons of household waste discarded annually *(7)*. The amount of glass containers produced and used each year is declining. In 1988, 1.5 million tons of waste glass was recycled *(37)*. Waste glass is usually available in some quantity only in major metropolitan areas.

The principal use of waste glass is as cullet for glass manufacturing. To be acceptable as cullet, glass must be color sorted and free from contaminants. In highway construction, waste glass has potential applicability as a fine aggregate in unbound base courses, pipe bedding, as an addition to soil in embankments, and as a partial replacement or supplement for aggregate in asphalt paving mixes (glasphalt). Although unlikely, finely crushed glass may conceivably be used to improve reflectivity in highway line striping, provided the particles are spherical. Waste glass is not recommended for use in concrete.

Ceramic waste consists of china and porcelain, resulting from factory rejects as well as discarded houseware and plumbing fixtures. Quantities of ceramic waste are generally less than waste glass, although there are localized instances where fairly substantial quantities of ceramic waste may become available.

At least 10 state highway agencies have researched the possible use of waste glass or ceramic waste in some type of highway construction. All but two of these (Maine and New Hampshire) have evaluated the use of finely crushed waste glass as an aggregate in asphalt paving. California is also evaluating crushed waste glass in a cement stabilized base, and Connecticut has investigated the use of waste glass in an embankment. Maine is evaluating the suitability of finely crushed waste glass as beads in traffic paint. New Hampshire is performing research on the use of crushed waste glass in an unbound base course.

The use of waste glass in asphalt (glasphalt) originated more than 20 years ago through experimental work at the University of Missouri-Rolla *(38)*. Since that time, numerous test strips of glasphalt have been placed in many parts of the country. A market survey was performed on the use of mixed waste glass in the City of New York *(39)* and asphalt mixes containing up to 15 percent by weight of glass were produced and placed in New York City during the 1990 and 1991 paving seasons *(R. Petrarca, Twin County Recycling, Private Communication)*.

At present, only six state highway agencies indicate any use of waste glass in asphalt paving. In only one state (New Jersey) is glasphalt not considered experimental. In Vermont, the use of waste glass in asphalt is considered unsuccessful because of poor performance. North Carolina is using waste glass as glass beads for traffic paint.

In California, crushed porcelain from used toilets has been used as an unbound base course aggregate for a roadway near Santa Barbara. The crushed porcelain was found to meet or exceed quality requirements for concrete aggregate *(40)*.

Plastics

The total amount of plastics in the MSW stream amounts to 14.4 million tons annually, a figure that continues to grow each year (7). Six main types of resins are used to make plastic products in this country:

- Low-density polyethylene (LDPE)—film and trash bags
- Polyvinyl chloride (PVC)—pipes, siding, and flooring
- High-density polyethylene (HDPE)—1-gal milk jugs
- Polypropylene (PP)—battery casings and luggage
- Polystyrene (PS)—egg cartons, plates, and cups
- Polyethylene terephthalate (PET)—2-l soda bottles

About 30 percent of PET and 7 percent of HDPE are currently being recycled *(41)*. Unfortunately, much of the post-consumer waste plastic is commingled, meaning a mixture of various resin types. Plastic lumber, sign and delineator posts, and other products are being made from reclaimed HDPE and commingled plastics, while LDPE has been recycled into pellets for use as an asphalt modifier in paving mixes. PET bottles are being used by at least one producer in geotextile manufacturing *(42)*. Recycled PET can also be modified chemically to produce a thermoset polyester that can be used to produce polymer concrete *(43)*. Composite piles have been made from steel pipe and recycled commingled plastic *(44)*.

At least 15 state highway agencies are researching highway uses for waste plastic. Seven are evaluating the use of commingled or mixed plastic in fence or sign posts. At least two states are investigating the use of extruded waste plastic as timber or wood substitute. Four others are studying the performance of pellets made from scrap LDPE plastic waste as an asphalt cement modifier, and two different states are evaluating the recycling of plastic waste in making sign blanks. Three states are evaluating delineators made from waste plastic and at least one state is also conducting research into the use of plastic waste as a component of reinforcing steel chairs.

At least six states have used plastic waste in some type of highway application. Three states (Colorado, Nevada, and New York) have placed asphalt pavements in which recycled LDPE pellets were used as an asphalt-cement modifier. The recycled pellets were made from plastic trash bags and sandwich bags, then mixed with asphalt and aggregate in conventional hot-mix plants at about 7 percent by weight of polyethylene to asphalt cement. In two other states (Florida and North Carolina), mixed or commingled plastic has been used to manufacture fence and sign posts. Florida is also using reinforcing steel chairs made from waste plastic. North Carolina and Kansas are both using delineators containing waste plastic.

The Florida Department of Transportation (FDOT) has had considerable laboratory and field experience in evaluating recycled HDPE plastic posts. Their work has included determination of mechanical strength and resistance to exposure and insect attack, crash testing, and development of specifications *(45)*.

A portland-cement concrete pedestrian bridge utilizing scrap plastic was built in Elgin, Illinois. The bridge deck contained 30 percent granulated plastic as a partial replacement of sand to reduce dead weight at comparable compressive strength *(43)*.

Used Motor Oil

Of the 2.6 billion gal of lubricating oil sold annually in the United States, approximately 1.4 billion gal becomes used oil. Of this total, about 800 million gal are handled through the used oil management system. At this time, about 90 percent of reclaimed oil is burned as fuel, with asphalt plants among the users *(46)*. Some state highway agencies indicate that used motor oil is recycled for use in state vehicles and equipment.

Four state highway agencies have done research on the recycling and reuse of used motor oil. Georgia, Maine, and Massachusetts have evaluated used motor oil as a fuel in asphalt plants. Missouri is investigating the recycling of used motor oil as lubricant in state vehicles. At least ten states are now using reclaimed motor oil as fuel. North Dakota has tried used motor oil as fuel and considers its use unsuccessful.

Waste Paper

Approximately 72 million tons of paper and paperboard are discarded annually, making up approximately 40 percent of the domestic solid waste stream *(18)*. During 1988, 18 million tons of waste paper (cardboard boxes, newspapers, office paper, etc.) were recycled *(37)*. Recycled paper products are primarily used for producing paper, cardboard, and other related materials. Shredded waste paper, particularly slick paper (magazines), has occasionally been used as a mulching material.

According to questionnaire responses, only four states (Georgia, Kansas, Missouri, and Pennsylvania) are now or at one time have performed research on the use of waste paper as a mulching material. Georgia and Missouri both consider their research to be successful, while Kansas and Pennsylvania indicate that their research has been inconclusive. Only one state, Wisconsin, has indicated that the use of waste paper for mulch material will be included in future research activities.

Eight states (Georgia, Illinois, Kansas, Missouri, New Hampshire, Oregon, Pennsylvania, and Wisconsin) are using or have used waste paper as a mulching material on their highway systems. Missouri, in particular, reported that hydraulic mulch oversprays using slick paper have performed very successfully and have been recommended for adoption as a standard specification option for asphalt emulsion in Type 2 mulches *(47)*.

Use of Sanitary Landfill Refuse

Refuse from sanitary landfills is ordinarily undesirable for use in highway construction. There are, however, occasions when the right of way of a new or widened highway facility may have to traverse a portion of a sanitary landfill and require excavation or a change in grade of a part of the landfill. In most cases, refuse excavated from a sanitary landfill will be hauled off site and disposed of properly; however, the rising costs of disposal may warrant an evaluation of reusing some or all of the refuse material in embankment construction, either by processing and placing the refuse in thin layers, or by mixing the refuse with earth and compacting it.

Processing of refuse may involve milling, shredding, or screening, or any of these steps in combination. Mixing of processed refuse and soil may be accomplished by either

placing the refuse and soil in alternating layers in sandwich fashion, or by blending the refuse and soil together in a predetermined proportion before placement and compaction. A cover of natural soil should be placed on the top and sides of the refuse.

There is no active research in progress on the use of sanitary landfill refuse in highway construction. Any use of such a material should be preceded by a thorough sampling and laboratory testing program to identify and define the variability of the physical properties of the refuse, the degree of decomposition of the refuse, and the engineering and environmental characteristics of refuse and refuse-soil blends.

Sanitary landfill refuse has been incorporated into earthwork for road construction in several locations. Refuse was recycled into embankment and berm construction in southern California *(48)* as well as in Connecticut *(49)*. In each state, it was removed, processed, and placed back into the fill area in thin layers, alternating with native soil. In Connecticut, recycled refuse has also been used as core material for filling depressions and building raised medians.

There is a need to provide workers and other personnel who may be in the vicinity of compost or recycled refuse with information concerning its composition, the possible health risks, and the protective measures to be taken.

CHAPTER THREE

PRODUCTION AND USE OF INDUSTRIAL WASTES

The annual generation of non-hazardous industrial wastes in the United States involves between 350 and 400 million tons of materials, not counting dredge spoils. Industrial wastes included in this synthesis are

- Coal ash by-products,
- Advanced SO_2 control by-products,
- Construction and demolition debris,
- Iron and steel slags,
- Non-ferrous slags,
- Cement and lime kiln dusts,
- Baghouse fines,
- Reclaimed asphalt pavement,
- Reclaimed concrete pavement,
- Foundry wastes,
- Silica fume,
- Roofing shingle waste,
- Sulfate waste,
- Lime waste,
- Paper mill sludge, and
- Petroleum contaminated soils.

This chapter provides information on sources, quantities, possible uses, research pertaining to highway uses, and an overview of highway applications. Table 4 is a summary of the production and uses of these industrial wastes.

COAL ASH BY-PRODUCTS

Coal ash results from the burning of coal for power generation. Most of the coal is pulverized and burned at electric utility generating plants. The by-products resulting from coal combustion are fly ash, bottom ash, and boiler slag. There are approximately 420 coal-burning power plants located in 44 states. These plants generate nearly 66 million tons of coal ash annually, including 48 million tons of fly ash, 14 million tons of bottom ash, and 4 million tons of boiler slag, making coal ash one of the most plentiful mineral resources. Overall, only about 25 percent of all coal ash is used *(50)*.

Fly ash is often classified according to the type of coal from which it has been derived. The American Society for Testing and Materials (ASTM) divides fly ash into two classes:

- Class F–Fly ash produced from the burning of anthracite or bituminous coal, and
- Class C–Fly ash produced from the burning of lignite or sub-bituminous coal *(51)*.

Fly ash is a pozzolan, meaning that it reacts with calcium and water at ordinary temperatures to form cementitious compounds. Class F ash is pozzolanic, but Class C ash can also be hydraulic or self-setting because it has higher lime content than Class F ash. Class F ash is more plentiful, although Class C ash (from coals mined west of the Mississippi River) is now becoming available in more states east of the Mississippi River because a growing number of utilities are burning more low-sulfur coals *(52)*.

A survey of all 50 states indicates that 35 state highway agencies are now or have been performing research on various uses for fly ash. Of these, 30 states are investigating the use of fly ash as a cement replacement in portland cement concrete. Six states are evaluating fly ash as an embankment material, and six states are evaluating fly ash in stabilized base course applications. Five states are conducting research into the use of fly ash in soil subgrade stabilization. Four states are evaluating fly ash as a mineral filler in asphalt. Also, nine universities are now performing some research on fly ash uses, including evaluating the properties of high-volume fly ash in concrete.

Bottom ash and boiler slag have been or are now being studied by 11 states. Four states each are evaluating the use of bottom ash or boiler slag as either an embankment material, an unbound aggregate base material, an aggregate in asphalt paving, or as an anti-skid material. Also, one state is performing research on the use of bottom ash or boiler slag as an aggregate in stabilized base course construction.

The leading use of fly ash is as a partial replacement for portland cement in ready-mixed concrete or as a component of blended portland-pozzolan (IP) cement. To be acceptable for use in cement or concrete, fly ash must meet the physical and chemical requirements of ASTM C618 specifications. It is possible that up to 25 percent of all fly ash produced annually may be of C618 quality. This would amount to 14 million tons of fly ash, twice the amount now used annually in cement and concrete.

Fly ash in concrete is specified in 46 states, including all 44 ash-producing states, as well as California and New Hampshire. The only states that do not specify fly ash in concrete are Alaska, Hawaii, Idaho, and Maine. Six other states (Connecticut, Delaware, Kansas, Massachusetts, Rhode Island, and Vermont) specify fly ash in concrete, but have yet to use it. Of the 38 states that have used fly ash in concrete, all are using the material as partial cement replacement, 20 are using it in Type IP blended cement, and 7 allow the use of portland cement in which fly ash is part of the raw feed materials. There are 12 states that have some restrictions on the use of fly ash in concrete.

In most states, fly ash substitution rates range from 15 to 25 percent by weight of the cement in the concrete. However, Florida has replaced up to 50 percent by weight of cement in concrete in the mass foundations of the largest bridge in Florida, the Sunshine Skyway bridge. The performance of high-volume fly ash in concrete has been very good with respect to strength and durability, as supported by laboratory tests *(53)*.

TABLE 4
PRODUCTION AND USE OF INDUSTRIAL WASTES

Waste Type	Amount Generated Annually	Uses (by highway agencies)
Coal ash	66 million tons	
Fly ash	48 million tons	**Cement replacement Flowable fill and grout** **Embankments and fills** **Stabilized base Mineral filler in asphalt** **Soil stabilization**
Bottom ash	14 million tons	**Anti-skid material Embankments and backfill Stabilized base Asphalt paving**
Boiler slag	4 million tons	**Blasting grit Asphalt paving Stabilized base** Roofing granules
Advanced SO_2 Control by-products	5 million tons	**Stabilized base** **Soil stabilization**
Construction & demolition debris	25 million tons	**Embankment borrow Unbound base course** Wood as mulch
Blast-furnace slag (air cooled) (granulated)	15.5 million tons	**Concrete aggregate Asphalt paving** **Unbound base course** **Cement replacement**
Steel-making slag	7.9 million tons	**Asphalt paving Anti-skid material** Railroad ballast
Non-ferrous slags	10 million tons	**Concrete aggregate Asphalt paving** **Unbound base course** **Blasting grit** Railroad ballast
Baghouse fines	8 million tons	**Mineral filler**
Cement kiln dust	20 million tons	Recycled into clinker Waste stabilization Agricultural lime **Mineral filler in asphalt** **Stabilized base Soil stabilization**
Reclaimed asphalt pavement (RAP)	50 million tons	**Pavement Recycling Ashphalt paving** **Unbound base course** **Stabilized base**
Reclaimed concrete pavement (RCP)	3 million tons	**Coarse aggregate in concrete Unbound base course** **Stabilized base Asphalt paving**
Foundry sand	10 million tons	**Fill material Pipe bedding Asphalt paving**
Roofing shingle waste	10 million tons	**Asphalt paving and (Industrial scrap) cold patch material**
Sulfate waste	18 million tons	Wallboard manufacture (FGD scrubber sludge) **Cement production Stabilized base Embankment fill**
Lime waste	2 million tons	**Mineral filler in asphalt** **Soil stabilization**
Carpet waste	2 million tons	Fibers in concreteSilica fume < 1 million tons Mineral admixture orcement replacement
Paper mill sludge	Not determined	**Dust palliative** **Cement replacement Fly ash-bark ash blend**
Petroleum-contaminated soils	Not determined	**Stabilized base Asphalt paving (after thermal treatment)**

The Technical Appendix discusses in greater detail the use of fly ash in concrete on a state-by-state basis. Results of a follow-up questionnaire sent to 45 states that specify fly ash for use in concrete are also presented in the Technical Appendix. In addition, the Transportation Research Board (TRB) in 1986 published a Synthesis of Highway Practice on the use of fly ash in concrete *(54)*.

Fly ash is also used with portland cement in grouts for undersealing concrete pavements and flowable fill mixes. A total of 30 states report using such mixes, but at least 5 consider the use of flowable fill to be experimental. Most states specify flowable fill mixes in which sand, not fly ash, is the principal component. Kansas and Pennsylvania permit the use of bottom ash in lieu of sand in flowable fill mixes. There are also five states (Delaware, Maryland, Michigan, Pennsylvania, and Wyoming) that specify and have made some use of flowable fill mixes containing fly ash with no sand or other fillers.

At least 10 states have used fly ash to construct embankments and at least 3 states have used bottom ash as an embankment material. Fly ash has been used as a stabilized base material in at least 20 states during the past 35 years. In a number of these states, bottom ash or boiler slag has occasionally also been used as an aggregate in stabilized base mixes. Fly ash, mostly Class C ash, has been used for soil and subgrade stabilization in at least 6 states, mainly to treat expansive clay soils. Bottom ash or boiler slag has been used as an aggregate in asphalt paving mixtures in at least 4 states. Fly ash has been used as a mineral filler in asphalt paving in at least 9 states. Bottom ash or boiler slag has been used as an anti-skid material on snow- and ice-covered roadways in at least 4 states.

Advanced SO_2 Control By-Products

Advanced SO_2 control by-products are typically dry powdery materials physically resembling fly ash and chemically similar to Class C fly ash because of their relatively high calcium content. These materials are by-products of emerging "clean" coal-burning technologies, such as fluidized bed combustion, spray drying, and dry limestone or sodium furnace injection. Each of these technologies involves burning coal under controlled conditions and reacting the flue gas with a dry chemical reagent to remove sulfur dioxide from the emissions. Wet scrubbing of coal burning flue gases is discussed later in this chapter under sulfate wastes. However, advanced SO_2 control by-products also contain fairly high percentages of sulfate.

There are presently 60 operating fluidized bed combustion boilers, most of which are industrial cogeneration units. These boilers produce both a fly ash and a bed or bottom ash. The resultant ash will be predominantly bottom ash in most cases, depending on the sizing of the coal and the gradation of the limestone in the bed. There are at least 10 coal-fired power plants with spray dryer or dry scrubber systems. Spray dryer by-product is a very fine powdery material, normally collected in baghouses, that results from dry flue gas scrubbing. Dry limestone or sodium furnace injection is still in the developmental stages, with only a few test installations in place at this time. Dry furnace injection by-products are also fine powdery materials *(55)*.

To date, at least one field experiment has been conducted on private property in Minnesota on the use of dry scrubber by-product in subgrade and base course stabilization and as a possible embankment material. The Tennessee Valley Authority and the Kentucky Transportation Cabinet have each co-sponsored an experimental stabilized base course installation using bottom ash from a utility fluidized bed combustion boiler *(56, 57)*.

Due to the relatively small quantities of these by-products at present, plus the expansive tendency of these materials due to the presence in them of unreacted lime and sulfate, advanced SO_2 control by-products are still very much in the experimental stage. The unreacted lime in some of these materials also makes them difficult to handle, sometimes resulting in an exothermic reaction when mixed with water.

CONSTRUCTION AND DEMOLITION DEBRIS

Although precise figures are not readily available, it is estimated that at least 20 to 30 million tons per year of construction and demolition (C&D) debris are generated in the United States. C&D debris consists largely of wood and plaster, but also includes concrete, glass, metal, brick, shingles, and asphalt *(58)*. Portions of this debris that are reclaimed, crushed, and processed into aggregate include concrete, bricks, glass, and old asphalt. Recycling of C&D debris is done regularly at numerous processing locations around the country, mainly in large metropolitan areas. To be marketed effectively, the processed material must be free of deleterious components such as wood, drywall, and plastic, and must be capable of meeting gradation and other aggregate quality requirements. Wood and tree stumps can also be separated, shredded, and converted into wood chips and mulch. The wood chips can be used as fuel, landscaping material, or as a bulking agent in sludge composting.

Many of the materials dumped at C&D landfills are not accepted at sanitary landfills and cannot be composted. Although C&D debris is intended to be inert and essentially inorganic (except for wood), potential problems can occur if illegal dumping is not prohibited. Possible contaminants that could be included in C&D debris are sewage sludge, which causes odors, and asbestos, which is hazardous *(59)*.

At least five state highway agencies have been researching the possible use of rubble from C&D debris as a highway construction material. Three states are investigating its potential for use as an embankment borrow source. Two states are evaluating this material as an unbound base course aggregate, and one state is examining the possibility of using it as an aggregate in asphalt paving. Three states have indicated some limited use of C&D debris. Two states have used the rubble portion as embankment borrow. One other state has used this material as an aggregate base and a concrete coarse aggregate. It is quite likely that C&D debris has been used in local road construction.

Although not mentioned in the questionnaire responses, the wood fraction of C&D debris, when shredded and properly prepared, could be useful as lightweight fill, landscaping material, or mulch, provided the wood was not previously treated or painted.

IRON AND STEEL SLAGS

Blast-furnace slag is the non-metallic by-product derived from producing iron in a blast furnace. The slag consists mainly of silicates and alumino-silicates of lime. Three basic types of blast-furnace slag are produced: air-cooled, granulated, and expanded. Air-cooled blast-furnace slag is a fairly porous, lighter weight (75 lb/ft^3) aggregate material. In 1989, a total of 15.5 million tons of blast-furnace slag were sold, about 90 percent of which was air cooled. Blast-furnace slag is sold in 13 states, primarily Pennsylvania, Ohio, Indiana, Illinois, and Michigan *(60)*. Many large stockpiles or banks of slag have accumulated in these and other states. One deterrent to slag use is the commingling of blast furnace and steel slags in old slag banks. Air-cooled blast-furnace slag is commonly used in concrete, asphalt, and road bases, and as fill material. Granulated slag is finely ground for use as slag cement. Expanded slag is sold as aggregate for lightweight concrete.

Steel slag is formed when lime flux reacts with iron ore, scrap metal, or other ingredients in a steel furnace. Steel slag consists of a fused mixture of oxides and silicates, mainly calcium, iron, unslaked lime, and magnesium. Three basic types of steel furnaces (open hearth, basic oxygen, and electric arc) produce three types of steel slags. Approximately half of all currently operating steel furnaces are electric arc furnaces. Many older slag banks contain open hearth slag. All steel slag is air cooled. In 1989, 7.9 million tons of steel slag were sold in the United States. There are steel slag processing locations in 26 states *(60)*. The largest quantities are produced in leading blast-furnace slag states. Steel slag has expansive tendencies unless properly aged with water. It is heavier than normal aggregate and is very hard, stable, and abrasion resistant. Steel slag has been used in asphalt paving, fill material, and railroad ballast, and for snow and ice control.

Air-cooled blast-furnace and steel slags have been well accepted sources of aggregate for many years, especially blast-furnace slag. Granulated blast-furnace slag has gained some acceptance within the past 10 years as a cementitious material. A number of state highway agencies have researched various uses for these slags. At least 18 states have evaluated air-cooled blast-furnace slag, with 13 states monitoring its use in asphalt, 6 states its use in concrete, and 4 states its use as an aggregate base. Four states are also investigating the use of ground granulated slag as a cement. At least 11 states have evaluated steel slag, with 9 states monitoring its use in asphalt, 4 states its use as an aggregate base or subbase, and 1 state each its use in embankments, chip seals, or as anti-skid material.

At least 22 states have made use of air-cooled blast-furnace slag, mainly as an aggregate in asphalt or cement, but also in aggregate bases and subbases. Granulated blast-furnace slag has been used as a cementitious material in at least two states. Steel slags have been used as aggregates in asphalt paving in at least 11 states. In at least two other states, steel slag has been used as a subbase aggregate or an embankment material. If used in applications other than asphalt paving, steel slag should be properly aged with water. Recently, there have been reports of leachate from slag fills and bases clogging drains and fouling nearby surface waters *(61, 62)*. Such problems are more often attributed to the use of steel slag, not blast-furnace slag.

Non-Ferrous Slags

Approximately 10 million tons of non-ferrous slags are produced annually from thermal processing of copper, lead, zinc, nickel, and phosphate ores. In the mid 1980s, there were 36 primary metal smelter operations located in 17 states, mostly west of the Mississippi River. Some of these operations may now have been closed, because of air emission concerns. Approximately 4 million tons each of copper and phosphate slag are produced annually, while lead, zinc, and nickel slags total 0.5 to 1.0 million tons per year. Non-ferrous slags are produced in either an air-cooled or a granulated form. Copper, lead, and zinc slags are ferrous silicates. Phosphate and nickel slags are calcium or magnesium silicates. All contain some concentration of the metals in the ores from which they were produced *(63)*. Some non-ferrous slags have been used successfully in asphalt and concrete mixtures, in road base materials, and as railroad ballast. Granulated copper slag has also been used as a bridge blasting abrasive *(64)*.

There is relatively little documentation concerning the research into or use of non-ferrous slags in highway construction, even though in many cases these slags may be suitable engineering materials. Only four states have indicated any current research on non-ferrous slags. All four states are evaluating the use of these slags as aggregate in asphalt mixes; one state is also investigating the possible use of non-ferrous slag as an anti-skid material on icy roadways. A number of years ago, in a cooperative study with Oklahoma State University, the Oklahoma Department of Highways tested zinc smelter residues for possible use in stabilized base mixtures, asphalt paving, and portland cement concrete. These materials were adjudged satisfactory for use as aggregate in asphalt and stabilized base mixtures, but not recommended for use in concrete *(65)*.

Only four states (California, Florida, Tennessee, and Texas) indicate any use of non-ferrous slags. California has made limited use of a copper oxide blasting slag in asphalt mixes. Florida and Tennessee have used phosphate slag as an aggregate in asphalt paving. Texas has used aluminum slag as an aggregate in asphalt paving, but the material tended to break down and is no longer used. A review of technical literature reveals that copper reverberatory slag from the Upper Peninsula of Michigan has been approved by the Department of Transportation for all aggregate uses, except as a fine aggregate in portland cement concrete *(66)*.

CEMENT AND LIME KILN DUSTS

An estimated total of 20 million tons of cement kiln dust are collected annually, approximately 60 percent of which is recycled at cement plants. This leaves approximately 8 million tons of cement kiln dust per year to be landfilled or reused in some way *(67)*. Cement kiln dusts are fine powdery materials, portions of which contain some reactive calcium oxide, depending on the location within the dust collection system where the material is collected. Some cement kiln dusts have been used with fly ash and aggregates to produce stabilized base course mixtures. Cement kiln dust has also been utilized as mineral filler in asphalt. Aside from cement production, the principal uses of cement kiln dust are for stabilization of mu-

nicipal sewage sludge and as a substitute for agricultural limestone. Because a number of cement kilns are burning hazardous waste as a supplemental fuel source, some investigation of fuel composition should be undertaken prior to using any given source of cement kiln dust.

Lime kiln dusts are physically similar to cement kiln dusts, although chemically different, depending on whether high calcium or dolomitic lime is being produced. Some high-calcium lime kiln dusts contain considerable free lime and may be very reactive when mixed with water. An estimated total of 2 to 4 million tons per year of lime kiln dust is generated at commercial lime plants, primarily from rotary kilns *(K. Guttschick, National Lime Association. Private Communication).* Much of this dust is disposed of in landfills, although some has been used as a mineral filler, fill material, or in soil or road base stabilization. Lime kiln dust is also being used in agriculture and in municipal sewage sludge stabilization.

Although kiln dusts are potentially useful construction materials, research and actual use of kiln dusts for highway-related applications has been limited. Only eight states have indicated they have researched possible uses for cement kiln dust—in stabilized base mixes in four states, as mineral filler in three states, for soil stabilization in two states, and as an embankment material in two states. Only four states have researched possible uses for lime kiln dust—for soil stabilization in three states, and as mineral filler and stabilized base mix in the fourth state. The South Carolina Department of Transportation intends to conduct research on the use of cement kiln dust as a stabilization reagent for graded aggregate bases.

Very few states have actually used either cement kiln dust or lime kiln dust in highway construction and several of these states do not consider such use to have been successful. Five states have used cement kiln dust—as mineral filler in two states, as stabilized base in two states, and for soil stabilization and as an embankment material in one state. The embankment and soil stabilization uses were considered unsuccessful, as were the mineral filler and stabilized base uses (in one state each). Lime kiln dust has been used in only one state (Kentucky) as a reagent in a successful stabilized base installation.

Baghouse Fines

The majority of hot-mix asphalt plants in the United States are equipped with dust collection systems. The resultant dusts, which are finely graded, are collected in baghouses and typically returned to the plant as a portion of the mineral filler. Most baghouse fines are reused routinely in this manner with little to no adverse impact on hot-mix characteristics. Some states do limit the percentage of baghouse fines that can be recycled as filler because of concerns with tender mixes *(68).* It is estimated that approximately 8 million tons of baghouse fines are generated annually, based on 2.5 percent dust per ton of stone used *(68).*

RECLAIMED ASPHALT PAVEMENT

Based on extrapolations from state agency questionnaire responses, it is estimated that approximately 50 million tons of asphalt paving material are currently being milled annually. Much of this material is returned to producers' yards for use in paving mixes. In order to maintain mix temperatures satisfactorily, only about 20–50 percent of all the milled asphalt paving material is able to be recycled into hot-mix asphalt paving mixtures *(69).* Reclaimed asphalt pavement (RAP) can be recycled into hot mixes, cold mixes, or in-place mixes. RAP can also be used in other highway uses, as in unbound aggregate base and subbase, stabilized base course, shoulder aggregate, and open-graded drainage courses.

At least 36 states have been or are now performing research on various uses for RAP. This includes 32 states that are investigating the recycling or reuse of RAP in new asphalt paving, 10 states evaluating RAP in aggregate base or subbase, 3 states studying RAP use in stabilized base course, and 1 state that is evaluating the use of RAP as a coarse aggregate in concrete mixes. At least three states are planning research into uses for RAP. Also, there are at least three research investigations on uses for RAP being conducted at the university level.

Virtually every state is making use of RAP in some way, with recycling into asphalt paving mixes being the most predominant application. At least 16 states report they have used RAP as unbound aggregate base or subbase. Two states have used asphalt millings as aggregate in stabilized base courses. One state has actually reused RAP as a concrete aggregate.

A follow-up questionnaire on the use of RAP in asphalt was distributed to all 50 state highway agencies (see Appendix B). All 50 of these state agencies responded to the questionnaire. Information was sought on the maximum percentages of RAP in hot-mix asphalt specified for various layers of pavement, compared with percentages of RAP actually being used. The questionnaire also obtained information on states using cold in-place recycling and states with growing RAP stockpiles in state or contractors' yards. Generally, the percentage of RAP used in various pavement layers for hot-mix recycling is less than the maximum percentage of RAP specified. Only 3 states reported adding RAP at the maximum specified percentage, while 8 states reported that the percentage of RAP added was less than half the maximum specified. Eleven states used no RAP in surface mixes, 3 used no RAP in binder mixes, and 5 used no RAP in base course mixes. A total of 32 states perform some cold in-place recycling. A microwave process that has the potential to recycle up to 100 percent of RAP into hot-mix asphalt is currently being evaluated *(70).*

Concerning the growth of RAP stockpiles, 18 states believed they are growing, 29 states did not, and 3 were uncertain. The growth of RAP stockpiles does not appear to be considered a serious problem among state highway agencies, probably because asphalt producers and paving contractors find many uses for RAP materials.

RECLAIMED CONCRETE PAVEMENT

The American Concrete Pavement Association (ACPA) has indicated that approximately 200 mi of concrete pavement are being recycled each year *(M. Knutson, American Concrete Pavement Association. Private Communication).* Assuming these pavements are two lanes wide and 10 in. thick, and using a recovery factor of 75 percent, then approximately 6,000

tons of concrete can be reclaimed from every mile of concrete pavement. This indicates that roughly 2.9 million tons of reclaimed concrete are being recycled annually. Generally speaking, recycled coarse aggregate (material larger than 3/8 in.) is more suitable than recycled fine aggregate (material smaller than 3/8 in.), especially when reused in concrete mixes *(71)*. Reclaimed concrete pavement (RCP) is also useful as an unbound base course aggregate, in cement-treated base, as an asphalt paving aggregate, as embankment base material, and as riprap.

The recycling of concrete pavements in this country began about 20 years ago. Early efforts reused concrete paving rubble as an unbound aggregate base and in asphalt base and binder courses. Within a few years, recycled concrete aggregate was being used in asphalt-wearing surfaces. The FHWA coordinated research among state highway agencies to evaluate the suitability of RCP as an aggregate source in concrete mixes. This work included laboratory studies, mix design testing, and performance evaluation of RCPs. These studies have proven that recycled concrete aggregates produce strong, durable concrete suitable for use in pavements, even when RCP aggregate is derived from distressed paving concrete (D-cracking or alkali-silica reaction).

Over the years, the recycling of concrete pavements has become more cost competitive with the development of improved methods and equipment for breaking concrete pavements, removing the steel from the broken concrete, and crushing slabs with reinforcement *(71)*. In many instances, concrete pavement recycling is a viable alternative to complete reconstruction, concrete pavement rehabilitation (CPR), or an overlay of an existing deteriorated pavement. Existing concrete pavement must be considered as a resource that can and should be recycled or reused in some application, much in the same way as asphalt pavement recycling is now commonly practiced.

Although techniques for recycling pavements have advanced markedly, a number of state highway agencies are still evaluating the use of RCP aggregates. Responses to the questionnaires indicated that at least 12 states are performing, or have performed, research into the use of RCP aggregate in new concrete. Six states have also investigated the use of RCP aggregate in unbound base courses. Two states each have evaluated RCP aggregate in stabilized base or as a subbase material. One state has studied the use of RCP aggregate as riprap. Two other states will be undertaking research on uses for RCP aggregate: Mississippi will examine the reuse of RCP aggregate into asphalt pavement mixes, while Ohio will investigate the recycling of RCP aggregate into new concrete pavement.

According to the questionnaire responses, at least 16 states are now recycling concrete pavements. In eight of these states, the RCP aggregate is being reused in new concrete. Five states use RCP aggregate as a subbase material. Four states report using RCP aggregate in unbound base course construction. Four states are using RCP aggregate in asphalt paving mixes. One state is recycling RCP aggregate into stabilized base course mixes.

FOUNDRY WASTES

The principal types of foundry wastes include furnace dust, arc furnace dust, and foundry sand residue. The overall estimated quantity of foundry waste produced annually is believed to range from 10 to 15 million tons. There are approximately 2,300 active foundry operations in the United States, with Illinois, Wisconsin, Michigan, Ohio, and Pennsylvania having the most foundries *(G. Mosher, American Foundrymen's Society. Private Communication)*. The presence of trace metals generally precludes the use of foundry dusts as fill material, since these dusts are normally disposed of as a hazardous waste. Foundry sand is not hazardous, occurs in greater volume, and has been used sporadically as a fill or pipe bedding material or as a fine aggregate in asphalt paving mixtures. The principal concerns with using foundry sands are its fine, uniform gradation and the presence of contaminants (stones, trash, etc.) in the sand; some trace chemicals may also be present.

Through the efforts of the foundry industry, attempts are being made in a number of states to gain approval for the recycling and reuse of the sand reclaimer residues from foundries as a useful construction material. As an example, the Pennsylvania Department of Environmental Resources (DER) recently granted a beneficial reuse approval for the use of foundry sand in asphalt paving and as pipe bedding material *(G. Boyd, Pennsylvania Foundrymen's Association. Private Communication)*.

Responses to the questionnaires reveal that only five states are engaged in research efforts aimed at finding highway construction uses for foundry wastes, in particular foundry sands. Four of these states are investigating the potential for using waste foundry sand as a fine aggregate in asphalt paving. One state is evaluating foundry sand as a sand substitute for pipe bedding, and one state is studying the possible use of foundry sand as an embankment borrow material. Also, Missouri is planning to evaluate foundry sand as an aggregate in asphalt paving.

Research at Purdue University has identified types and characteristics of foundry waste sands, together with potential highway construction uses *(72)*. In addition, the University of Wisconsin–Milwaukee is researching potential highway uses for foundry sand.

Only two states have indicated any field use of foundry waste sand in highway construction. Illinois has used the material as a sand substitute, but did not consider its performance to be acceptable. Wisconsin has used foundry waste sand as an embankment material and considers it acceptable for this use, as long as it can meet environmental standards.

SILICA FUME

Condensed silica fume or microsilica is a by-product of the manufacture of silicon and ferrosilicon alloys. Silica fume particles are 10 to 20 times finer than fly ash and are very pozzolanic because of their high silica content and specific surface area. Nearly 100,000 tons per year of silica fume are produced at 15 alloy furnace locations in 8 states. The material is available commercially as a powder or as an aqueous dispersion or slurry for use as a partial replacement for portland cement in concrete, especially for bridge decks, parking garages, and other surfaces subjected to deicing salts and freeze-thaw cycles *(73)*.

The original investigations of the use of silica fume in concrete were undertaken in Norway in the early 1960s. Research organizations in Canada and the United States initiated silica fume research in the 1980s. The use of silica fume increases the strength of the bond between the paste and the aggregate through a pozzolanic reaction, in which the finely divided amorphous silica particles combine with lime from the hydration of the portland cement to form a calcium silicate hydrate. For this mechanism to occur, it is essential that silica fume particles be well dispersed in a concrete mixture. To achieve this dispersion, the use of high-range water reducers or superplasticizers is almost mandatory *(74)*.

The use of silica fume as an admixture gives a darker color to the surface of concrete. Because of its extremely fine, spherical particles, silica fume fills the pores in the concrete, significantly reducing permeability, decreasing chloride ion penetration, and improving resistance to freezing and thawing, as well as chemical attack. The use of a pozzolanic admixture also helps control alkali-silica reactivity. Silica fume contributes to an optimum development of compressive strength in concrete mixes, especially with the addition of a superplasticizer. Silica fume is typically substituted for portland cement at a rate of 10 to 20 percent by weight of the cement *(74)*.

According to questionnaire responses, only three states (Florida, New Hampshire, and Oregon) are conducting any research into the use of silica fume in concrete mixes. No other state highway agencies are contemplating any research on silica fume, nor is there any current research on uses for this material at the university level.

Only five states have indicated any field use of silica fume as an admixture in concrete. Alabama reports excellent results. Florida found that concrete with silica fume shows excellent strength and durability. Specifications are being prepared that will allow extensive use of silica fume in highway bridges in Florida. Oregon experienced mixed results after observing micro-cracking on a bridge deck surface on one project. Missouri and New Hampshire did not indicate how the material has performed.

ROOFING SHINGLE WASTE

Approximately 10 million tons of roofing shingle waste are generated annually as scrap and leftover materials at shingle manufacturing operations. The waste consists of shingle fragments and tabs, together with asphaltic binder and granules. Lower quantities of waste shingles are also generated by roofers and demolition contractors, but such sources may be contaminated. Roofing shingle waste has been recycled into asphalt paving materials, either in hot-mix or as cold-patch materials *(75)*.

According to questionnaire responses, Florida and Minnesota are the only states known to be performing any research on the possible use of waste roofing shingles in asphalt paving mixes. Research underway at the University of Minnesota has also included a test section on a bike path in Minneapolis. Illinois, Minnesota, and Missouri are the only states that have indicated some use of waste roofing shingle material. In Illinois, waste shingles are being used by an asphalt contractor in Chicago as an aggregate in cold-patch material *(76)*.

SULFATE WASTE

The principal source of sulfate waste in the United States is the wet scrubbing of flue gases at coal-burning power plants, using either a lime or limestone sorbent. This results in a calcium sulfate or silfite slurry, referred to as flue gas desulfurization (FGD) sludge. Most wet scrubbing systems are of the forced oxidation variety, which generates a gypsum or calcium sulfate by-product.

At least 52 coal-fired boiler units at 88 power plants have operating wet scrubbing systems. These plants are located in 28 states *(77)*. These units are generating approximately 18 million tons of FGD sludge annually *(50)*. Additional scrubbers are either planned or under construction in order to achieve compliance with the 1991 Clean Air Act. The additional scrubbers will result in the production of even higher volumes of FGD sludge.

FGD sludge may be disposed of in landfills by ponding the gypsum slurry, landfilling gypsum filtercake, interblending filtercake with fly ash, or through stabilization/fixation by interblending the filtercake with lime and fly ash to achieve a pozzolanic reaction. In lieu of disposal, the stabilized or fixated by-product has some reuse potential, either as raw feed material for the production of portland cement, as by-product gypsum for the manufacture of wallboard, or as a road construction material *(78)*.

To be useful as a road construction material, FGD sludge must be dewatered. Calcium sulfate sludges are easier to dewater than calcium sulfite sludges. A stabilized by-product can be produced by blending dewatered sludge filtercake with either lime fly ash, cement fly ash, or portland cement. The blended filtercake can then be placed and compacted as stabilized base material, capable of attaining field-cured compressive strengths ranging from 400 psi to in excess of 1,000 psi, depending on the percentage addition of the reactant(s). Stabilized FGD sludge road base compositions have been placed in the field and have demonstrated acceptable durability and load-carrying capability *(79)*.

Questionnaire responses reveal that six states are conducting research into possible uses for FGD scrubber sludge. Two states are evaluating the use of stabilized FGD sludge in stabilized road base. The potential for using this material in embankments or in shoulders is also being investigated (by one state each). One state is studying the possible use of FGD sludge as a dust palliative, and one state is researching its potential as an asphalt-cement modifier. Southern Illinois University is studying the geotechnical properties of FGD sludge.

Only five state highway agencies have made any use of sulfate waste or FGD sludge in construction projects. Kentucky and Pennsylvania have incorporated fixated scrubber sludge into embankments. Alaska has used wet sludge as a dust palliative. Louisiana has used stabilized FGD sludge as shoulder material. Texas has made limited use of sulfate waste in stabilized bases.

Carpet Waste

Approximately 2 million tons of carpet wastes are disposed of annually. Recycled polypropylene fibers from used carpets have been studied for possible reinforcement of concrete. Re-

inforcement with 2 percent carpet waste fiber was found to be as effective as that with 0.5 percent virgin polypropylene fibers. Although compressive strengths of fiber-reinforced specimens were reduced, there was some improvement in flexural strength and toughness *(80)*. No state agencies indicate any research or use of recycled carpet fibers in concrete at this time. Georgia Tech University is performing research on the potential use of recycled carpet fibers for reinforcement of concrete.

Lime Waste

Carbide lime is a waste product generated in the manufacture of acetylene. The process may be carried out with or without excess water, resulting in either a sludge or a powdery byproduct. The amounts of carbide lime being generated are somewhat limited and are decreasing due to an increase in the production of acetylene from petroleum feedstock. The physical and chemical properties of dry carbide lime are similar to those of commercial hydrated lime. Carbide lime has some potential for use in soil stabilization or as a mineral filler in asphalt paving mixes *(81)*.

Carbide lime waste is being evaluated by two states (Kentucky and Missouri) as a soil stabilization reagent. Ohio is investigating its potential for use as a mulching material. A recent study was made of the potential for using dewatered carbide lime sludge as a mineral filler in asphalt paving mixtures. The results showed that carbide lime waste was particularly effective in improving the viscosity and temperature susceptibility of the trial mixes and easily satisfied all stability, flow, and air voids criteria *(82)*.

There is no research underway or planned at the university level into applications for lime waste. No field use has been made of lime waste, according to state highway agency questionnaires, nor is any research being planned.

Paper Mill Sludge

Most of the waste material generated by the pulp and paper industry is in the form of inorganic sludges of relatively low solids content. The paper industry also generates spent sulphite liquor or lignin sulphonate, which has occasionally been used as a dust palliative. Spent sulfite liquor may have some potential for soil stabilization, although it is probably of greater use as a filler in the paper industry *(81)*. Present quantities and disposition of paper mill sludge can not be readily determined.

There is no indication of any research by either state highway agencies or universities into the potential highway applications for paper mill sludge. However, Wisconsin has made use of paper mill sludge for dust control purposes.

Florida has conducted a study to evaluate the use of a fly ash-bark ash blend to replace up to 20 percent of the portland cement in concrete. The blend consists of 92 percent Class F fly ash and 8 percent bark ash. The bark ash is a residue of burning bark in paper mills. The bark ash is fed into coal pulverizers, ground along with the coal, and burned. The blend of fly ash and bark ash is then retrieved. Results of this study have shown that concrete with this blend has performance equal to that of concrete with Class F fly ash. The Florida Department of Transportation is considering a request to allow the use of the fly ash-bark ash blend in concrete *(L. Smith, Florida Department of Transportation. Private Communication)*.

PETROLEUM-CONTAMINATED SOILS

Promulgation of underground storage tank regulations by the EPA has resulted in increased remediation efforts for leaking storage tanks, including the removal of petroleum-contaminated soils in the vicinity of the leaking tanks. It is estimated that at least 25 percent of all underground oil and gasoline storage tanks more than 2 years old show some signs of leakage and that each leaking tank results in approximately 30 to 50 yd^3 of contaminated soil *(83)*.

There are at least three construction-related alternatives to the disposal of petroleum-contaminated soils. One is to treat the soil with portland cement and use it as a stabilized base material. These soils can also be remediated and used as fill material or as fine aggregate in asphalt paving mixes. Or, the hydrocarbons can be removed either by thermal treatment facilities or as the soil is processed in a hot-mix plant. Contaminated soils have also been used as aggregate material in emulsified asphalt cold mixes.

No current research on the potential highway uses for petroleum-contaminated soils is being conducted by state highway agencies. Research on the potential use of petroleum-contaminated soils in hot-mix asphalt is being conducted at the New Jersey Institute of Technology *(84)*. Although no state highway agencies have indicated any use of petroleum-contaminated soils on state road facilities, there is growing use of these soils in construction of private roads and streets, parking lots, and local roads.

CHAPTER FOUR

PRODUCTION AND USE OF MINERAL WASTES

Approximately 1.8 billion tons of mineral processing wastes are generated in the United States every year. In addition to these huge volumes, there are literally mountains of solid waste accumulated from past mining activities that are visible in many parts of the country. Mineral processing wastes can be further classified as follows:

- Waste rock,
- Mill tailings,
- Quarry waste,
- Coal refuse,
- Washery rejects,
- Phosphogypsum, and
- Spent oil shale.

Table 5 presents a summary of the production and uses of mining and mineral processing wastes.

WASTE ROCK

Approximately 1 billion tons of waste rock, including overburden, are generated by the mining industry each year. The largest amounts of waste rock are produced from surface mining operations, such as open-pit copper, phosphate, uranium, iron ore, and taconite mines *(85)*. Although some waste rock has been crushed and used as construction aggregate, many of the largest open pit mines are located in remote areas, far removed from markets where construction materials are needed.

Waste rock can range in size from boulders to gravel. Geologically, many waste rock sources are similar to rock types used to produce crushed stone and possess considerable hardness, especially waste rock from iron mining. As with natural aggregate, waste rock can be crushed and screened to a desired gradation.

Among the environmental concerns that may be associated with some waste rock sources are the following:

- Acidic leachate from sulfide-based metallic ores,
- Low-level radiation from uranium and phosphate rocks, and
- Sulfuric acid contact during heap leaching.

No state highway agencies or universities are conducting research involving waste rock and its potential uses. A review of published and unpublished reports reveals that at least 13 states have made use of some source of waste rock in their state highway construction programs, sometimes dating back as many as 50 years ago. There is probably also a substantial number of counties, small towns, or local road agencies that have been able to use waste rock from a nearby mining operation as a construction material. According to the responses to the questionnaires, New York is the only state now using waste rock as a highway material. It is being used as stone fill for embankments and as riprap for bank and channel protection. Performance has been described as very good in each application.

MILL TAILINGS

Mill tailings are the fine-graded waste products generated from ore concentration processes. Approximately 500 million tons per year of tailings are produced from milling operations. The largest amounts of tailings are generated from the concentration of copper, iron and taconite, lead, zinc, and uranium ores. Typically, tailings range from sand to silt-clay in particle size and are disposed of in slurry form by pumping into large ponds. The grain size distribution of mill tailings can vary considerably, depending on methods of ore processing, the percentage of solids in the tailing slurry, and the location of the sample in the tailing pond relative to the point of discharge. Because trace metals remaining from ore processing may be able to leach from fine-grained tailings that have a high surface area, the chemical composition and leaching characteristics of tailings sources must be determined before making any decision to use these materials.

Mine or mill tailings have a relatively long history of being used as construction materials in areas where they are plentiful and supplies of more conventional materials may be limited. There are many instances in which such tailings have been used extensively in embankments and in asphalt pavements by state and local highway agencies. From time to time, some sources of mill tailings have been used by state and local highway agencies as fill materials, in base courses, and in asphalt paving mixes *(85)*.

A review of responses to state highway questionnaires shows that five state agencies are involved in research with mine or mill tailings. These states are Kansas, Missouri, Nevada, New York, and Oklahoma. All five have been evaluating tailings as aggregate in asphalt mixes. Individual states are investigating the use of tailings as an aggregate in concrete, as riprap aggregate, or as chip seal aggregate. No other state research on tailings is now planned and no university is conducting research on tailings.

At least 16 states have indicated some construction use of tailings, with 10 of these states having built embankments out of tailings. As an example, during the 1970s, more than 3 million tons of copper mill tailings were used to construct embankments for Interstate Highway 215 near Salt Lake City,

TABLE 5
PRODUCTION AND USE OF MINERAL WASTES

Waste Type	Amount Generated Annually	Uses (by highway agencies)
Waste rock (includes overburden)	1.0 billion tons	**Crushed Aggregate** **Riprap** **Embankment fill**
Mill tailings	500 million tons	**Embankment fill** **Base courses** **Asphalt aggregate** **Chip seal aggregate**
Quarry waste	175 million tons	**Borrow material** **Cement-treated subbase** **Flowable fill**
Coal refuse	120 million tons	**Embankment fill**
- Coarse refuse	90 million tons	**Stabilized base**
- Fine refuse	30 million tons	Fuel source
Washery rejects		
- Phosphate slimes	100 million tons (wet)	None
- Alumina mud	5 million tons (wet)	**Subbase material (unsuccessful)**
Phosphogypsum	35 million tons	**Stabilized base (use now prohibited)**
Phosphogypsum slag	Currently experimental Several million tons are possible in the future	**Asphalt aggregate** **Mineral filler**

Utah *(D.R. Cummings, Kennecott Copper Company. Private Communication)*. Tailings have also been used in aggregate base courses, in concrete mixes, as subbase material, as riprap, and as an anti-skid material, although that use was not considered successful.

QUARRY WASTE

Quarry waste consists mainly of the fines from stone washing, crushing, and screening at quarries, as well as some wet silty clay material from the washing of sand and gravel. These materials are not sized to meet specification requirements and are usually placed in ponds or stockpiled in a saturated condition. Consequently, these materials must be reclaimed and dewatered prior to use. It is estimated that at least 175 million tons per year of quarry waste are being generated, mostly from crushed stone operations. As much as 4 billion tons of quarry waste have accumulated. The physical properties, chemical composition, and mineralogy of quarry and fines vary with aggregate type and producer source, but are relatively consistent at each quarry location *(86)*.

Quarry waste fines may be useful as fill or borrow material, as filler in concrete and flowable fills, in base or subbase stabilization, or as cement-stabilized base material for parking lots or low-volume roads *(86)*. A study of potential uses for quarry fines was performed for the National Stone Association. Applications recommended as having potential for using the highest volumes of quarry waste are cement-treated subbase and flowable fill. Other uses are as mineral filler in asphalt or as slurry seal aggregate *(87)*. Responses to state highway agency questionnaires indicate that quarry wastes have been used in Arkansas, Florida, Georgia, Illinois, Missouri, and Vermont.

COAL REFUSE

Approximately 120 million tons of coal refuse result each year from the cleaning of coal (predominantly bituminous coal) at more than 600 preparation plants in 21 coal-producing states. Total accumulations of coal refuse are in the range of 3 to 4 billion tons *(85)*. States with the largest amounts of coal refuse are Kentucky, West Virginia, Pennsylvania, Illinois, Virginia, Ohio, and Indiana. Coal refuse can be classified as

either coarse or fine, with the dividing size usually being the No. 4 sieve. About 70 to 80 percent of coal refuse is coarse, consisting largely of slate or shale with some sandstone or clay. Coarse refuse is usually disposed of in large banks. Fine refuse is a silt-size slurry that is sluiced into impoundments or holding ponds.

Coarse coal refuse is a well-graded material, with nearly all particles being less than 4 in. Coarse coal refuse is subject to weathering and degradation, but once the refuse has been compacted to its maximum dry density, its basic physical properties are usually stable. The main environmental concerns with using coal refuse are the possibility of the refuse being subject to spontaneous combustion and the potential for acidic leaching into groundwater. Both of these concerns can be alleviated by placing the refuse material in thin, well-compacted layers and covering all exposed surfaces with several feet of earthen material.

Presently, only two states are researching the possible use of coal refuse in highway construction. Maryland is investigating the use of the material in embankments, and West Virginia is evaluating it as a subbase material. No other state agency research is planned for this material. There is also no current research on coal refuse in any universities, although both Penn State University and West Virginia University have performed a number of excellent studies involving coal wastes in the past.

A review of the literature indicates that embankments constructed out of coal refuse have been built over the years in at least four states (Illinois, Maryland, Ohio, and Pennsylvania). West Virginia has used coarse coal refuse as stabilized subbase material.

WASHERY REJECTS

This category of mineral wastes deals with the by-products of the phosphate and aluminum industries. Benefication of phosphatic clay results in the generation of sand tailings and phosphate slimes. Phosphate slimes are colloidal materials, mostly less than 1 micron in diameter, that are disposed of in huge ponds at solids contents ranging from 2 to 6 percent. Because of their fine particle size, settlement rates are extremely slow. Even after many years, solids contents rarely exceed 20 percent. In excess of 100 million wet tons of slimes must be disposed of annually by the phosphate industry, mainly in central Florida, but also in North Carolina and Tennessee *(85)*.

The extraction of alumina from bauxite ores also produces clay-like by-products, which are disposed of in slurry form as alumina muds. Solids contents at the time of disposal are about 20 percent and may approach 50 percent after many years of consolidation. Approximately 5 million tons per year of alumina muds are generated from refining plants in Louisiana, Texas, Arkansas, and Alabama. Because of relatively low solids contents and handling difficulties, no practical uses have as yet been found for these washery reject materials *(88)*.

There is no known research underway that is aimed at evaluating highway construction uses for either phosphate slimes or alumina muds, either at state highway agencies or at the university level. Only Arkansas has attempted to use alumina brown mud: it has been evaluated as a base and a subgrade material, but the brown mud was considered unacceptable as a subbase material because of its lack of strength and durability.

PHOSPHOGYPSUM

Phosphogypsum is a by-product of wet-process phosphoric acid production from finely ground phosphate rock. Phosphogypsum is a calcium sulfate hydrate which is pumped into ponds, eventually dewaters, and is ultimately disposed of in stacks. Approximately 35 million tons of phosphogypsum are produced annually, mostly in central Florida, but also in Louisiana and southeastern Texas. Total accumulations of phosphogypsum stacks are probably in excess of 700 million tons *(89)*.

Phosphogypsum has been recovered and reused in stabilized road base mixes, but there are environmental concerns about the radon emanation from phosphogypsum. In 1989, the EPA issued a ban on the use of phosphogypsum because of uncertainty about the possible health effects of radiation from phosphogypsum stacks. This ban encompasses research studies as well as practical uses. The EPA has called for studies to determine the health related risks associated with the use of raw or stabilized phosphogypsum for use as embankment material or in road base construction *(90)*.

As a consequence of the EPA ruling, there is no current or planned research into construction uses for phosphogypsum. There is also no state highway agency research on phosphogypsum applications, although considerable research in this area has been performed during the past 6 years by the University of Miami, Louisiana State University, and Texas A&M University. Researchers at the University of Miami and at Texas A&M have placed experimental sections of cement-stabilized phosphogypsum road base at several locations in South Florida and around Houston, Texas. Louisiana State University researchers, in addition to evaluating phosphogypsum uses, are also investigating the potential use in asphalt of a phosphogypsum slag by-product from a sulfuric acid production process *(91)*.

Although experimental road base test sections containing stabilized phosphogypsum bases have been installed in Florida and Texas, no construction use of phosphogypsum is indicated in either of these two states, or elsewhere.

SPENT OIL SHALE

Oil shale deposits in the Green River formation, which covers parts of Colorado, Utah, and Wyoming, may contain billions of barrels of recoverable oil. Approximately 70 percent of those oil shale reserves are on federal lands. During the energy crisis of the 1970s, several pilot installations were established to extract petroleum from these oil shale reserves. Oil shale was mined, crushed to 1/2 in. and heated to 900°F in a retort furnace. Oil vapors were drawn off and condensed,

leaving an oil shale ash that varied in size from mainly granular particles to occasional lumps of up to 3 in. in diameter *(92)*. During the 1980s, most, if not all, of the experimental shale retorting facilities were closed, but an estimated several million tons of spent oil shale had accumulated at these sites, which are located mainly in northwestern Colorado.

Spent oil shale appears to have potential for use as either a fine aggregate or a mineral filler in asphalt paving. There is no known research to evaluate spent oil shale for such uses. There has also been no documented use of spent oil shale in highway construction. During 1988, a laboratory investigation was conducted to evaluate the feasibility of incorporating oil shale ash into asphalt-concrete mixtures as a partial replacement for the asphalt-cement binder. It was found that oil shale ash significantly increased the stability and cohesion of the test mixtures. The use of 10 percent oil shale ash by volume was considered an optimum replacement. The oil shale ash also improved the stiffness of the test mixes while reducing the potential for stripping *(93)*.

CHAPTER FIVE

RESEARCH AND HIGHWAY USES FOR WASTE MATERIALS

HIGHWAY RESEARCH PERSPECTIVE

The use of waste materials and by-products in highway construction and maintenance activities is often preceded or accompanied by research directed at the properties and behavior of the waste material or by-product in one or more applications. The research may consist of a formal laboratory testing program, a pilot field trial, a performance evaluation of a full-scale installation, or any combination of these elements. The research may be conducted by personnel from a state highway agency (or environmental agency), a college or university engineering department, industry, a private consultant, or by several of these entities acting cooperatively. From a timing standpoint, research may be completed, in progress, or planned for the future.

STATE HIGHWAY AGENCY RESEARCH ACTIVITIES

There are a number of research activities related to waste material or by-product utilization in some form of highway construction or maintenance. In the state highway agency questionnaire, state materials engineers indicated the extent of research on uses of waste materials or by-products in highway construction, the potential acceptability of such uses, and future research activities. Based on questionnaire responses, 45 states have performed or plan to perform some research into using one or more waste materials or by-products in highway construction. At least 26 of these intend to conduct research on the use of specific waste materials or by-products in some form of highway construction.

Research performed by state highway agencies on waste material and by-products involved at least 42 different highway related applications. Table 6 provides a list of these applications, presented alphabetically according to code letters. Table 7 is a summary of research activities performed by state highway agencies for 28 waste materials, with applications studied for each waste or by-product indicated by the appropriate letter code denoted in Table 6. In a few instances, more than two end uses were evaluated for a given waste or by-product by certain states.

In addition to the waste materials indicated in Table 7, Texas has investigated the use of crushed clay pipe as an aggregate in hot-mix asphalt, Maryland has evaluated landfill material as fill, and Ohio has researched the use of cheese whey in the production of calcium magnesium acetate (CMA) for deicing. Colorado is evaluating the performance of pipe-supported stacks of scrap tires as an attenuation system for mitigating the effect of rockfalls in Glenwood Canyon. Michigan has investigated the use of blast-furnace slag as a concrete aggregate and as mineral filler in asphalt.

According to Table 7, the following wastes or by-products were most frequently researched:

- RAP (36 states)
- Scrap tires (35 states)
- Coal fly ash (35 states)

TABLE 6
LIST OF POSSIBLE USES FOR WASTE MATERIALS AND BY-PRODUCTS EVALUATED BY STATE HIGHWAY AGENCY RESEARCH

CODE	DESCRIPTION OF USE OR APPLICATION
ABC	Aggregate base course
ABF	Aggregate backfill
ACM	Asphalt-cement modifier
AGG	Aggregate in asphalt
AR	Asphalt rubber
ATT	Attenuation systems
BAR	Barricades
CEM	Cement replacement
CON	Concrete aggregate
CS	Chip seal
DEL	Delineators or cones
DP	Dust palliative
EMB	Embankment borrow
FF	Flowable fill
FL	Fuel for asphalt plants
FSP	Fence or sign post
GB	Glass beads for traffic paint
GRT	Grout or subsealing
ICE	Ice control or anti-skid material
JCS	Joint and crack sealant
LCB	Lean concrete base (econocrete)
LWF	Lightweight fill material
MF	Mineral filler in asphalt
MUL	Mulch or topsoil amendment
OS	Overlay sealant
PB	Pipe bedding
RC	Reinforcing bar chairs
RCC	Roller-compacted concrete
REC	Recycled pavement
RMO	Reclaimed motor oil
RR	Riprap or slope protection
RTA	Rockfall tire attenuator
SAM	Stress-absorbing membrane
SB	Stabilized base course
SHL	Shoulder aggregate
SIG	Sign blanks
SLU	Slurry seal
SM	Soil modifier
SND	Sand substitute
SS	Soil or subgrade stabilization
SUB	Subbase materials
TIM	Plastic timbers, tables or benches

TABLE 7

SUMMARY OF STATE HIGHWAY AGENCY RESEARCH ACTIVITIES ON USES FOR WASTE MATERIALS AND BY- PRODUCTS

	Coal Ash		Other Ash		Slag Materials			Paving & Building Debris				Mining Wastes		
	Fly Ash	Bottom Ash	MSW Ash	Sludge Ash	Blast Furnace	Steel Making	Non-Ferrous	RAP	RCP	Broken Concrete	C & D Debris	Mine Tailings	Quarry Waste	Coal Waste
1. Alabama*														
2. Alaska								SUB						
3. Arizona	CEM, SS[1]							ABC,AGG	ABC,CON					
4. Arkansas	CEM	AGG,EMB						REC					ABC,EMB	
5. California					ABC,AGG	ABC,AGG	AGG	REC,SB		ABC,CON				
6. Colorado	SB							REC						
7. Connecticut			EMB					ABC,CON		ABC,CON	ABC,CON			
8. Delaware	EMB				CON					EMB	EMB			
9. Florida	CEM,EMB		EMB		AGG,CEM		AGG	REC	AGG					
10. Georgia	CEM,SB							REC						
11. Hawaii*														
12. Idaho*														
13. Illinois										EMB			EMB	
14. Indiana	AR,EMB				AGG,ABC	AGG,ABC		AGG,ABC			AGG,ABC			
15. Iowa	CEM							ABC,REC	ABC,CON					
16. Kansas	MF,SS	ICE			AGG	AGG		REC	CON,SB	EMB,RR		AGG,CON		
17. Kentucky	SS													
18. Louisiana	CEM,MF				AGG,ABC	AGG,CS		ABC,REC	ABC,CON					
19. Maine								REC						
20. Maryland	CEM,GRT				CEM	EMB,SUB		REC	SUB					EMB
21. Massachusetts			AGG,CON					AGG		ABC				
22. Michigan	CEM,SS				AGG,ABC	AGG		REC,ABC	ABC,CON					
23. Minnesota			AGG,EMB	MF										
24. Mississippi	CEM,SB	ABC,SB						AGG						
25. Missouri	CEM,GRT	EMB,AGG			AGG	AGG		REC	ABC,RR	RR	EMB	AGG	EMB	

* Has not performed any recent research on uses for waste materials or by-products

[1]Refer to Code letters for various uses in Table 6

TABLE 7 (CONTINUED)
SUMMARY OF STATE HIGHWAY AGENCY RESEARCH ACTIVITIES ON USES FOR WASTE MATERIALS AND BY- PRODUCTS

	Coal Ash		Other Ash		Slag Materials			Paving & Building Debris				Mining Wastes		
	Fly Ash	Bottom Ash	MSW Ash	Sludge Ash	Blast Furnace	Steel Making	Non-Ferrous	RAP	RCP	Broken Concrete	C & D Debris	Mine Tailings	Quarry Waste	Coal Waste
26. Montana	CEM													
27. Nebraska	CEM,MF							ABC,AGG	ABC,AGG					
28. Nevada								REC				AGG		
29. New Hampshire	CEM, FF		AGG		CEM			AGG,SB						
30. New Jersey	CEM,MF									ABC,AGG				
31. New Mexico*														
32. New York	CEM,MF	ICE	SUB		CON,CEM	SUB		REC,SB	REC,SUB	RR	EMB	AGG,RR[1]		
33. North Carolina	CEM							REC						
34. North Dakota	CEM													
35. Ohio								REC						
36. Oklahoma	CEM,SS											AGG,CS		
37. Oregon	CEM,SB				CEM			REC						
38. Pennsylvania	CEM,EMB	EMB,ICE			AGG,CON	AGG,SUB	AGG,ICE	REC	CON,SUB	SUB				
39. Rhode Island	CEM							REC,SUB						
40. South Carolina	CEM	EMB			AGG	AGG		AGG		ABC				
41. South Dakota														
42. Tennessee	CEM				AGG		AGG	REC						
43. Texas	CEM,SS	ABC,AGG			AGG,CON		AGG			ABC				
44. Utah	CEM	ABC						REC						
45. Vermont								SB,SHL					ABC,SB	
46. Virginia	CEM,SB				AGG,CON			REC						
47. Washington	CEM							AGG						
48. West Virginia	CEM,EMB	ICE			AGG,CON	AGG,ICE		ABC,AGG						SUB
49. Wisconsin	CEM,EMB							ABC						
50. Wyoming	CEM,SB	ABC,AGG						REC	CON					

* Has not performed any recent research on uses for waste materials or by-products

[1] Waste Rock[1]

TABLE 7 (CONTINUED)
SUMMARY OF STATE HIGHWAY AGENCY RESEARCH ACTIVITIES ON USES FOR WASTE MATERIALS AND BY- PRODUCTS

	Domestic Wastes					Kiln Dusts		Roofing Shingles	Sulfate Waste	Lime Waste	Silica Fume	Foundry Wastes	Wood Chips, Sawdust	Used Motor Oil
	Scrap Tires	Glass	Plastic	Paper	Compost	CKD	LKD							
1. Alabama*														
2. Alaska	AR								DP				LWF	
3. Arizona	AR					MF								
4. Arkansas	AR					SB,EMB								
5. California	AR,CS	AGG,SB												
6. Colorado	EMB,SAM		ACM											
7. Connecticut	AR,ATT	AGG,EMB			MUL									
8. Delaware														
9. Florida	AR	AGG,EMB	FSP,RC					AGG			CEM			FL
10. Georgia	JCS		FSP,SIG	MUL										FL
11. Hawaii*														
12. Idaho*														
13. Illinois			BAR				SS					SND		
14. Indiana												AGG		
15. Iowa	AR	AGG												
16. Kansas	AR		DEL	MUL		EMB,SS								
17. Kentucky							SS		EMB	SS				
18. Louisiana									SHL					
19. Maine	AR,CS	GB	FSP,TIM		MUL[1]									FL
20. Maryland	AR				MUL[1]								MUL	
21. Massachusetts	AR													FL
22. Michigan	AR		FSP,TIM											
23. Minnesota	AR,EMB							AGG						
24. Mississippi	AR													
25. Missouri	AR			MUL		SS	SS			SS				RMO

* Has not performed any recent research on uses for waste materials or by-products

[1] Sewage Sludge

TABLE 7 (CONTINUED)
SUMMARY OF STATE HIGHWAY AGENCY RESEARCH ACTIVITIES ON USES FOR WASTE MATERIALS AND BY- PRODUCTS

	Domestic Wastes					Kiln Dusts		Roofing Shingles	Sulfate Waste	Lime Waste	Silica Fume	Foundry Wastes	Wood Chips, Sawdust	Used Motor Oil
	Scrap Tires	Glass	Plastic	Paper	Compost	CKD	LKD							
26. Montana														
27. Nebraska	AR													
28. Nevada	CS		ACM											
29. New Hampshire	AR,SAM	ABC		MUL	MUL						CEM		MUL	
30. New Jersey														
31. New Mexico*														
32. New York	AR,JCS	AGG	ACM		MUL[1]	MF,SB	MF,SB		ACM				MUL	
33. North Carolina	AR,EMB		FSP										MUL	
34. North Dakota														
35. Ohio	ACM									MUL				
36. Oklahoma	AR													
37. Oregon	AR,LWF										CEM			
38. Pennsylvania	AR,AGG	AGG,ABC[2]		MUL				AGG[3]				AGG		
39. Rhode Island	AR													
40. South Carolina	AR,CS					SB						AGG		
41. South Dakota														
42. Tennessee	JCS		SIG											
43. Texas	AR								SB					
44. Utah						MF								
45. Vermont	EMB	AGG	FSP											
46. Virginia	AR	AGG				SB			SB					
47. Washington	AR												LWF	
48. West Virginia														
49. Wisconsin	ACM,EMB											AGG,EMB		
50. Wyoming	AR												LWF	

* Has not performed any recent research on uses for waste materials or by-products [1] Sewage Sludge [2] Also used experimentally in embankments and as backfill [3] Factory Scrap

- Blast-furnace slag (18 states)
- RCP (12 states)
- Broken concrete (12 states)
- Reclaimed plastic (12 states)
- Coal bottom ash (11 states)
- Steel-making slag (11 states)
- Recycled glass (10 states)

Of the states that researched RAP, 23 evaluated its use in asphalt pavement recycling (hot or cold). Nine states investigated RAP for reuse as aggregate in asphalt mixes. Nine states evaluated RAP for use as aggregate base course material. Other applications for RAP included stabilized base (4 states), subbase (2 states), concrete aggregate (1 state), and shoulder aggregate (1 state).

Scrap tires were investigated for use in asphalt-rubber mixes (wet or dry) by 27 states. Five states evaluated chipped tires as an embankment material (sometimes mixed with soil), and two states evaluated tire chips for lightweight fill. Five states investigated the use of ground tires in chip seals. Other applications for scrap tires included joint sealant (3 states), asphalt-cement modifier (2 states), stress-absorbing membrane (2 states), and crash attenuator (1 state).

Coal fly ash was evaluated primarily as a partial cement replacement in concrete by a total of 29 states. Six states have investigated fly ash as an embankment or fill material. Six states have also studied the use of fly ash as a soil stabilization agent, and six states have evaluated fly ash in stabilized road bases. Four states have researched the use of fly ash as a mineral filler in asphalt paving. Two states have studied fly ash for grouting or pavement subsealing.

Air-cooled blast-furnace slag was investigated primarily as an aggregate in asphalt mixes (13 states) or concrete mixes (6 states). Four states have evaluated air-cooled blast-furnace slag as an aggregate in base course construction. Five states have conducted research into the use of ground granulated blast-furnace slag as a partial replacement for portland cement in concrete mixes.

Coal bottom ash has been evaluated as an embankment material (4 states), as an aggregate in hot-mix asphalt (4 states), and as an aggregate in unbound base courses. Bottom ash has also been investigated by 3 states as anti-skid material on icy roadways.

The principal use evaluated for broken concrete by six states has been as an aggregate for base course construction. Other uses that were investigated include as riprap (3 states), embankment material (3 states), concrete aggregate (2 states), and asphalt paving aggregate (1 state).

Reclaimed plastic (mainly HDPE or PET) has been investigated by six states primarily for use in fence and sign posts. Other potential applications include plastic timber (two states), sign faces (two states), and reinforcing bar chairs (one state). Also, LDPE has been evaluated by at least two states as an asphalt modifier.

Steel-making slag has been investigated for a number of possible uses, mainly as an aggregate in asphalt paving (eight states), but also as a subbase material (three states), as an aggregate in subbase (three states), and in unbound base courses (two states). Other possible uses for steel slag that were evaluated include embankment or fill material (one state) and ice control (one state).

Recycled glass was investigated primarily for its possible use as a fine aggregate in hot-mix asphalt paving (eight states). It was investigated for potential use in embankments by three different states and in unbound base course by two states. Several other applications for recycled glass were each investigated by one state, including subbase aggregate, concrete aggregate, and as glass beads for traffic paint.

The District of Columbia has conducted research on the use of reclaimed asphalt paving material as subbase, scrap tires in asphalt rubber, and recycled LDPE as an asphalt modifier. None of these materials is being used routinely.

To continue or supplement current research activities, at least 26 state highway agencies have planned to perform research work on one or more wastes or by-products. Table 8 is a list of these 26 states and the 47 research projects they intend to undertake. These projects involve investigating at least 14 waste materials or by-products, with scrap tires, reclaimed plastic, and RAP receiving the most attention.

STATE REPORTING OF WASTE GENERATION AND USE

In addition to conducting investigations of certain waste materials in highway uses, a number of states have undertaken a more encompassing investigation of the sources, locations, quantities, and uses of various wastes available within their state. Ten state highway agencies enclosed reports of such investigations when returning their questionnaires:

- Kansas,
- Connecticut,
- Florida,
- Maine,
- Minnesota,
- Missouri,
- Pennsylvania,
- Virginia, and
- Washington.

A number of these states, as well as some others, also enclosed reports describing the findings from waste material research that has been conducted in their states:

- California: RAP, scrap tires, and glass;
- Connecticut: demolition debris, scrap tires, and glass;
- Florida: scrap tires, glass;
- Illinois: scrap tires;
- Kansas: RAP;
- Maine: scrap tires and plastic;
- Michigan: plastic;
- Minnesota: scrap tires and sewage sludge ash;
- Missouri: glass;
- New York: slag, RAP, scrap tires, and fly ash;
- North Carolina: use of fly ash, glass, plastic, tires and wood chips in a road-widening project;
- Oregon: RAP, fly ash, scrap tires, silica fume;
- Vermont: scrap tires;
- Virginia: glass; and
- Washington: wood waste.

TABLE 8
SUMMARY OF PLANNED OR FUTURE RESEARCH ACTIVITIES BY STATE HIGHWAY AGENCIES

STATE	DESCRIPTION OF PLANNED OR FUTURE RESEARCH
California	Various wastes in pavement construction or rehabilitation
Colorado	Shredded scrap tires as embankment fill material
Connecticut	Reclaimed plastic for sign posts, lumber, and guardrail
Florida	Fly ash, blast-furnace slag, and silica fume in concrete
Illinois	Scrap tires in asphalt-rubber hot mix and seal coats
	Roofing shingles in asphalt pothole repair mixtures
Iowa	Reclaimed plastic for sign and guiderail posts
Kansas	Scrap tires in hot recycled asphalt-dry process
Louisiana	Scrap tires as lightweight fill or embankment material
Maine	Fly ash from wood fired boilers as soil amendment
	Sewage sludge-compost mixture as soil amendment
	Reclaimed plastic for sign posts and picnic tables
Minnesota	Ground glass as asphalt or granular base additive
Mississippi	Reclaimed concrete pavement as asphalt pavement aggregate
Missouri	Scrap tires, coal bottom ash, and incinerator residue for use in bituminous mixtures
Nebraska	Coal fly ash for use in concrete products, road bases and subbases, and as structural fill material
New Hampshire	Ground scrap tires for use in bituminous pavement and in stress-absorbing membrane interlayers
	Coal fly ash for use in flowable fill
	Crushed glass as aggregate in asphalt paving
New Jersey	Reclaimed asphalt pavement as aggregate base course
	Incinerator ash in hot-mix asphalt
	Granulated scrap tires (-80 mesh) in hot-mix asphalt
	Sewage sludge in hot-mix asphalt
New York	Reclaimed plastics for lumber and other applications
	Fly ash in embankments and flowable fill
	Sandblast grit reduction methods
North Dakota	Recycling of reclaimed asphalt pavement
Ohio	Reclaimed concrete pavement in new concrete pavement
Oklahoma	Scrap tires as an asphalt modifier
Oregon	Ground or granulated scrap tires in asphalt mixes
	Reclaimed plastics and composites for posts and fences
Pennsylvania	Shredded tires and plastics in bituminous concrete
	Curbside plastics as materials for geo-blankets
	Mixing scrap tires in portland cement concrete
	Scrap rubber sheeting as expansion joint material
	Use of devulcanized tire rubber/plastic modified asphalt cement in hot-mix asphalt
South Carolina	Kiln dusts for stabilizing graded aggregate bases
	Scrap tires in hot-mix asphalt and lightweight fill material
Tennessee	Reclaimed plastic for fence posts
Texas	Ground scrap tires for use in hot-mix asphalt
Vermont	Continued or expanded use of recycled asphalt pavements
	High-density polyethylene plastic for traffic cones
Wisconsin	Use of waste paper for mulch material
	Recycled asphalt pavement in wearing course
	Reclaimed plastics for use in sign posts

Several of the state reports on waste material availability and use deserve special mention. In particular, the Missouri report (*94*) provides a detailed inventory of all waste material sources by town and county, type of storage (wet or dry), estimated annual production and accumulation, and product type rating. Total available quantities of 10 waste categories are provided in terms of tons and cubic yards. A description is also given of 48 types of waste materials found throughout the state. This report is an excellent example for other state highway agencies to follow in developing an inventory of waste material sources within their state borders.

In addition to Missouri, other states that have reported on waste material availability and use within their states include the following:

- Arkansas: fly ash, bottom ash, quarry waste, cement kiln dust, and alumina brown mud (*95*);
- Connecticut: sanitary landfill earth waste structures (SLEWS) (*49*); reclaimed paving materials, demolition debris, coal fly ash, resource recovery ash, scrap tires, composted leaves, and garbage (*96*);
- Florida: used motor oil, scrap tires in asphalt, coal fly ash, glass, and RAP (*97*);
- Kansas: chat tailings, cement kiln dust, quarry waste, asphalt pavement recycling, Class C fly ash, scrap tires (*98*);
- Maine: scrap tires, recycled plastics, fly ash, construction steel, waste glass, compost, and RAP (*99*);

- Minnesota: sewage sludge incinerator ash, scrap tires, municipal incinerator ash, waste roofing shingles, coal fly ash, boiler slag, waste glass, and sand-blasting grit (*100*);
- Pennsylvania: waste glass, plastic waste, paper waste, compost, scrap tires, and aluminum cans (*101*);
- Virginia: RAP, used guiderails, scrap tires, old sign blanks, used motor oil, discarded batteries, scrap metal, aluminum cans, and waste paper (*102*); and
- Washington: scrap tires, waste glass, coal fly ash, bottom ash, compost, mixed plastic, aluminum sign stock, and scrap tires in both wet and dry process asphalt rubber (*103*).

University Research

In addition to, or often in conjunction with, research by state highway agencies, there has also been a considerable amount of research performed by universities on possible highway applications for waste materials or by-products. According to state highway agency questionnaire responses, and supplemented by the literature, university research in this area has been, or is being, conducted by at least 32 universities in at least 27 states, involving a total of 44 research projects. Table 9 is a list of these projects, indicating the state, university, principal researcher, and title of the research project. These research projects encompass at least 15 waste materials or by-products, although scrap tires and coal fly ash are the materials that are evaluated most frequently.

OVERVIEW OF WASTE USE IN HIGHWAY CONSTRUCTION

The use of waste materials and by-products in highway construction and maintenance projects is not a recent development. In the early part of the 20th century, asphalt was for the most part an unwanted by-product of petroleum refining, until it was discovered that the material performed well as a binder of aggregate materials. It was through research and development, coupled with a strong marketing effort, that the American asphalt paving industry was established and has evolved into the nationwide network of high quality material producers and contractors that exists today.

State highway agencies have been evaluating and using suitable waste materials and by-products in highway construction and maintenance operations for many years. Scrap steel is a prime example. State highway agencies have traditionally investigated the potential usefulness of recycled materials by laboratory research, small-scale field demonstrations and experimental projects, then by performance evaluations. Some examples of waste materials or by-products evaluated by state agencies include blast-furnace and steel slags, coal ash, and RAP. Many of these investigations resulted from state agency initiatives to find more economical ways to build highway facilities. Some research and development efforts were undertaken in response to requests from producers of unconventional materials.

On the maintenance side, recovery and reuse of highway materials has been a long-time practice, often necessitated by tight budgets and the absence of surplus materials. Some examples of waste use by maintenance forces include the recycling of damaged steel guide rails and aluminum sign faces.

Three notable research and development programs provide documentation of waste material usage in highway construction. One is a program originating in the early 1970s sponsored by the FHWA involving at least 10 types of waste materials. Another includes four different series of FHWA-sponsored demonstration projects involving various sources of waste materials. The third, conducted by the Electric Power Research Institute (EPRI), encompassed six high-volume coal ash utilization projects.

Federal Documentation Of Waste Material Use

The main impetus to investigate the potential use of waste materials in highway construction applications was first provided more than 20 years ago by the FHWA. As early as the 1950s, FHWA had begun research on the use of fly ash in concrete (*104,105*). However, it was in the early 1970s that FHWA initiated a research program called "Use of Waste Materials for Highways." This program evaluated a broad spectrum of by-products over roughly 15 years, resulting in a number of field demonstrations and the publication of at least three dozen technical reports. Among the waste materials evaluated by FHWA in this program were the following:

- Cellulosic wastes (*11*),
- Coal fly ash (*106-108*),
- Coal bottom ash (*109,110*),
- Coal refuse (*111,112*),
- Incinerator residue (*113–116*),
- Lime and cement kiln dusts (*117*),
- Mining wastes (*85,118,119*),
- Scrap rubber (*120*),
- Sewage sludge (*121*),
- Sulfate wastes (*122–127*), and
- Wood lignins (*128*).

A number of reports from this program document the design, placement, and technical performance of actual test sections containing certain of these waste materials, particularly those dealing with incinerator residue. In many of the reports, extensive laboratory testing of different waste materials was conducted to document engineering properties and to develop mix design characteristics. Certain reports also provide economic comparisons between conventional construction products and those incorporating one or more wastes or by-products.

Although the technical data contained in these reports are still valid, comparatively little attention was given at that time to the environmental evaluation and monitoring of highway products containing waste materials or by-products. Nevertheless, these reports provide an impressive collection of technical information on the use of various waste and/or by-product materials in highway construction.

FHWA Demonstration Projects

FHWA has an Office of Technology Applications in Washington, D.C. The function of this office is to disseminate

TABLE 9

UNIVERSITY RESEARCH ON WASTE MATERIAL USE

State	University	Research Contact	Project Definition
Connecticut	University of Connecticut	Richard Long	Properties, Leachability, Treatment and Use of Incinerator Ash
Florida	University of Florida	Charles Beatty	Recycled Plastics for Fence and Guard Rail Posts
Florida	University of Florida	Byron Ruth	Ground Tire Rubber in Asphalt
Florida	University of Florida	Byron Ruth	Recycling Asphalt Pavements
Florida	University of Florida	Frank Townsend	Fly Ash in Embankments
Georgia	Georgia Institute of Technology	Youjiang Wang	Recycled Carpet Fibers in Concrete
Illinois	Southern Illinois University	Braja Das	Geotechnical Properties of Flue Gas Desulfurization Sludge
Iowa	Iowa State University	Ken Bergeson	Use of Fly Ash in Highway Construction
Kansas	Kansas State University	Alex Mathews	Production of Acetic Acid for CMA From Milling and Baking Industry Waste
Kentucky	University of Kentucky	Tom Hopkins	Testing of All Roadway Materials and New Products
Maine	University of Maine	Dana Humphrey	Recycled Chipped Tires in Embankments
Maryland	University of Maryland	Matthew Witczak	Synthesis on the Use of Ground Rubber in Hot Mix Asphalt
Minnesota	University of Minnesota	David Newcomb	Polymerized Crumb Rubber
Minnesota	University of Minnesota	David Newcomb	Tires in Lightweight Fill
Minnesota	University of Minnesota	David Newcomb	Laboratory Properties of Shingle/Asphalt Mixes
Missouri	University of Missouri-Rolla	Dave Richardson	Waste Glass as Aggregate in Bituminous Mixtures
Nebraska	University of Nebraska	Roy Sheddon	High Volume Utilization of Coal Ash in Nebraska
New Hampshire	University of New Hampshire	David Gress	Use of Incinerator Bottom Ash in Bituminous Pavement
New Hampshire	University of New Hampshire	David Gress	Use of Fly Ash in Flowable Fill
New Hampshire	University of New Hampshire	George Estes	MSW Compost
New Jersey	New Jersey Institute of Technology	Namunu Meegoda	Use of Petroleum Contaminated Soils
New York	SUNY-Stony Brook	Frank Roethel	MSW Ash Stabilization

TABLE 9 (CONTINUED)

UNIVERSITY RESEARCH WASTE MATERIAL USE

State	University	Research Contact	Project Definition
North Carolina	North Carolina State University	Paul Khosla	Rubber From Tires in Bituminous Paving Mixtures
North Dakota	University of North Dakota	Charles Moretti	Testing of Fly Ash
Ohio	University of Akron	C. B. Doennon	Rubber Additive to Asphalt Concrete
Ohio	Ohio State University	K. Majizadeh	Sulfur Additive to Asphalt Concrete
Ohio	Ohio State University	S. T. Yang	Cheese Whey for Production of Calcium Magnesium Acetate
Oklahoma	University of Oklahoma	Joakim Laguros	Fly Ash as Soil Stabilizer (in conjunction with ODOT)
Oregon	Oregon State University	Gary Hicks	Cold In-Place and Hot Recycled Asphalt Concrete
Oregon	Oregon State University	Gary Hicks	Rubber Modified Asphalt Concrete
Pennsylvania	Villanova University	S.K. Ciesielski	Crumb Rubber Additive in Portland Cement Concrete
Pennsylvania	University of Pennsylvania	Iraj Zandi	Properties of Fly Ash Concrete
Pennsylvania	University of Pennsylvania	Iraj Zandi	Conversion of Fly Ash to Construction Material by Vitrification Process
Rhode Island	University of Rhode Island	K. Wayne Lee	Utilization of Vinyl Materials in Asphalt-Concrete Mixtures
South Carolina	Clemson University	Jim Burati	Use of Recycled Asphalt Pavement
Texas	University of Texas-Austin	Ramon Carrasquillo	Use of Fly Ash in Concrete
Texas	Texas A & M University	Cindi Estakhri	Use of Ground Tire Rubber in Hot Rubber Asphalt Seal Coats
Texas	Texas A & M University	Donald Saylak	Applications for FGD By-Product Gypsum
Washington	University of Washington	Joe Mahoney	Sulfur Asphalt Concrete Pavement
Wisconsin	University of Wisconsin-Madison	Tuncer Edil	Uses for Scrap Tires
Wisconsin	University of Wisconsin-Milwaukee	Robert Harmon	Foundry Sand
Wisconsin	University of Wisconsin-Milwaukee	Tarun Naik	High Volume Fly Ash Concrete
Wisconsin	Marquette University	Keith Faherty	Recycled Asphalt Pavement
Wyoming	University of Wyoming	Dave Sheesley	Fly Ash for Stabilization of Gravel Roads

information, provide seed money for research, document research programs that have been authorized, and encourage new or innovative technology in the design and construction of transportation facilities.

FHWA has sponsored at least four demonstration projects that have involved the use or reuse of waste materials and/or by-products as highway construction materials:

- Demonstration Project No. 37—Use of Discarded Tires in Highway Construction (*120*),
- Demonstration Project No. 38—Recycling Asphalt Pavements,
- Demonstration Project No. 47—Recycling Concrete Pavements, and
- Demonstration Project No. 59—Fly Ash in Highway Construction.

Each of these demonstration projects is further described in the Technical Appendix, including the time period during which the project was conducted, the number of states participating, and the types of applications involved. Further details can be obtained by contacting FHWA's Office of Technology Applications.

Electric Power Research Institute (EPRI) Demonstration Program

EPRI sponsored a multi-year demonstration program to promote the high-volume use of coal ash in highway construction applications, principally involving fills and embankments, subgrade and base course stabilization, grouting, backfills, and high-percentage fly ash concrete. EPRI and participating utility companies co-funded six field demonstration projects of roadway sections containing coal ash products on state highway projects, in cooperation with state highway agencies.

Field demonstration projects in the EPRI program were placed and monitored during the late 1980s in Delaware, Georgia, Kansas, Michigan, North Dakota, and Pennsylvania. Monitoring activities for each project lasted for 3 years and involved materials characterization, construction placement and monitoring, post-construction performance, and environmental performance. These projects involved the following applications of coal ash:

- Delaware: Class F fly ash embankment (*129*),
- Georgia: Class F fly ash stabilized base (*130*),
- Kansas: Class C fly ash base recycling (*131,132*),
- Michigan: Class F fly ash stabilized base (*133,134*),
- North Dakota: Class C fly ash in concrete (*135*),
- Pennsylvania: Class F fly ash embankment (*136*).

State Highway Agency Use Of Waste Materials

In addition to identifying research work on waste materials, the state highway agency questionnaire also requested information on the actual use of waste materials and by-products. The in-formation obtained from this questionnaire was supplemented by a survey of waste materials used in highway construction that was published in mid 1991 by Purdue University (*137*). The information presented in the Purdue report was also obtained through state questionnaires. Waste use reported in this chapter also includes reported uses of waste materials from the Purdue study.

Based on the questionnaire responses from all 50 states, and a review of published and unpublished literature, it has been determined that every state has had some experience with the use of at least one waste material or by-product in highway construction. The extent of state highway agency exposure to waste use ranges from Hawaii's experience with only one waste material (RAP) to New York's experience with 16 waste materials or by-products, some in multiple applications.

Uses of waste materials and by-products by state highway agencies have involved at least 42 highway related applications, as shown in Table 6. Table 10 is a summary of the various waste materials and by-products that have been used in highway construction by state highway agencies.

Table 11 is a list of all waste materials or by-products used, arranged in descending order according to the number of states indicating use of each particular waste or by-product. As shown in Table 11, 49 states have indicated use of RAP. A total of 42 states have used coal fly ash. Also, 42 states have used scrap tires, most of these in rubberized asphalt applications. At least 14 waste materials have been used by 10 or more states. In all, a total of 32 waste materials or by-products have been used by at least one state.

A further breakdown of the different highway construction applications in which waste materials and by-products have been used by state transportation agencies is provided in Table 12. The code letters from Table 6 are used to designate these applications. In some states, more than two end uses were indicated for a particular waste or by-product. In such cases, the two end uses that constitute the highest volume or are used the most routinely, are indicated in Table 12.

Some of the end uses in Table 12 are considered by the states to be experimental. At least 17 states have indicated that one or more of the waste materials is being used for testing or demonstration purposes only. The most frequent highway uses of waste materials are as follows:

- RAP in new or recycled asphalt,
- Fly ash as a cement replacement in concrete mixes,
- Scrap tires in asphalt-rubber paving mixes,
- Mining wastes as embankment or fill material,
- RAP as aggregate base course,
- Blast-furnace slag as aggregate in asphalt paving,
- Steel-making slag as aggregate in asphalt paving,
- Fly ash as an embankment or backfill material, and
- Scrap tires in embankments or lightweight fills.

The most frequent end uses for RAP were as an aggregate in new or recycled asphalt pavements. A total of 35 states use RAP as an aggregate in new asphalt pavement mixes, while 12 states recycle RAP into the same asphalt pavement from which it was removed. In at least 13 states, RAP is used as an aggregate in unbound base courses. Four states have used RAP as a subbase aggregate, and at least two states have used RAP as a shoulder material.

Coal fly ash is used as a partial replacement for portland cement in concrete in 38 states. Fly ash is specified for this

TABLE 10

Use of Waste Materials and By-Products by State Highway Agencies

Name of State	Broken Concrete	Coal Fly Ash	Bottom Ash	Compost	Demolition Rubble	Foundry Waste	Glass or Ceramics	Incinerator Residue	Kiln Dusts	Lime Waste	Mining Wastes	Paper Waste
Alabama		X									X	
Alaska											X	
Arizona		X							X*		X	
Arkansas		X	X								X*	
California	X			X			X				X	
Colorado	X	X		X							X	
Connecticut	X			X	X		X	X				
Delaware	X	X			X							
Florida		X										
Georgia		X	X								X	X
Hawaii												
Idaho											X	
Illinois	X	X				X*		X	X		X	X
Indiana		X			X	X					X	
Iowa		X					X					
Kansas	X	X	X						X*		X	X
Kentucky		X	X*						X		X	
Louisiana		X							X*			
Maine				X			X					
Maryland		X		X							X	
Massachusetts	X	X						X				
Michigan		X				X		X			X	
Minnesota		X						X			X	
Mississippi		X	X									
Missouri	X	X	X		X				X		X	X

* Considered unsuccessful or uneconomical–no further use contemplated

TABLE 10 (Continued)

Use of Waste Materials and By-Products by State Highway Agencies

Name of State	Broken Concrete	Coal Fly Ash	Bottom Ash	Compost	Demolition Rubble	Foundry Waste	Glass or Ceramics	Incinerator Residue	Kiln Dusts	Lime Waste	Mining Wastes	Paper Waste
Montana		X*										
Nebraska		X										
Nevada											X	
New Hampshire		X		X			X					X
New Jersey	X	X	X	X	X		X	X			X	
New Mexico		X									X	
New York	X	X	X		X		X	X	X		X	
North Carolina		X		X			X				X	
North Dakota		X										
Ohio		X									X	
Oklahoma		X								X*	X	
Oregon		X		X								X
Pennsylvania	X	X	X			X	X	X			X	X
Rhode Island		X**										
South Carolina	X	X	X*			X			X*			
South Dakota	X	X									X	
Tennessee		X									X	
Texas	X	X	X					X			X	
Utah		X	X						X*		X	
Vermont							X					
Virginia		X					X		X		X	
Washington		X	X*								X	
West Virginia		X	X								X	
Wisconsin		X				X					X	X
Wyoming		X	X*								X	

* Considered unsuccessful or uneconomical—no further use contemplated

**Permitted as cement replacement in concrete, but not used to date

TABLE 10 (Continued)

Use of Waste Materials and By-Products by State Highway Agencies

Name of State	Plastic Waste	Quarry Waste	Reclaimed Asphalt	Reclaimed Concrete	Scrap Tires	Sewage Sludge	Slags	Sulfate Waste	Used Motor Oil	Wood Wastes	Miscellaneous
Alabama			X	X			X				Silica Fume
Alaska			X		X			X*		X	
Arizona			X	X	X						
Arkansas		X	X		X						Alumina Brown Mud
California			X		X		X				Ceramic Waste, Landfill Refuse
Colorado	X		X		X						
Connecticut			X	X	X						
Delaware			X		X		X				
Florida	X	X	X	X	X		X		X		
Georgia	X	X	X		X		X		X		
Hawaii			X								
Illinois	X	X	X	X	X	X	X			X	Roofing Shingles
Indiana			X	X	X		X				Ebonite (bowling balls)
Iowa	X		X	X	X						
Kansas	X		X	X	X		X				
Kentucky			X				X	X			FGD Scrubber Sludge
Louisiana			X	X			X	X			
Maine	X		X		X				X	X	
Maryland			X	X	X		X			X	Landfill Refuse
Massachusetts			X		X		X		X		
Michigan	X		X	X	X		X		X		
Minnesota			X	X	X	X	X		X		Roofing Shingles, Blasting Grit
Mississippi			X		X						
Missouri		X	X	X	X		X		X	X	

* Considered unsuccessful or uneconomical—no further use contemplated

TABLE 10 (Continued)

Use of Waste Materials and By-Products by State Highway Agencies

Name of State	Plastic Waste	Quarry Waste	Reclaimed Asphalt	Reclaimed Concrete	Scrap Tires	Sewage Sludge	Slags	Sulfate Waste	Used Motor Oil	Wood Wastes	Miscellaneous
Montana			X	X	X				X*		
Nebraska			X	X	X						
Nevada	X		X	X	X						
New Hampshire			X		X	X	X			X	Silica Fume
New Jersey			X		X	X	X			X	Recycled Steel in Rebars
New Mexico			X		X				X		
New York	X		X	X	X	X	X			X	
North Carolina	X		X		X					X	
North Dakota			X	X	X*				X*		
Ohio			X		X		X				Cheese Whey
Oklahoma			X		X						
Oregon	X		X		X		X			X	Silica Fume
Pennsylvania			X	X	X		X	X			
Rhode Island	X		X	X	X						
South Carolina			X		X		X				
South Dakota			X	X						X*	
Tennessee	X		X		X		X		X		
Texas					X		X	X			Crushed Clay Pipe
Utah			X								
Vermont	X	X	X		X						
Virginia			X		X						
Washington			X		X					X	
West Virginia			X				X				
Wisconsin			X		X						Spent Paper Mill Liquor
Wyoming			X	X	X					X	

* Considered unsuccessful or uneconomical—no further use contemplated

application in 44 states, but has not been used in several of these states, either because contractors have not successfully bid it for use, or because there are no sources of fly ash available in or near those states that meet ASTM C618 specification requirements for use as a pozzolan in concrete (*51*).

TABLE 11
STATE HIGHWAY USAGE OF WASTE MATERIALS AS INDICATED FROM QUESTIONNAIRE RESPONSES AND A REVIEW OF AVAILABLE LITERATURE

WASTE MATERIAL	NUMBER OF STATES USING
1. Reclaimed Asphalt Pavement	49
2. Coal Fly Ash	42
3. Scrap Tires	42
4. Mining Wastes	33
5. Blast-Furnace Slag	25
6. Reclaimed Concrete Pavement	21
7. Plastic Waste	15
8. Coal Bottom Ash	15
9. Broken Concrete	14
10. Steel Slag	13
11. Wood Waste	13
12. Kiln Dusts	10
13. Waste Glass/Ceramics	10
14. Used Motor Oil	10
15. Compost	9
16. MSW Incinerator Ash	8
17. Paper Waste	8
18. Foundry Waste	6
19. Quarry Waste	6
20. Demolition Debris	5
21. Sewage Sludge or Ash	5
22. Silica Fume	5
23. Sulfate Waste	4
24. Non-Ferrous Slags	3
25. Roofing Shingle Waste	2
26. Landfill Refuse	2
27. Crushed Clay Pipe	1
28. Lime Waste	1
29. Alumina Brown Mud	1
30. Blasting Grit	1
31. Cheese Whey	1
32. Ebonite (Bowling Balls)	1

Scrap tires have been used in rubberized asphalt paving, either as part of an asphalt-rubber binder (wet process) or as a fine aggregate substitute in gap-graded mixes (dry process), in a total of 38 states. The dry process has been used in at least 20 of these states. In at least 27 of the 38 states in which scrap tires have been used in asphalt, their use is still considered experimental by the highway agency. In eight of these states, scrap-rubber use in asphalt is not considered successful by the highway agency, either because of poor performance or because its use is not economical.

Mining wastes have been used to construct embankments or as fill materials in at least 16 different states. Waste rock, mill tailings, coal refuse, and phosphogypsum have all been successfully used. Four states have used waste rock, seven have used mill tailings, four have used coal refuse, and one state has used phosphogypsum as an embankment or fill material.

Air-cooled blast-furnace slag has been used as an aggregate in asphalt paving mixes in at least 15 states. Blast-furnace slag has also been used as a coarse aggregate in concrete and in unbound aggregate base courses and subbases. Steel-making slags have been used as an aggregate in asphalt paving mixes in at least 11 states, most of which are the same states that use blast-furnace slag. Steel slags are a very heavy, stable, skid-resistant aggregate, used primarily in wearing surfaces. Use of blast-furnace and steel-making slags in asphalt normally requires an increase in the asphalt content of the mixture because of the porosity of the slag particles.

Fly ash has been used in the construction of embankments or structural backfills in at least 14 states. Fly ash has also been used as a component of stabilized base courses (together with lime, portland cement, or kiln dust) in at least 16 states. One of the most promising high-volume uses of fly ash is in flowable fill or slurry backfill type mixes. At least 26 states have indicated some degree of flowable fill experience.

Scrap tires have been used to construct embankments or as a lightweight fill material in at least seven states. The tires are processed either to recover and use the sidewalls as soil reinforcement or to shred the tires into chips, which are then placed in layers in an embankment. In some cases, the tire chips are blended with soil to reduce the unit weight of the fill material.

USE OF WASTE MATERIALS IN EMBANKMENTS

According to responses from state highway agency questionnaires and a review of the technical literature, at least 14 waste materials or by-products have been used at some time by various state transportation agencies as embankment or fill material. Table 13 provides a list of these waste materials and the number of states where these materials have been used. In some instances, the use may have involved a small, isolated fill project by state maintenance personnel or a local road crew. In other cases, large embankments have been constructed by states that have repeatedly used a given waste material. A good example is the use of wood wastes by the state of Washington, where these materials have been used to construct embankments at 14 locations (*15*).

USE OF WASTE MATERIALS IN SUBGRADE STABILIZATION

The only waste materials or by-products used for stabilization of soils or subgrade materials are coal fly ash, cement kiln dust, wood lignin, and fluidized bed bottom ash or residue. In at least seven states (Arkansas, Georgia, Kansas, Kentucky, Minnesota, Oklahoma, and Texas), fly ash has been used for soil or subgrade stabilization. In the western states, Class C

TABLE 12

SUMMARY OF STATE HIGHWAY AGENCY USE OF WASTE MATERIALS AND BY-PROUCTS IN HIGHWAY CONSTRUCTION

	Coal Ash		Other Ash		Slag Materials			Mining Wastes		
	Fly Ash	Bottom Ash	MSW Ash	Sludge Ash	Blast Furnace	Steel Making	Non-Ferrous	Mine Tailings	Quarry Waste	Coal Waste
1. Alabama	CEM,SB				AGG	AGG		ABC,AGG		ABC,AGG
2. Alaska								ABC,EMB		
3. Arizona	CEM,EMB							ABC		
4. Arkansas	CEM,SS,MF	AGG,EMB						ABC*,SUB[1]*	ABC,EMB	
5. California					AGG,ABC	AGG,EMB		EMB		
6. Colorado	CEM,SB							EMB		
7. Connecticut			EMB							
8. Delaware	EMB,FF				CON					
9. Florida	CEM				AGG,CEM		AGG	SB,SUB**	SUB	
10. Georgia	CEM,SB	SUB			AGG				SUB	
11. Hawaii										
12. Idaho								EMB,ICE*		
13. Illinois	CEM,EMB		SB		CON,ABC	AGG		AGG,SHL	EMB	EMB
14. Indiana	CEM,SB				AGG,ABC	AGG				EMB
15. Iowa	CEM,FF									
16. Kansas	CEM,MF	ICE			AGG			AGG,CON		
17. Kentucky	SB,SS	SS[3]*			AGG	AGG				SUB,SHL
18. Louisiana	CEM,MF				CS	AGG				
19. Maine										
20. Maryland	FF,SB				CON,CEM	EMB				EMB
21. Massachusetts	CEM,EMB		AGG		CEM					
22. Michigan	CEM,SB,MF				ABC,AGG	AGG		EMB		
23. Minnesota	CEM,EMB		AGG	MF	REC			AGG,EMB		
24. Mississippi	CEM,SB	SB								
25. Missouri	CEM,EMB	AGG,ICE			AGG	AGG		AGG,EMB	EMB	

* Not considered successful due to poor performance or economics **Used Phosphogypsum [1] Red Mud [2] Dredgings [3] Fluidized Bed Residue

TABLE 12

SUMMARY OF STATE HIGHWAY AGENCY USE OF WASTE MATERIALS AND BY-PROUCTS IN HIGHWAY CONSTRUCTION

	Paving and Building Debris				Domestic Wastes				
	RAP	RCP	Broken Concrete	C & D Debris	Scrap Tires	Glass	Plastic	Paper	Compost
1. Alabama	AGG	AGG							
2. Alaska	SUB				AR				
3. Arizona	AGG,ABC	CON,ABC			AR				
4. Arkansas	AGG				AR				
5. California	AGG,SB		CON,ABC		AR,EMB	AGG[4]			MUL[5]
6. Colorado	AGG		ABC,RR		EMB		ACM[5]		MUL[5]
7. Connecticut	AGG	AGG	CON	ABC,CON	AR[5],ATT[5]	AGG,EMB			MUL
8. Delaware	AGG		EMB	EMB	JCS				
9. Florida	AGG	ABC			AR[5]		FSP,RC		
10. Georgia	REC				AR[5], JCS		FSP,SIG	MUL	
11. Hawaii	AGG								
12. Idaho					AR				
13. Illinois	AGG,ABC	CON	EMB		JCS		BAR	MUL	
14. Indiana	AGG,SHL	ABC, SB		AAG,ABC	AR[5],JCS				
15. Iowa	AGG,CON	AGG,ABC			AR[5]	AGG[5]	FSP[5]		
16. Kansas	REC	CON,SB	EMB,RR		AR[5]		DEL	MUL	
17. Kentucky	AGG								
18. Louisiana	AGG,ABC	CON,ABC							
19. Maine	AGG,ABC				JCS,CS[5]		FSP,TIM		MUL
20. Maryland	AGG	SUB			AR[5]				MUL[6]
21. Massachusetts	AGG		SUB		ACM,AGG*				
22. Michigan	REC	REC			AR[5]*		DEL,TIM		
23. Minnesota	REC	ABC			AR[5],LWF				
24. Mississippi	AGG				AR[5]				
25. Missouri	AGG	ABC,RR	RR	EMB	AR[5]			MUL	

* Not considered successful due to poor performance or economics [4] Ceramic Waste [5] Considered Experimental [6] Sewage Sludge

TABLE 12

SUMMARY OF STATE HIGHWAY AGENCY USE OF WASTE MATERIALS AND BY-PROUCTS IN HIGHWAY CONSTRUCTION

	Kiln Dusts		Roofing Shingles**	Sulfate Waste	Lime Waste	Silica Fume	Foundry Wastes	Wood Chips, Sawdust	Used Motor Oil
	CKD	LKD							
1. Alabama						CEM			
2. Alaska				DP				EMB	
3. Arizona	MF*								
4. Arkansas									
5. California									
6. Colorado									
7. Connecticut									
8. Delaware									
9. Florida						CEM			FL
10. Georgia									FL
11. Hawaii									
12. Idaho									
13. Illinois		SS	AGG				SND,AGG*	EMB,MUL	
14. Indiana							AGG		
15. Iowa									
16. Kansas	EMB*,SS*								
17. Kentucky		SB		EMB					
18. Louisiana	SB*			SHL					
19. Maine								MUL	FL
20. Maryland								MUL	FL
21. Massachusetts									
22. Michigan							AGG		
23. Minnesota			AGG						FL
24. Mississippi									
25. Missouri			AGG***			CEM		MUL	FL****

* Not considered successful due to poor performance or economics **Including Factory Scrap ***Used as pre-mix maintenance patching material ****Used in state owned vehicles.

TABLE 12

SUMMARY OF STATE HIGHWAY AGENCY USE OF WASTE MATERIALS AND BY-PROUCTS IN HIGHWAY CONSTRUCTION

	Coal Ash		Other Ash		Slag Materials			Mining Wastes		
	Fly Ash	Bottom Ash	MSW Ash	Sludge Ash	Blast Furnace	Steel Making	Non-Ferrous	Mine Tailings	Quarry Waste	Coal Waste
26. Montana	CEM,SS									
27. Nebraska	CEM,MF									
28. Nevada								AGG		
29. New Hampshire	CEM				CEM					
30. New Jersey	CEM,MF	ICE,SND			ABC,SUB			AGG,CON		
31. New Mexico	CEM							AGG		
32. New York	CEM,MF	ICE,SND	SUB	MUL	CON,SUB	SUB		AGG,RR[7]		
33. North Carolina	CEM							EMB**		
34. North Dakota	CEM,SB									
35. Ohio	CEM,SB				AGG					EMB
36. Oklahoma	CEM,SS							AGG,CS		
37. Oregon	CEM,RCC									
38. Pennsylvania	CEM,EMB	EMB,ICE	AGG		AGG,ABC	AGG,ABC		AGG		EMB,ICE*
39. Rhode Island										
40. South Carolina	CEM	EMB			AGG	AGG				
41. South Dakota	CEM							EMB		
42. Tennessee	CEM						AGG[8]	CON		
43. Texas	CEM,SS	AGG,ABC	AGG		AGG,CON		AGG,ABC[9]*	SB**		
44. Utah	CEM	ABC						EMB,MF		
45. Vermont									ABC,SUB	
46. Virginia	CEM,SB							ABC		ABC
47. Washington	CEM	EMB*						EMB		
48. West Virginia	CEM,EMB	AGG,ICE			AGG,CON	AGG,SHL				SUB
49. Wisconsin	CEM,EMB							AGG,SHL		
50. Wyoming	CEM,SB	ABC*						ICE		

* Not considered successful due to poor performance or economics **Used Phosphogypsum [7] Waste Rock [8] Phosphate Slag [9] Aluminum Slag

TABLE 12

SUMMARY OF STATE HIGHWAY AGENCY USE OF WASTE MATERIALS AND BY-PROUCTS IN HIGHWAY CONSTRUCTION

	Paving and Building Debris				Domestic Wastes				
	RAP	RCP	Broken Concrete	C & D Debris	Scrap Tires	Glass	Plastic	Paper	Compost
26. Montana	REC	REC			AGG[5]				
27. Nebraska	AGG,ABC	AGG,ABC			AR[5]				
28. Nevada	REC	CS			CS		ACM[5]		
29. New Hampshire	AGG,ABC				AR,SAM[5]	ABC		MUL	MUL[6]
30. New Jersey	AGG		ABC		AGG,JCS	AGG,SUB			MUL[6]
31. New Mexico	AGG				AR[5],SAM[5]				
32. New York	REC,SUB	SUB	RR	EMB	AGG[5],JCF	AGG[5]	ACM[5]		
33. North Carolina	REC				AR[5],EMB[5]	GB[5]	DEL[5],FSP[5]		MUL[5]
34. North Dakota	AGG,ABC	AGG,ABC			AR[5]*				
35. Ohio	AGG,SUB	ABC,SUB			AR[5]				
36. Oklahoma	AGG				AR[5],JCS				
37. Oregon	REC,ABC				AR[5]*,EMB		FSP[5]	MUL	MUL
38. Pennsylvania	AGG,REC	CON,SUB			AR[5]**	AGG,ABF		MUL	
39. Rhode Island	AGG,ABC	SUB			AGG*		ACM		
40. South Carolina	AGG		ABC		CS				
41. South Dakota	ABC,REC	REC	EMB						
42. Tennessee	AGG				JCS		SIG		
43. Texas	AGG,ABC		ABC		CS,AR				
44. Utah	REC,SUB								
45. Vermont	SB,SHL				EMB	AGG*	FSP		
46. Virginia	AGG,ABC				AR[5]	AGG[5]			
47. Washington	AGG				AR[5],AGG[5]*				
48. West Virginia	AGG								
49. Wisconsin	ABC				EMB,AR[5]*			MUL,DP	
50. Wyoming	AGG	CON			AR[5]*,JCS				

* Not considered successful due to poor performance or economics ** Also used as fuel in cement kilns [5] Considered Experimental [6] Sewage Sludge

TABLE 12

SUMMARY OF STATE HIGHWAY AGENCY USE OF WASTE MATERIALS AND BY-PROUCTS IN HIGHWAY CONSTRUCTION

	Kiln Dusts		Roofing Shingles	Sulfate Waste	Lime Waste	Silica Fume	Foundry Wastes	Wood Chips, Sawdust	Used Motor Oil
	CKD	LKD							
26. Montana									DP*
27. Nebraska									
28. Nevada									
29. New Hampshire						CEM		MUL	
30. New Jersey								MUL	
31. New Mexico									FL
32. New York	MF,SB							MUL	
33. North Carolina								MUL	
34. North Dakota									FL*
35. Ohio									
36. Oklahoma					SM*				
37. Oregon						CEM		EMB,MUL	
38. Pennsylvania			AGG[5]	EMB			SND,CEM		
39. Rhode Island									
40. South Carolina	SB*						AGG		
41. South Dakota								SS[10]*	
42. Tennessee									FL
43. Texas				SB					
44. Utah	MF*								
45. Vermont									
46. Virginia	SB								
47. Washington								EMB	
48. West Virginia									
49. Wisconsin							EMB		
50. Wyoming								LWF	

* Not considered successful due to poor performance or ecomomics

[5]Considered experimental

[10]Wood Lignin

TABLE 13

WASTE MATERIALS USED IN VARIOUS HIGHWAY APPLICATIONS

	NUMBER OF STATES THAT HAVE USED SPECIFIC WASTES IN				
WASTE MATERIAL	EMBANKMENTS	BASES AND SUBBASES	CONCRETE	ASPHALT PAVING	MISCELLANEOUS USES
Reclaimed Asphalt Pavement		16	1	46	
Coal Fly Ash	14	22	38	8	
Scrap Tires	7			38	11
Mining Wastes	16	6	2	12	2
Reclaimed Concrete Pavement		15	10	5	1
Blast-Furnace Slag		7	9	15	
Steel Slag	2	2		11	1
Plastic Waste				4	11
Coal Bottom Ash	2	5		4	6
Broken Concrete	4	6	2		4
Wood Waste	6				9
Kiln Dusts	1	4		3	2
Waste Glass/Ceramics	1	2		8	
Used Motor Oil					10
MSW Incinerator Ash	1	2	1	4	
Paper Waste					8
Compost					8
Foundry Waste	1			4	2
Demolition Debris	3	2	1	1	
Quarry Waste	3	3		1	
Sewage Sludge or Ash				1	3
Sulfate Waste	2	1			2
Non-Ferrous Slags		1		3	
Silica Fume			5		
Roofing Shingle Waste				2	
Crushed Clay Pipe				1	

fly ash has proven to be an effective stabilizer of expansive clay soils. Lime is normally used with Class F fly ash for stabilization of clayey soils, as well as in injection grouting to stabilize embankments for slide prevention. Cement kiln dust, wood lignin, and fluidized bed bottom ash have each been used by only one state as a soil stabilization agent.

Use Of Waste Materials In Bases And Subbases

At least 15 waste materials or by-products have been used in the construction of bases or subbases. Table 13 provides a list of these waste materials and the number of states in which they have been used. Most of these 15 wastes or by-products are coarse, granular materials (including RCP, slag, broken concrete, bottom ash, mine tailings, and demolition rubble), which have been used as unbound aggregate bases and subbases. Even some of the finer silty or sandy materials (such as crushed waste glass or quarry waste) have been used in an unstabilized condition. However, coal fly ash and cement or lime kiln dusts, which are fine, powdery materials, have been used as chemical reagents for base stabilization. Fly ash has been used extensively in combination with lime, portland cement, or kiln dust for the stabilization of aggregate bases in highways and for airport pavements, as well as in parking lot construction (*128*).

Use Of Waste Materials In Portland Cement Concrete

Waste materials or by-products have been used in portland cement concrete as either an aggregate, a mineral admixture, or a partial replacement for portland cement. Some use has been made of at least nine waste materials or by-products in concrete. Table 13 lists the materials and the number of states in which they have been used. Most of these materials are coarse, granular materials (including slag, RCP, broken concrete, demolition rubble, RAP, mill tailings, and incinerator ash). For the most part, these materials have been used to replace some or all of the coarse aggregate in concrete and very little of the fine aggregate. Recycling of old concrete pavements into new concrete has become common practice in a number of states (71).

Three very fine-grained by-products (coal fly ash, silica fume, and granulated slag) have been successfully used as cementitious materials in concrete. Fly ash has been used routinely as a partial replacement for portland cement in most states for many years (*54*). Fly ash is also being used frequently as a component of flowable fills or backfills, which are sometimes referred to as controlled low-strength materials.

Use Of Waste Materials In Asphalt Construction

In general, a greater number of types of wastes and by-products have been used, in practice or experimentally, in asphalt paving than in any other type of highway application. Table 13 lists 19 waste materials or by-products that have been used in asphalt paving and the number of states in which these various materials have been used. Table 14 provides a state-by-state summary of the use of these waste materials and by-products by each state. Selected waste materials or by-products and their use in asphalt related applications are described in this chapter.

At least 46 states indicate routine use of RAP in hot-mix asphalt. Scrap tires, mainly tire chips or crumb rubber, have been used in asphalt in a total of 38 states, although at least 27 of these states still consider their use experimental. Several other states do not intend to use scrap tires in asphalt paving any longer, because of either poor performance or unfavorable economics, or both. Other concerns related to the use of scrap tires in asphalt paving involve recyclability, air emissions, and worker safety. At this time there is no reliable evidence to indicate that mixes containing recycled rubber from scrap tires behave any differently than conventional asphalt paving mixes in terms of these concerns (*139*).

Although a wide variety of waste materials and by-products has been used in asphalt paving, only RAP and scrap tires have been used in a large number of states. Blast-furnace slag has been used as an aggregate in asphalt paving for many years, but only 15 states indicate using blast-furnace slag in their highway projects. Similarly, steel slag is reportedly an excellent skid-resistant aggregate for asphalt wearing surfaces, yet only 11 states report having used steel slag in paving.

Although only 12 states report using mill tailings as either coarse or fine aggregate in asphalt, it is likely that mining wastes (either waste rock or tailings) have been used for that purpose years earlier in a number of mining states. Fly ash has also been used in asphalt paving mixes in eight states, but as a mineral filler, not as an aggregate. Glass has been used as fine aggregate in asphalt in eight states, but it is still considered experimental in at least one state (Iowa).

RCP has been used as an asphalt aggregate in five states. Coal bottom ash, incinerator ash, and foundry sand have also been used in asphalt paving as an aggregate in four states. LDPE has been used as an asphalt modifier in four states. No other waste or by-product has been used in asphalt paving in more than two or three states.

SPECIFICATIONS FOR WASTE MATERIALS AND BY-PRODUCTS

A survey was conducted of all 50 state highway agencies to determine which waste materials or by-products were included in their state specifications for materials or construction, and for which applications. A one-page specification questionnaire was developed and sent to each state agency. Appendix B includes a typical specification questionnaire, in which 20 different types of end uses for various wastes or by-products are designated, with a space provided to indicate whether a state has a specification for that particular end use. Additional spaces are provided at the bottom of the questionnaire for other specifications, or for special provisions, that are not included on the questionnaire.

All 50 states returned the specification questionnaire. Every state has specified at least one waste material or by-product for use in construction, and some states include at least 10 waste materials or by-products in their state specifications.

TABLE 14
SUMMARY OF WASTE MATERIALS AND BY-PRODUCTS USED IN ASPHALT CONCRETE PAVEMENTS (Including Chip Seals, Crack Fillers, and Joint Sealants)

	RAP[1]	SCRAP TIRES			METALLURGICAL SLAGS			COMBUSTION ASH BY-PRODUCTS				
		Tire Chips	Crumb Rubber	Rubberized Asphalt	Blast Furnace	Steel Mill	Non-Ferrous	Coal Fly Ash	Bottom Ash	Boiler Slag	Incinerator Ash	Sludge Ash
1. Alabama					X	X						
2. Alaska		X										
3. Arizona		X										
4. Arkansas	X	X							X	X		
5. California	X	X			X		X					
6. Colorado	X	X										
7. Connecticut		X*										
8. Delaware												
9. Florida	X	X			X		X					
10. Georgia	X											
11. Hawaii												
12. Idaho												
13. Illinois												
14. Indiana			X*	X								
15. Iowa	X	X*										
16. Kansas	X	X*			X	X		X				
17. Kentucky					X	X						
18. Louisiana	X				X	X		X				
19. Maine	X	X*	X*	X								
20. Maryland	X	X										
21. Massachusetts	X	X	X								X	
22. Michigan	X	X	X		X	X		X				
23. Minnesota		X*						X			X	X
24. Mississippi	X	X										
25. Missouri	X		X		X	X			X	X		

[1] Reclaimed Asphalt Pavement

* Considered unsuitable for further use

TABLE 14 (CONTINUED)

SUMMARY OF WASTE MATERIALS AND BY-PRODUCTS USED IN ASPHALT CONCRETE PAVEMENTS (Including Chip Seals, Crack Fillers, and Joint Sealants)

	RAP[1]	SCRAP TIRES			METALLURGICAL SLAGS			COMBUSTION ASH BY-PRODUCTS				
		Tire Chips	Crumb Rubber	Rubberized Asphalt	Blast Furnace	Steel Mill	Non-Ferrous	Coal Fly Ash	Bottom Ash	Boiler Slag	Incinerator Ash	Sludge Ash
26. Montana												
27. Nebraska	X	X*						X				
28. Nevada	X		X									
29. New Hampshire	X		X									
30. New Jersey	X		X					X			X[2]	
31. New Mexico												
32. New York	X		X*	X				X				
33. North Carolina	X		X*									
34. North Dakota												
35. Ohio				X								
36. Oklahoma	X	X										
37. Oregon	X	X*	X*					X				
38. Pennsylvania	X		X		X	X	X					
39. Rhode Island												
40. South Carolina	X	X				X	X					
41. South Dakota												
42. Tennessee	X	X					X					
43. Texas		X			X		X		X			
44. Utah	X											
45. Vermont	X											
46. Virginia	X	X*										
47. Washington	X		X									
48. West Virginia	X				X	X		X				
49. Wisconsin	X	X										
50. Wyoming	X		X						X			

[1] Reclaimed Asphalt Pavement
[2] Experimental Use

* Considered unsuitable for further use

TABLE 14 (CONTINUED)
SUMMARY OF WASTE MATERIALS AND BY-PRODUCTS USED IN ASPHALT CONCRETE PAVEMENTS (Including Chip Seals, Crack Fillers, and Joint Sealants)

	Crushed Clay Pipe	Crushed Concrete	Demolition Debris	Foundry Waste	Waste Glass	Kiln Dust	Lead-Zinc Chat	Mining Waste	Plastic Waste	Quarry Waste	Roofing Shingles	Scrubber Sludge
1. Alabama		X						X				
2. Alaska												
3. Arizona						X*						
4. Arkansas												
5. California												
6. Colorado					X				X			
7. Connecticut												
8. Delaware												
9. Florida					X							
10. Georgia												
11. Hawaii												
12. Idaho												
13. Illinois											X	
14. Indiana				X								
15. Iowa		X			X*							
16. Kansas		X					X					
17. Kentucky												
18. Louisiana												
19. Maine												
20. Maryland												
21. Massachussetts												
22. Michigan												
23. Minnesota								X			X	
24. Mississippi												
25. Missouri							X	X				

[1] Includes Reclaimed Concrete Pavement

* Considered unsuitable for further use

TABLE 14 (CONTINUED)
SUMMARY OF WASTE MATERIALS AND BY-PRODUCTS USED IN ASPHALT CONCRETE PAVEMENTS (Including Chip Seals, Crack Fillers, and Joint Sealants)

	Crushed Clay Pipe	Crushed Concrete	Demolition Debris	Foundry Waste	Waste Glass	Kiln Dust	Lead-Zinc Chat	Mining Waste	Plastic Waste	Quarry Waste	Roofing Shingles	Scrubber Sludge
26. Montana												
27. Nebraska		X										
28. Nevada								X	X			
29. New Hampshire												
30. New Jersey		X			X							
31. New Mexico												
32. New York					X	X		X	X			
33. North Carolina												
34. North Dakota												
35. Ohio												
36. Oklahoma								X				
37. Oregon												
38. Pennsylvania				X	X						X**	
39. Rhode Island									X			
40. South Carolina				X								
41. South Dakota												
42. Tennessee												
43. Texas	X											
44. Utah						X*						
45. Vermont					X					X		
46. Virginia					X							
47. Washington												
48. West Virginia												
49. Wisconsin				X								
50. Wyoming												

* Considered unsuitable for further use

TABLE 15

HIGHWAY AGENCY SPECIFICATIONS FOR USING WASTE MATERIALS AND BY-PRODUCTS IN HIGHWAY CONSTRUCTION APPLICATIONS

	RAP		RCP or Crushed Concrete			Blast Furnace Slag				Steel Slag	Crushed Glass	
	AGG in AC	Base or SubBase	AGG in PCC	AGG in AC	Base or SubBase	AGG in AC	AGG in PCC	Base or SubBase	Cement in PCC	AGG in AC	AGG in AC	Base Course
1. Alabama	X					X				X		
2. Alaska	X											
3. Arizona	X											
4. Arkansas	X											
5. California	X						X			X		X
6. Colorado	X		X			X				X		
7. Connecticut	X		X	X								X
8. Delaware							X		X			
9. Florida	X			X		X			X		X	
10. Georgia	X											
11. Hawaii	X											
12. Idaho	X											
13. Illinois	X		X	X	X	X	X			X		
14. Indiana	X		SP	SP		X	X		X	X		
15. Iowa	X		X								X	
16. Kansas	X		X[1]	X						X		
17. Kentucky	X					X	X			X		
18. Louisiana	X		X	X		X	X					
19. Maine	X											
20. Maryland	X			X					X			
21. Massachusetts	X								X			
22. Michigan	X		X	X		X	X		X	X		
23. Minnesota	X		X	X						X		
24. Mississippi	X			X								
25. Missouri	X									X		

SP - Special Provisions

[1] Current moratorium on construction - only one project constructed

TABLE 15 (CONTINUED)

HIGHWAY AGENCY SPECIFICATIONS FOR USING WASTE MATERIALS AND BY-PRODUCTS IN HIGHWAY CONSTRUCTION APPLICATIONS

	RAP		RCP or Crushed Concrete			Blast Furnace Slag				Steel Slag	Crushed Glass	
	AGG in AC	Base or SubBase	AGG in PCC	AGG in AC	Base or SubBase	AGG in AC	AGG in PCC	Base or SubBase	Cement in PCC	AGG in AC	AGG in AC	Base Course
26. Montana	SP		SP									
27. Nebraska	X			X								
28. Nevada	X											
29. New Hampshire	X	X							X			X
30. New Jersey	X							X			X	
31. New Mexico	X											
32. New York	X	X				X					X	
33. North Carolina	X						X[1]		X[1]			
34. North Dakota	X		X									
35. Ohio	X					X	X					
36. Oklahoma	X		X									
37. Oregon	X											
38. Pennsylvania	X				X	X	X		X	X	X	X
39. Rhode Island	X	SP		X								
40. South Carolina	X						X		X	X		
41. South Dakota	X			X[2]								
42. Tennessee	X					X				X		
43. Texas	X					X	X			X		
44. Utah	X					X						
45. Vermont	X											
46. Virginia	X			X		X	X		X	X	X	X
47. Washington	X											SP
48. West Virginia	X					X	X			X		
49. Wisconsin	X					X						
50. Wyoming	X		X									

SP -Special Provisions

[1] Limited use on an experimental basis

[2] Used in only one project thus far

TABLE 15 (CONTINUED)

HIGHWAY AGENCY SPECIFICATIONS FOR USING WASTE MATERIALS AND BY-PRODUCTS IN HIGHWAY CONSTRUCTION APPLICATIONS

	Coal Fly Ash					Bottom Ash		Scrap Tires				
	Cement in PCC	Flowable Fill	Fill Material	Base or SubBase	Filler in AC	Anti-Skid	AGG in AC	Asphalt-Rubber	AGG in AC	Fill Material	Seal Coat	Crack Sealant
1. Alabama	X	X										
2. Alaska								X				
3. Arizona	X		X					X			X	
4. Arkansas	X	X	X	X				X			X	
5. California	X	X						X	X		X	
6. Colorado	X		X									X
7. Connecticut	X		X		X							
8. Delaware	X	X	X	SP								
9. Florida	X	X			X			X				
10. Georgia	X			X							X	
11. Hawaii												
12. Idaho					X							
13. Illinois	X	X		X	X	X						
14. Indiana	X				X			X	X			
15. Iowa	X	X						X				
16. Kansas	X	X		X	X	X		X	X			SP
17. Kentucky	X	X		X	X	X		X			X	
18. Louisiana	X				X							
19. Maine								SP		SP	SP	
20. Maryland	X	X						X				
21. Massachusetts	X							X				
22. Michigan	X	X			X							
23. Minnesota	X											
24. Mississippi	X			X	X				SP[1]			
25. Missouri	X	X	X	X				X				

SP - Special Provisions

[1] Have placed one research project using ground scrap tires

TABLE 15 (CONTINUED)

HIGHWAY AGENCY SPECIFICATIONS FOR USING WASTE MATERIALS AND BY-PRODUCTS IN HIGHWAY CONSTRUCTION APPLICATIONS

	Coal Fly Ash					Bottom Ash		Scrap Tires				
	Cement in PCC	Flowable Fill	Fill Material	Base or SubBase	Filler in AC	Anti-Skid	AGG in AC	Asphalt-Rubber	AGG in AC	Fill Material	Seal Coat	Crack Sealant
26. Montana	X			SP	X			SP	SP		SP	
27. Nebraska	X	X			X			X				
28. Nevada	X										X	
29. New Hampshire	X							X				
30. New Jersey	X			X	X						X	
31. New Mexico	X							X				
32. New York	X	X			X				X[2]			
33. North Carolina	X				X[1]				X[1]	X[1]		
34. North Dakota	X			X		X						
35. Ohio	X	X		X	X	X			X		X	
36. Oklahoma		X						X				
37. Oregon	X				X			X		X		
38. Pennsylvania	X	X	X	X	X	X		X				X
39. Rhode Island	X											
40. South Carolina	X	X			X			X				
41. South Dakota	X	X			X						X	
42. Tennessee	X	X		X								
43. Texas	X	X		X	X			X			X	
44. Utah	X	X	X					X			X	
45. Vermont	X									X[1]		
46. Virginia	X	X			X			X		X		
47. Washington	X											
48. West Virginia	X		SP		X	X						
49. Wisconsin	X	X	X							X		
50. Wyoming	X	X										

SP - Special Provisions

[1] Limited use on an experimental basis

[2] Maximum of 2% shredded tire rubber

TABLE 15 (CONTINUED)

HIGHWAY AGENCY SPECIFICATIONS FOR USING WASTE MATERIALS AND BY-PRODUCTS IN HIGHWAY CONSTRUCTION APPLICATIONS

	Boiler Slag			Copper Slag	Mine Tailings			Scrap Plastic	Quarry Waste	Used Motor Oil	Scrap Paper	Wood Waste
	Anti-Skid	AGG in AC	AGG in PCC	Lower Uses	AGG in AC	AGG in PCC	AGG Uses	Fence Posts	Fill Material	Fuel in AC Plants	Mulch	Mulch
1. Alabama												
2. Alaska												
3. Arizona												
4. Arkansas												
5. California												
6. Colorado												
7. Connecticut												
8. Delaware												
9. Florida								X				
10. Georgia												
11. Hawaii												
12. Idaho												
13. Illinois				X								
14. Indiana												
15. Iowa												
16. Kansas							SP	1			SP	
17. Kentucky												
18. Louisiana												
19. Maine												
20. Maryland												
21. Massachusetts												
22. Michigan												
23. Minnesota												
24. Mississippi												
25. Missouri	X	X			X	X			X		X	X

SP - Special Provisions

[1] Not specified directly, but not excluded by specifications

TABLE 15 (CONTINUED)

HIGHWAY AGENCY SPECIFICATIONS FOR USING WASTE MATERIALS AND BY-PRODUCTS IN HIGHWAY CONSTRUCTION APPLICATIONS

	Boiler Slag			Copper Slag	Mine Tailings			Scrap Plastic	Quarry Waste	Used Motor Oil	Scrap Paper	Wood Waste
	Anti-Skid	AGG in AC	AGG in PCC	Lower Uses	AGG in AC	AGG in PCC	AGG Uses	Fence Posts	Fill Material	Fuel in AC Plants	Mulch	Mulch
26. Montana												
27. Nebraska												
28. Nevada								X				
29. New Hampshire												
30. New Jersey												
31. New Mexico												
32. New York												
33. North Carolina								X				
34. North Dakota												
35. Ohio												
36. Oklahoma												
37. Oregon												
38. Pennsylvania												
39. Rhode Island												
40. South Carolina												
41. South Dakota												
42. Tennessee												
43. Texas								X[1]				
44. Utah												
45. Vermont												
46. Virginia												
47. Washington												
48. West Virginia												
49. Wisconsin												
50. Wyoming												

SP - Special Provisions

[1] Allowed in delineator posts as long as all other requirements are met

TABLE 16
WASTE MATERIALS OR BY-PRODUCTS INCLUDED IN STATE HIGHWAY AGENCY SPECIFICATIONS

WASTE OR BY-PRODUCT	NUMBER OF STATES SPECIFYING
Reclaimed Asphalt Pavement (RAP)	48
Coal Fly Ash	47
Scrap Tires	34
Blast-Furnace Slag	24
Reclaimed Concrete Pavement (RCP)	21
Steel-Making Slag	16
Crushed Glass	7
Coal Bottom Ash	7
Recycled Plastic	4
Mine Tailings	3
Crushed Concrete	2
By-Product Lime	1
Coal Boiler Slag	1
Quarry Waste	1
Copper Slag	1
Shredded Paper	1
Wood Chips	1
Recycled Motor Oil	1

NOTE: The total number of states specifying a particular waste material or by-product also includes special provisions.

Hawaii specifies only RAP in new or recycled asphalt paving, while Missouri has 18 specifications that include 12 waste materials or by-products. Seven states (Illinois, Kansas, Michigan, Missouri, Pennsylvania, Texas, and Virginia) have at least 10 specifications that include waste materials or by-products.

Table 15 provides a breakdown of the specifications that have been prepared or are being used by each state. This table also includes special provisions for certain waste materials or applications. It indicates all end uses that may be specified for each waste material or by-product. At least 18 waste materials or by-products are included in one or more state specifications. Table 16 shows the different wastes or by-products that are specified and the number of states in which these materials are specified. The wastes or by-products most frequently included in state specifications are RAP, fly ash, scrap tires, blast-furnace slag, RCP, and steel slag.

Table 17 provides a list of the most frequently used state specifications that include waste materials or by-products. Nearly every state has a specification for RAP in either new or recycled asphalt pavement. All but five states have a specification for fly ash as a partial replacement for portland cement in concrete. Half the states now have a specification for using fly ash in flowable fill or backfill mixes. Granulated or crumb rubber is specified as an additive or binder component in asphalt-rubber mixes in at least 25 states. Blast-furnace slag and steel slag are specified as aggregates in asphalt paving mixes in 17 states and 16 states, respectively.

TABLE 17
MOST FREQUENTLY USED STATE SPECIFICATIONS INCLUDING WASTE MATERIALS OR BY-PRODUCTS

DESCRIPTION OF MATERIAL SPECIFICATION	NUMBER OF STATES SPECIFYING
• Reclaimed asphalt pavement as aggregate in new or recycled asphalt mixes	48 states
• Fly ash as partical replacement for portland cement in concrete	44 states
• Fly ash in flowable fill mixtures	24 states
• Granulated tire rubber in asphalt-rubber paving mixtures or in stress-absorbing membrane interlayers	22 states
• Fly ash as mineral filler in asphalt	20 states
• Air-cooled blast-furnace slag as an aggregate in asphalt mixes	16 states
• Steel slag as an aggregate in asphalt wearing surface or base mixes	14 states
• Fly ash as chemical reactant in lime or cement stabilized road base compositions	13 states
• Air-cooled blast-furnace slag as an aggregate in portland cement concrete	12 states
• Reclaimed concrete pavement as an aggregate in new asphalt pavement	12 states
• Granulated tire rubber in asphalt-rubber seal coats	11 states
• Reclaimed concrete pavement as an aggregate in new concrete	
• Fly ash in embankments or backfills	9 states
• Granulated blast-furnace slag as a partial replacement for cement	8 states
• Bottom ash as an anti-skid material	7 states
• Crushed glass as a fine aggregate in asphalt paving mixes	5 states
• Shredded scrap tires as fill material	5 states

CHAPTER SIX

LEGISLATIVE AND REGULATORY CONSIDERATIONS

Growing volumes of solid waste, together with a declining number of landfills, have resulted in an increasing sense of public concern over the problem of how to handle society's waste. The raised public consciousness of solid waste management has begun to be reflected in the mounting number of legislative initiatives and laws targeting various aspects of the problem. The purpose of this chapter is to present and summarize the extent and status of federal and state laws or regulations encouraging the recycling and reuse of various components of solid waste.

FEDERAL LEGISLATION

Resource Conservation and Recovery Act

The Resource Conservation and Recovery Act (RCRA) of 1976 was probably the first statute to call attention to the seriousness of the solid waste disposal problem and the need to develop alternative solutions to handling solid waste. In promulgating RCRA, the U.S. Congress stated with respect to solid waste materials that

- Millions of tons of recoverable materials which could be used are needlessly buried each year.
- Methods are available to separate usable materials from solid waste.
- The recovery and conservation of such materials can reduce the dependence of the United States on foreign resources and reduce the deficit in its balance of payments.

Although RCRA has not been formally reauthorized by Congress during its current session, the act has been amended since it was originally enacted. In 1984, the Hazardous Solid Waste Amendments were passed. These amendments banned the disposal of bulk or non-containerized liquid wastes in sanitary landfills, thus establishing what is often referred to as the "land bans." This legislation also spelled out specific technologies for stabilizing or otherwise treating such wastes in order to render them suitable for disposal in a sanitary landfill. Despite such amendments, the original intent of RCRA has remained unchanged.

Section 6002 of RCRA requires that procuring agencies of the federal government, and certain other entities receiving funds from the federal government, must procure items composed of the highest practical percentage of recovered or recycled materials, consistent with maintaining a satisfactory level of product quality, technical performance, and price competition. In addition, procuring agencies must undertake a review and revision of specifications to eliminate exclusion of recovered materials and to require recovered materials to the maximum extent practical, without jeopardizing the intended end use of the item.

Under Section 6002 of RCRA, the Administrator of the EPA was authorized to prepare, and from time to time to revise, guidelines for the use of procuring agencies in complying with the requirements of this section. Such guidelines were to set forth recommended practices with respect to the procurement of recovered materials and items containing such materials, and to provide information as to the availability, sources of supply, and potential uses of such materials and items.

Procurement Guidelines for Recovered Materials

To date, the EPA has promulgated five procurement guidelines for the use or reuse of recovered materials in items or materials that are purchased with federal funds in excess of $10,000 per year. These five guidelines cover

- Coal fly ash in portland cement concrete,
- Recycled paper,
- Retreaded tires,
- Building insulation, and
- Rerefined oil.

The first guideline, effective January 28, 1983, was entitled "Guideline for Federal Procurement of Cement and Concrete Containing Fly Ash" *(140)*. It designated cement and concrete, including concrete products such as pipe and block, containing fly ash as a product area for which government procuring agencies must exercise affirmative procurement. This guideline did not mandate the use of fly ash in concrete for federally construction projects, but did require that cement or concrete containing fly ash be allowed to be bid as an alternate on such projects. This guideline was determined to be applicable to the federal-aid highway construction program and has been implemented fully at the federal and state levels. With few exceptions, all federal and state agencies, including highway and transportation departments, have modified their specifications for portland cement concrete to permit the use of fly ash. Only six states—in which no fly ash is generated—do not have provisions in their specifications for using fly ash in concrete.

Intermodal Surface Transportation Efficiency Act of 1991

Section 1038 of the recently enacted Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 addresses the

use of recycled paving material, specifically the use of asphalt pavement containing recycled rubber *(6)*. The Secretary of Transportation and the Administrator of the EPA have been authorized to coordinate and conduct, in cooperation with the states, a study to determine the following:

- The threat to human health and the environment associated with the production and use of asphalt pavement containing recycled rubber,
- The degree to which asphalt pavement containing recycled rubber can be recycled, and
- The performance of the asphalt pavement containing recycled rubber under various climate and use conditions.

The Secretary of Transportation and the Administrator of the EPA, in cooperation with the states, have also been authorized to conduct a joint study to determine the economic savings, technical performance qualities, threats to human health and the environment, and environmental benefits of using recycled materials in highway projects, including asphalt containing more than 80 percent reclaimed asphalt, asphalt containing recycled glass, and asphalt containing recycled plastic.

The ISTEA legislation also has a provision for the required use of asphalt pavement containing recycled rubber. Beginning on January 1, 1995, and annually thereafter, each state must certify to the Secretary of Transportation that it has satisfied the following minimum utilization requirement for asphalt pavement containing recycled rubber:

Year	*Percentage of Asphalt Tonnage Containing Recycled Rubber*
1994	5 percent
1995	10 percent
1996	15 percent
1997	20 percent

This requirement applies to all highway construction financed by federal-aid highway funds. There is, however, a further stipulation in Section 1038 of ISTEA that any recycled material or materials determined to be appropriate by the studies referred to earlier may be substituted for recycled rubber under the minimum utilization requirement, up to a maximum of 5 percent. Furthermore, the minimum utilization requirement for asphalt pavement containing recycled rubber may be increased by the Secretary of Transportation to the extent it is technologically and economically feasible to do so, and if an increase is appropriate to ensure markets for the reuse and recycling of scrap tires. As noted previously, Congress is considering an amendment to expand the uses for crumb rubber. In the Department of Transportation Appropriations Act for FY 1994 (section 325 of H.R. 2750), the minimum utilization requirement for asphalt pavement containing recycled rubber was rescinded. Instead, the first applicable minimum utilization requirement will be the 10 percent required in FY 1995 as provided in 1038 td.

Executive Order for Federal Agency Recycling

On October 31, 1991, President George Bush signed an Executive Order requiring that all federal agencies use recycled products whenever possible. The Executive Order also established a Federal Recycling Coordinator and individual recycling coordinators for each federal agency. The main objectives of this Executive Order are as follows:

- To require that all federal agencies promote cost-effective waste reduction and recycling of reusable wastes generated by federal government activities,
- To develop policy options and procurement practices to promote environmentally sound, economically efficient waste reduction and recycling within the federal government, and
- To encourage market demand for designated items produced using recovered materials by implementing federal procurement preference programs favoring such items *(141)*.

This Executive Order is applicable to the Department of Transportation, FHWA, and Federal Aviation Administration. Its implementation should eventually stimulate further use of recovered materials in transportation construction projects that are federally funded.

STATE LEGISLATION

State Environmental AgencyQuestionnaire

A questionnaire was distributed to all 50 state environmental agencies seeking information on the extent of state laws or mandates requiring state transportation agencies to investigate possible uses for waste materials. The questionnaire also requested information on beneficial use provisions in state laws, mandatory recycling laws, landfill space availability, and out-of-state waste reuse. A total of 45 states responded to the questionnaire. Table 18 presents the summary of responses from this questionnaire.

A total of 26 states (57.8 percent) indicated that legislation had been passed in their state requiring the Department of Transportation or other state agencies to investigate waste material use. At least 27 states (60.0 percent) have some form of beneficial reuse provision either in their state laws or in their waste regulations. Some 17 (37.8 percent) have enacted mandatory recycling laws. However, enactment of mandatory recycling laws does not necessarily mean that waste materials or by-products will be recycled into highway construction materials. Only 6 states (13.3 percent) indicated in the questionnaire that they did not permit the reuse of out-of-state waste materials. These states were Hawaii, Montana, Nevada, North Dakota, Vermont, and West Virginia. Concerning the availability of landfill space, only 5 states (11.1 percent) indicated that they did not have sufficient landfill space now. However, 18 states (40.0 percent) indicated that they do not expect to have sufficient landfill space in the next 5 to 10 years.

TABLE 18

SUMMARY OF RESPONSES TO STATE ENVIRONMENTAL AGENCY QUESTIONNAIRE

	Legislation for Use of Waste Materials	Beneficial Reuse Provisions in Law	Mandatory Recycling Provisions in Law	Prohibited Out of State Waste Materials	Lack of Available Landfill Space		Aware of Highway Use of Wastes or By-Products by the State DOT
					Now	5 - 10 years	
1. Alabama	X		X			X	
2. Alaska*							
3. Arizona	X						
4. Arkansas*							
5. California			X			X	
6. Colorado		X					Petroleum Contaminated Soils
7. Connecticut	X						Glass, Compost, Incinerator Ash
8. Delaware		X					Coal Fly Ash
9. Florida	X		X				
10. Georgia*							
11. Hawaii				X	X	X	
12. Idaho	X	X	X			X	Sawdust, Glass, Tire Chips
13. Illinois							
14. Indiana	X	X					
15. Iowa*							
16. Kansas			X				RAP[1], Scrap Tires
17. Kentucky							
18. Louisiana	X		X				Scrap Tires, Glass
19. Maine	X	X	X		X	X	Oil Contaminated Soils, Tires
20. Maryland			X				Coal Ash, Tires, MSW Ash, Glass
21. Massachusetts		X				X	
22. Michigan	X	X				X	Plastic in Sign Posts
23. Minnesota	X	X	X			X	RAP, Glass, Tires, Sludge Ash
24. Mississippi	X	X	X			X	Scrap Tires in Asphalt
25. Missouri	X	X					Scrap Tires in Asphalt

*Did not respond to questionnaire

[1] Reclaimed Asphalt Pavement

TABLE 18 (CONTINUED)

SUMMARY OF RESPONSES TO STATE ENVIRONMENTAL AGENCY QUESTIONNAIRE

	Legislation for Use of Waste Materials	Beneficial Reuse Provisions in Law	Mandatory Recycling Provisions in Law	Prohibited Out of State Waste Materials	Lack of Available Landfill Space		Aware of Highway Use of Wastes or By-Products by the State DOT
					Now	5 - 10 years	
26. Montana		X		X			
27. Nebraska		X					Coal Fly Ash
28. Nevada	X		X	X*			RAP, RCP[1]
29. New Hampshire	X	X					
30. New Jersey	X	X	X		X	X	RAP, Glass, Shingles, Wood
31. New Mexico		X					RAP, Scrap Tires, Glass
32. New York	X	X			X	X	Scrap Tires, Glass
33. North Carolina	X					X	RAP, Scrap Tires
34. North Dakota				X			Coal Fly Ash
35. Ohio		X					Construction Debris, Tires
36. Oklahoma		X					Coal Fly Ash
37. Oregon	X					X	Crumb Rubber
38. Pennsylvania	X	X	X				Scrap Tires, Glass, Plastic
39. Rhode Island	X	X	X			X	RAP, Scrap Tires
40. South Carolina		X				X	
41. South Dakota		X					
42. Tennessee*							
43. Texas	X	X					RAP, RCP, Fly Ash, Slag, Tires
44. Utah		X					Fly Ash, Glass, Scrap Tires
45. Vermont				X		X	Scrap Tires, Glass
46. Virginia	X	X	X				Fly Ash, Glass, Scrap Tires
47. Washington	X	X			X	X	Scrap Tires, Glass
48. West Virginia		X	X	X		X	
49. Wisconsin	X		X				RAP, Fly Ash Tires, Slag, Foundry Waste
50. Wyoming		X					

*Did not respond to questionnaire

[1] Reclaimed Asphalt Pavement

TABLE 19

SUMMARY OF STATE RECYCLING LEGISLATION AND SCRAP TIRE LEGISLATION

	States With Recycling Laws	Status of State Recycling Laws				Status of Scrap Tire Legislation			
		Recycling Plans Only	Mandatory Goals	Source Separation	Community Separation	No Tire Laws	No Landfill Disposal	Cut or Shred for Landfill	Tire Tax or Fee
1. Alabama									
2. Alaska						X			
3. Arizona	X							X	X
4. Arkansas	X	X						X	X
5. California	X		X						X
6. Colorado						X			
7. Connecticut	X			X					
8. Delaware	X					X			
9. Florida	X		X		X			X	X
10. Georgia	X				X	X		X	
11. Hawaii	X					X			
12. Idaho									X
13. Illinois	X				X				X
14. Indiana	X	X							
15. Iowa	X	X					X		
16. Kansas							X		X
17. Kentucky								X	X
18. Louisiana								X	X
19. Maine	X			X					X
20. Maryland	X		X		X				X
21. Massachusetts	X	X							
22. Michigan	X	X							X
23. Minnesota	X		X		X		X		
24. Mississippi								X	X
25. Missouri	X	X					X		X

TABLE 19 (CONTINUED)

SUMMARY OF STATE RECYCLING LEGISLATION AND SCRAP TIRE LEGISLATION

	States With Recycling Laws	Status of State Recycling Laws				Status of Scrap Tire Legislation			
		Recycling Plans Only	Mandatory Goals	Source Separation	Community Separation	No Tire Laws	No Landfill Disposal	Cut or Shred for Landfill	Tire Tax or Fee
26. Montana						X			
27. Nebraska						X			X
28. Nevada						X			
29. New Hampshire	X	X							
30. New Jersey	X		X			X			
31. New Mexico	X	X				X			
32. New York	X			X					
33. North Carolina	X				X			X	X
34. North Dakota						X			
35. Ohio	X		X		X			X	
36. Oklahoma	X	X							X
37. Oregon	X							X	X
38. Pennsylvania	X			X					
39. Rhode Island	X		X	X			X		X
40. South Carolina									X
41. South Dakota						X		X	
42. Tennessee	X	X					X		
43. Texas									
44. Utah						X			X
45. Vermont	X	X					X		
46. Virgina	X		X		X				X
47. Washington	X								X
48. West Virginia	X	X						X	
49. Wisconsin	X				X				X
50. Wyoming									

State Recycling Laws

In 1990, the National Solid Wastes Management Association (NSWMA) conducted a comprehensive study of state legislation related to recycling *(37)*. It found that, as of 1990, 33 states had passed some type of legislation concerning recycling. Of these 33 states, 17 either had mandatory recycling goals or requirements that recyclable materials be separated from solid waste at the source (home or business) or through the community (curbside collection or dropoff centers). Although these 17 states have established mandatory percentage goals for recycling, the goals do not include recycling of waste materials into highways. Table 19 provides a summary of the status of recycling legislation, as indicated from the NSWMA study.

Nine states have enacted beverage container deposit laws (so-called "bottle bills"). Michigan has a 10-cent deposit on all beverage containers. The following eight states have a 5-cent deposit on all beverage containers: Connecticut, Delaware, Iowa, Maine, Massachusetts, New York, Oregon, and Vermont.

The Scrap Tire Management Council periodically surveys the status of state legislation pertaining to the disposal or recycling of scrap tires within each state. Individual briefing sheets have been published for each state, indicating the status of current or pending legislation involving scrap tires. According to the most recent set, 34 states have enacted some form of recycling or disposal legislation that either includes or specifically targets scrap tires. Seven states prohibit landfilling of whole tires and 12 other states require that tires be cut, sliced, or chipped before being disposed of in landfills *(142)*. Table 19 also includes the findings from the Scrap Tire Management Council survey.

Disposal Bans

Disposal bans have become an increasingly common method of legislating the prohibition of bulky or toxic products from landfills or incinerators, thereby stimulating the potential for recycling of such products. As of 1990, according to an NSWMA report, at least 100 product disposal bans have been enacted by 29 states and the District of Columbia *(7)*. Materials most frequently cited in these disposal bans are lead-acid batteries (27 states), unprocessed tires (14 states), yard waste (13 states), and used oil (11 states).

State Procurement Laws

According to an NSWMA study, 42 states have passed laws to stimulate recycling markets by encouraging state agencies to purchase products with recycled content. Twenty-three states allow their agencies to pay from 5 to 10 percent more for products with recycled content. Because of the many types of resins used to make plastic products, at least 27 states now require codes on plastic containers so that consumers and industry can readily sort them for recycling *(37)*.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Waste Recovery and Use

- A wide variety of non-hazardous solid wastes and by-products have been used successfully as construction materials for highways and other applications.
- Most state highway agencies have been involved, either directly or indirectly, for many years in the research, development, demonstration, and utilization of various waste materials and by-products in highway construction.
- A wealth of technical literature documents the characteristics, uses, and performance of many different sources of solid wastes as construction materials, particularly for highway construction.
- Evaluation and eventual acceptance of new or unconventional materials by the highway construction industry is a gradual process that usually requires many years as the long-term performance of such materials is monitored under field conditions.
- Although the highway construction market consumes many millions of tons of materials annually, not all waste materials and by-products can be assimilated readily into this market.
- To be considered suitable for use in highways, a waste material must exhibit the proper engineering characteristics, consistently satisfy specification requirements, provide an acceptable level of performance, and be economically competitive with available construction materials without harming the environment.
- A number of waste materials and by-products are potentially usable in a variety of applications. Certain ones (scrap tires, as an example), although acceptable in highway construction, may also be used more appropriately in other types of applications.

Waste Use in Highway Applications

- Historically, state highway agencies have been pro-active in their efforts to evaluate and incorporate usable waste materials and by-products into the highway system.
- More than two dozen different waste materials or by-products have been used in at least three dozen different highway applications by state highway agencies. In some cases, waste use has been on a one-time or experimental basis, but state agencies have also been using certain wastes or by-products for many years.
- A number of frequently used by-products are not wastes, but material resources. Examples are blast-furnace slag, steel slag, coal ash, RAP, and RCP.
- RAP is the by-product specified and used most frequently, although the RAP percentages currently being used are generally lower than the maximum allowable. New processing techniques are being evaluated that have the potential to recycle up to 100 percent of RAP.
- Coal fly ash is used frequently as a cement replacement in concrete. Flowable fill represents an opportunity to increase fly ash use in highways significantly, especially if the mixes include only cement and fly ash. Fly ash use as a stabilizing agent for in-place pavement recycling is also a potentially large market.
- Although nearly three dozen states have used crumb rubber from scrap tires in some form of asphalt paving, most states (with the exception of Arizona, California, and Florida) still consider this use experimental. The use of shredded scrap tires as lightweight fill has been successful and utilizes a large number of scrap tires. Realistic leachate testing indicates little or no harmful impacts from placing shredded tires below the groundwater level.
- Air-cooled blast-furnace slag has been used with considerable success as an aggregate in base courses, asphalt paving, and concrete. Users of air-cooled slag should avoid stockpiles where blast-furnace slag and steel slag are commingled. Granulated blast-furnace slag is a high quality material that is a suitable replacement for portland cement in concrete.
- Steel slag is a very hard, heavy, abrasion-resistant source of aggregate, which is particularly suitable for use in asphalt wearing surfaces. When steel slag is used as an aggregate in unbound base courses, it should be aged to minimize expansion.
- RCP appears suitable for use as coarse aggregate in concrete, but is not as suitable as fine aggregate. The use of RCP as unbound aggregate or in asphalt mixtures is usually acceptable, although there may be some potential for leaching and clogging of underdrains when used in unbound bases.
- Although mining wastes are derived from rock and soil and are often suitable as highway construction materials, their use has been sporadic, because most mining waste accumulations are in remote locations.

Limitations to Waste Material Utilization

- The costs of handling and processing certain wastes or by-products could make it economically unattractive to recover and use those materials.
- Because of transportation costs, most waste materials and by-products will probably be limited to use within a relatively short distance of the source, unless they are located in an area with a shortage of construction materials.
- Materials with leachate concentrations for metals that exceed drinking water standards represent a potential environmental liability, even though such concentrations may not exceed toxicity limits. Municipal incinerator ash is an example of such a material.
- Embankments constructed out of potentially combustible waste materials (such as coal refuse or wood wastes) must be well compacted and sealed by several feet of earth cover to prevent spontaneous combustion. Embankments built using degradable wood waste may also need to be confined to below the water table.

TABLE 20
PROVEN APPLICATIONS FOR FREQUENTLY USED WASTE MATERIALS

Waste or By -Product	Proven Applications	Suggestions or Limitations
Reclaimed Asphalt Pavement	Hot-Mix Asphalt or Asphalt Recycling	RAP percentages within air emission requirements Increase RAP percentage with drum dryer mixers More cold-in-place recycling
Reclaimed Asphalt Pavement	Unbound Base and Subbase	Meet gradation specifications
Coal Fly Ash	Cement Replacement in Concrete Mixtures	Meets requirements of ASTM C618 specifications Investigate higher fly ash replacement percentages
Coal Fly Ash	Flowable Fill Mixtures	High percentages of fly ash, in lieu of sandfiller Non-C618 fly ash is acceptable in either wet or dry form
Coal Fly Ash	Embankment Material	Must place within the proper moisture content
Coal Fly Ash	Stabilized Base Course	Can use different reagents (lime, cement, or kiln dust) Cost savings possible when using pavement recycling
Coal Bottom Ash	Unbound Aggregate Base Cement-Stabilized Base Asphalt Paving Aggregate	Remove pyrites from bottom ash prior to use Test for pH and electrical resistivity if used as backfill
Reclaimed Concrete Pavement	Base Course Aggregate	Remove steel reinforcing Meet gradation specifications Use with natural sand as the fine aggregate fraction
Scrap Tire Chips Study	Lightweight Fill Material Embankment Material	Further environmental needed below water table Can use large numbers of tires in embankments
Scrap Tire Crumb Rubber	Asphalt-Rubber Paving (Wet or Dry Process)	Still considered to be experimental by many states Higher first costs compared to conventional asphalt Recyclability is questionable
Blast-Furnace Slag (Air-Cooled)	Concrete Aggregate Base Course Aggregate Asphalt Paving Aggregate	Do not use slag from commingled stockpiles Increased asphalt content due to slag porosity
Blast-Furnace Slag (Granulated)	Cement Replacement in Concrete Concrete Mixtures	Add at ready-mix plant or use Type I-S cement

RECOMMENDATIONS

Waste Use in Highway Construction—General

- Increased use should be made of non-hazardous solid wastes and by-products with a history of successful use as construction materials in highway applications where these materials are cost effective.
- The technical and environmental aspects associated with using waste materials should be investigated thoroughly before routine use is made of them. The potential for long-term liability should also be considered carefully.
- Marketers of waste materials and by-products being used, or being considered for use, as highway construction materials are advised to develop Material Safety Data Sheets for their particular materials. This should minimize potential liabilities associated with their use.
- Specifications for recovered materials, or products made from recovered materials, must be developed before or in conjunction with the use of such materials in highway construction applications. Specifications (or special provisions) should ensure the quality of the intended product without either disqualifying it from use or unnecessarily restricting competition.
- State transportation and environmental agencies will benefit from an inventory of the locations, quantities, characteristics, and appropriate end uses of potentially suitable waste materials and by-products generated or stockpiled within their state.

Use of Specific Waste Materials and By-Products

Frequently Used Waste Materials

Continued use of a number of frequently or commonly used wastes and by-products is considered acceptable for certain highway applications that have a proven service record, subject to various suggestions or limitations, as indicated in Table 20.

Occasionally Used Materials

A number of other occasionally used waste materials and by-products could be used in certain applications, provided prospective users are aware of applicable suggestions or limitations related to such applications, as indicated in Table 21.

Seldom Used Waste Materials

- Caution is advised when considering the use of a number of seldom used waste materials and by-products as high-

TABLE 21
POSSIBLE APPLICATIONS FOR OCCASIONALLY USED MATERIALS

Waste or By-Product	Possible Applications	Suggestions or Limitations
Broken Concrete	Unbound Base Course Embankment Base	Remove reinforcing steel Must be properly graded
Construction and Demolition Debris	Unbound Base Course	Remove any possible contaminants prior to use Must be properly graded Do not use in concrete
Steel Slag	Asphalt Paving Aggregate Base or Subbase Aggregate	Conditioning or aging should be considered prior to use Must pass an expansion test to be acceptable in bases
Mining Wastes (Waste rock and coarse tailings)	Embankment Borrow Riprap Aggregate Unbound Base Course Asphalt Paving Aggregate	Study leachate characteristics and groundwater impacts Evaluate aggregate properties Analyze stripping potential
Mining Wastes (Coarse coal refuse)	Embankment Borrow	Must be well compacted Cap top and sides with earth
Waste Glass or Ceramics	Unbound Base Course Asphalt Paving Aggregate	Crush to fine gradation Maximum of 15% by weight
Plastic Waste (Commingled)	Synthetic Lumber for Posts, Guiderails, Fences	Must meet specifications Must be crash tested
Plastic Waste (Recycled PET bottles)	Geotextile Manufacture	Avoid contaminants
Plastic Waste (Recycled LDPE pellets)	Asphalt-Cement Modifier	More performance and cost data are needed
Silica Fume	Pozzolanic Admixture in Concrete-Specialized Uses	Use carefully to avoid or reduce micro-cracking
Wood Waste	Mulching Material Lightweight fill material	Can use either sawdust or shredded timber
Non-Ferrous Slags	Unbound Base Course Asphalt Paving Aggregate	Determine chemical composition and leachate characteristics

way construction materials. A number of these materials may have environmental or engineering concerns associated with their use in certain applications. Included in this category are sewage sludge, incinerator ash, compost, foundry sands, and landfill refuse.

Future Research Needs

- More information is needed on the potential recyclability and associated health and safety impacts of different waste materials and by-products in asphalt pavements. Among the materials to be studied are scrap tire rubber, polymer-modified asphalt, sewage sludge ash, and municipal incinerator ash.
- Further investigation should be made of the behavior and performance of recycled wastes or by-products as coarse or fine aggregates in portland cement concrete. Information is needed on the leachate characteristics of waste materials used in the following applications:

  — Scrap tires in embankments below groundwater levels,
  — Wood waste in embankments below groundwater levels,
  — Incinerator ash in asphalt paving,
  — Petroleum-contaminated soil in asphalt paving, and
  — Selected mining wastes in embankments.

- In order to prepare Material Safety Data Sheets, more must be known about the potential health and safety effects on construction workers from using

  — Crumb rubber from scrap tires,
  — Municipal incinerator ash,
  — Sewage sludge,
  — Compost (from sewage sludge or MSW),
  — Mining wastes, and
  — Non-ferrous slags.

- Large quantities of petroleum-contaminated soils are becoming available from the remediation of leaking underground storage tanks. These soils have been stabilized with portland cement for use as base material, cleaned and used as fill, incorporated into emulsified asphalt cold mixes, or fed directly into hot-mix asphalt plants for use in private road construction. These materials should also be evaluated for possible use in state or local highway facilities.
- Research is needed on the long-term pavement performance of roadway sections containing waste materials or by-products. Of particular interest are asphalt pavements containing RAP, recycled concrete, slags, scrap tires, glass, bottom ash, mining wastes, and asphalt modifiers made from

recycled polyethylene. Also of interest are concrete pavements containing RCP, demolition debris, fly ash, slag aggregates, slag cement, and silica fume, as well as fly ash stabilized base course materials.

- Additional information is needed on the engineering behavior and field performance of blended cements in concrete, especially slag cement. Further investigation is warranted to determine whether higher percentages of fly ash or ground granulated blast-furnace slag can be used in blended cements.
- Further research is also warranted on the field performance of concrete mixes with high-volume replacement of portland cement using Class F fly ash with superplasticizers. More information must be developed on the durability, volume stability, and resistance to deicing salts of such mixes.
- Performance data are needed for concrete mixes containing varying proportions of silica fume, in terms of resistance to chemical attack, deicing salts, and alkali-aggregate reaction.
- Further investigation is suggested to determine more rational and consistent maximum recommended percentages of RAP for hot-mix asphalt in wearing surface, binder, and base course mixtures. Maximum percentages should take into account the engineering properties of the resultant mixtures.
- More research and analytical work is required to establish realistic thickness design coefficients for asphalt pavements containing significant amounts of waste materials or by-products, either as aggregates or in the binder. Such materials include scrap tires, RAP, glass, and asphalt modifiers made from recycled polyethylene.
- More accurate initial and life cycle cost data are needed for asphalt-rubber (wet process) and rubber-modified asphalt (dry process) paving applications so that reasonable cost comparisons can be made. Efforts should be made to further economize the use of scrap tires in asphalt paving.
- More information should be made available on the costs, benefits, and possible environmental and health impacts associated with using various types of compost or co-compost materials within the highway right of way.
- Further data are needed on engineering properties and performance of various highway products made from recycled plastic, including posts, lumber, geotextiles, delineators, and composite pipe piles.

Institutional Issues

- Meetings are encouraged between state transportation and environmental agency personnel concerning the reuse of wastes and by-products in highways, in order to establish a dialogue and try to find some common ground on regulations, monitoring, and other issues.
- There is a need for a national consensus among federal and state highway and environmental agency personnel regarding the beneficial reuse of non-hazardous waste materials or by-products. Such a consensus could eliminate the need to obtain solid waste permits for installations that are no threat to the environment.
- Wastes and by-products need not be used only at the state level. Often, such materials are well suited to local, county, or municipal construction projects, where traffic volumes are low, budgets are tight, and procedures are more flexible.
- The ISTEA provision for use of recycled scrap-tire rubber could be expanded to include other civil engineering highway applications for crumb rubber, such as crack sealing, bridge deck sealants, seal coats, and stress-absorbing membranes. Shredded scrap tires in embankments and lightweight backfill applications could also be included.

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APPENDIX A

GLOSSARY OF SOLID WASTE AND WASTE MANAGEMENT TERMINOLOGY

The following is a partial listing of terminology related to the generation, handling, management, and disposal of solid wastes. The definitions in this appendix were derived from a composite thesaurus prepared in 1979 by H.I. Hollander and C.L. Koppenhaver of Gilbert Associates, Inc. for the American Society for Testing and Material (ASTM) Committee E38 on Resource Recovery (now part of D34 on Waste Disposal) and the U.S. Environmental Protection Agency (EPA).

Ash is the inorganic residue remaining after the burning of wood, coal, coke, or other combustible substances. Ash may not be identified in composition or quantity with the inorganic substances present in the material before ignition.

Biomass is organic residue from the processing of agricultural and foresting products.

Blast-furnace slag is the slag produced in iron blast furnaces. It may be cooled slowly in air or more rapidly by granulation in water or by pelletization.

Bottom ash is the coarse-grained residue removed from the bottom of a boiler or incinerator that results from the burning of coal, wood, municipal solid wastes, or other com bustible material.

By-product is something produced secondarily or in addition to the main product in manufacture.

Combustible waste is material capable of combustion, including paper, cardboard, cartons, wood boxes, plastic, rags, leather, rubber, leaves, yard trimmings, and household waste.

Compost is the disinfected and stabilized product of the decomposition process that is used or sold for use as a soil amendment, artificial top soil, growing medium, or other similar uses.

Composting is a controlled process of decomposing organic matter by micro-organisms, yielding a product with potential value as a soil conditioner.

Construction and demolition wastes consist of waste building materials and rubble resulting from construction, remodeling, repair, and demolition operations.

Cullet is waste or broken glass, usually suitable as an addition to raw glass melt.

Fly ash is the finely divided residue recovered from exhaust gases that results from the combustion of ground or powdered coal. Fly ash can also be generated from the incineration of wood, municipal solid waste, or other combustible material.

Garbage is the animal and vegetable residues resulting from the handling, storage, sale, preparation, cooking, and serving of foods.

Incineration is the thermal reduction of solid waste by controlled burning, not necessarily accompanied by materials recovery or energy recovery.

Inert material is a substance that will not decompose, dissolve, or in any other way form a contaminated leachate after coming in contact with water or other liquids likely to be found at a disposal site, permeating through the substance.

Logging residues are the unused portions of poles or trees felled in land clearing or timber harvesting. These residues consist of all volume of timber left on the ground after logging operations.

Materials recovery refers to processes which separate and recover basic materials such as paper, glass, metals, rubber, plastics, or textiles from mixed municipal wastes. Materials recovery processes are considered as front-end systems.

Mining wastes are residues which result from the extraction of raw materials from the earth or after the benefication of ores.

Municipal waste is a general term used to designate essentially household waste but including all types of waste likely to be collected in an urban area and delivered to a public or private disposal facility.

Non-combustible waste includes materials which remain after combustion including inert materials such as metals, tin cans, dirt, gravel, bricks, ceramics, glass, sand, and ashes.

Organic materials contain volatile solids in the form of carbon, which oxidizes or burns. When these materials also contain nitrogen or sulfur, or both, odorous by-products are formed.

Processing refers to steps taken to convert a solid waste into something useful.

Product means that which is created as a result of a manufacturing process.

Recovered material is material recovered from or otherwise destined for the waste stream.

Recovery is the process of retrieving materials or energy resources from wastes.

Recyclable materials refer to source- or site-separated materials, including high-grade paper, glass, metal, plastic, aluminum, newspaper, corrugated paper, yard clippings, and other materials that may be recycled or composted.

Recycling refers to the separation of a given material from the waste stream and processing it so that it may be used again as the raw material for products that may or may not be similar to the original.

Refuse consists of solid wastes including rubbish, ashes, incinerator residue, street cleanings, and industrial wastes.

Refuse-derived Fuel (RDF) is a form of fuel derived from the shredding of refuse for burning as a supplementary fuel in utility or industrial boilers. Using a front-end separation system, metal, glass, and other inorganics are first removed, with the remaining organic or combustible fraction processed to form RDF.

Residue is the solid materials remaining after burning, comprising ash, metal, glass, ceramics, and unburned organic substances.

Resource is a new or reserve source of materials or energy, representing an immediate or possible source of revenue.

Resource recovery is a general term used to describe the extraction of materials or energy from waste.

Reuse is the return of a commodity or product into the economic stream for use in exactly the same kind of application as before, without any change in its identity. The classic example is the returnable beverage container.

Rubbish is a general term for solid waste, excluding food waste and ashes, taken from residences, commercial establishments and institutions.

Rubble consists of broken pieces of masonry and concrete.

Sanitary landfill is a controlled method for the disposal of waste on land. The technique includes careful preparation of the fill area, control of leachate, and a specified volume of soil to be spread over a given volume of trash.

Scrap refers to waste collected from industrial, commercial, or household sources and destined for disposal facilities.

Sewage sludge is a semi-solid substance consisting of settled sewage solids combined with varying amounts of water and dissolved materials.

Slag is a semi-liquid mineral substance formed by chemical action and fusion at furnace operating temperatures.

Sludge is the accumulated semi-liquid suspension of settled solids deposited from waste waters or other fluids.

Solid waste is a general term for discarded materials destined for disposal, but not discharged to a sewer or to the atmosphere. Solid waste can be composed of a single material or a heterogeneous mix of various materials, including semi-solids. The following material categories are not usually included:

— Domestic sewage and/or waste water sludges
— Materials having value, salvaged for reuse, recycling or sale
— Abandoned vehicles

Source separation is the sorting of specific materials such as newspapers, glass, metal cans, and vegetative matter, into specified containers to provide separate collection.

Tailings are the reject material resulting from the screening or processing of a raw material.

Transfer station is a facility where solid waste is transferred from collection trucks to larger vehicles for movement to disposal areas or processing plants.

Trommel is a perforated rotating horizontal cylinder used to screen large pieces of glass and remove small abrasive items such as stones and debris.

Virgin material is a raw material used in manufacturing that has not yet become a product.

Vitrification is a process whereby high temperatures effect permanent chemical and physical changes in a ceramic body, most of which is transformed into glass.

Waste is useless, unwanted, or discarded material, including solids, liquids, and gases. Solid wastes are classified as refuse.

Waste processing involves operations such as shredding, compaction, composting, and incineration, in which the physical or chemical properties of wastes are changed.

Yard clippings include fallen leaves, cut grass, or other organic debris that can be converted to humus.

APPENDIX B

QUESTIONNAIRES SENT TO STATE HIGHWAY AND ENVIRONMENTAL AGENCIES

At the outset of this investigation, a two-page questionnaire was sent to the chief materials engineer at each state highway agency, and that of the District of Columbia. Around the same time, a similar two-page questionnaire was sent to the director of solid waste management at each state environmental regulatory agency or health department. A copy of each of these questionnaires is included in this appendix.

A follow-up one-page questionnaire was then sent to the state highway agency personnel, all of whom had responded to the original two-page questionnaire. This second questionnaire requested information concerning any current specifications and special provisions relating to waste materials or by-products, or to finished products containing some type of waste material. A copy of this questionnaire is also included in this Appendix.

After all 50 states had responded to the specification questionnaire, a third questionnaire, also one page, was circulated to the 44 states that had indicated some use of fly ash as a mineral admixture in concrete. All 44 states returned this questionnaire, a copy of which is included in this appendix.

Finally, a two-page questionnaire was sent to all state highway agencies requesting more detailed information on their use of RAP and scrap rubber in asphalt paving. A copy of this asphalt questionnaire is also found in this appendix.

NCHRP PROJECT 20-5
TOPIC 22-10

"Use of Waste Materials and By-Products in Highway Construction"

STATE DOT QUESTIONNAIRE
MATERIALS ENGINEERS

1. Is your state now performing, or has it ever performed, research into the potential uses of waste materials or by-products as highway construction materials? ☐ YES ☐ NO

2. Are you aware of any such research performed at a university within your state? ☐ YES ☐ NO
If yes, please provide the following information.

Name of University	Contact Person	Telephone Number

Brief Description of Research Work Performed

3. If the answer to question 1 is YES, which waste materials from the attached list were investigated and for what prospective uses?

WASTE MATERIAL	PROSPECTIVE USE(S)

4. Based on this research, what were the conclusions regarding the potential acceptability for using these waste materials?

WASTE MATERIAL AND USE	POTENTIAL ACCEPTABILITY		
	☐ YES	☐ NO	☐ INCONCLUSIVE
	☐ YES	☐ NO	☐ INCONCLUSIVE
	☐ YES	☐ NO	☐ INCONCLUSIVE
	☐ YES	☐ NO	☐ INCONCLUSIVE

5. What other research, if any, on waste material use in highway construction is being planned for your state? NONE

WASTE MATERIAL	PROSPECTIVE USE(S)

6. Which waste materials or by-products that your state has investigated have actually been used in highway construction in your state? Please comment on the relative success of these uses, if known.

WASTE MATERIAL AND USE	COMMENTS ON RELATIVE SUCCESS

Thank you for taking the time and effort to respond to this questionnaire. Please indicate your name, address, and telephone number in case any follow-up information is desired. Any other comments you wish to make would be welcomed. Please include a separate letter attached to this questionnaire if you wish to make additional comments.

NAME	ADDRESS	TELEPHONE NUMBER

WASTE MATERIALS OR BY-PRODUCTS
WITH SOME POTENTIAL FOR USE IN HIGHWAY CONSTRUCTION

1. Broken Concrete

2. Ceramic Waste

3. Coal Ash
   a. Fly Ash
   b. Bottom Ash
   c. Boiler Slag
   d. Scrubber Sludge

4. Compost

5. Demolition Debris (Rubble)

6. Foundry Waste

7. Incinerator Ash

8. Kiln Dusts (Lime or Cement)

9. Lime Waste

10. Mining Wastes
    a. Coal Refuse
    b. Mine Tailings
    c. Phosphate Slimes
    d. Phosphogypsum
    e. Waste Rock

11. Paper

12. Plastic

13. Quarry Waste

14. Reclaimed Pavement Material
    a. Asphalt
    b. Concrete

15. Rubber Tires

16. Sewage Sludge

17. Slags
    a. Blast Furnace
    b. Metallurgical
    c. Steel Mill

18. Sulfate Waste

19. Used Motor Oil

20. Wood Waste
    a. Sawdust
    b. Wood Chips

NCHRP PROJECT 20-5
TOPIC 22-10

"Use of Waste Materials and By-Products in Highway Construction"

STATE ENVIRONMENTAL AGENCY QUESTIONNAIRE

1. Are there any state laws or legislative mandates in your state which require State DOT's or other state agencies to investigate possible uses for waste materials? ___ YES ___ NO

   If YES, please provide the following information.

   State Law or Mandate _____ State Agency (or Agencies) Involved _____

   Waste Material(s) or By-Product(s) Being Investigated _____

2. Are you aware of any waste materials or by-products that have been evaluated or used as a highway construction material by your State's Department of Transportati

WASTE MATERIAL	TYPE OF HIGHWAY USE

3. Are there any provisions in your state's laws or regulations exempting certain waste materials or by-products from solid waste permitting requirements if they are recycled or reused in a beneficial manner, such as in highway construction? ___ YES ___ NO
   If YES, please provide the following information.

   State Law or Regulation _____ Waste Material Exempted _____

   Description of Beneficial Use(s) Exempted From Permits _____

4. Have any waste material or by-products been approved by your agency for beneficial reuse in highway construction? ___ YES ___ NO
   If YES, please provide the following information.

WASTE MATERIAL	TYPE OF HIGHWAY USE

5. Is there a mandatory recycling law in your state? ___ YES ___ NO

   If YES, does it also apply to the recycling or reuse of waste materials or by-products other than household waste? ___ YES ___ NO

   If YES, which waste materials or by-products are being recycled?

WASTE MATERIAL OR BY-PRODUCT	TYPE OF REUSE OR RECYCLING

6. Are any waste materials or by-products from out of state allowed to be beneficially reused within your state? ___ YES ___ NO

   If YES, which waste materials or by-products have been reused?

WASTE MATERIAL OR BY-PRODUCT	TYPE OF REUSE OR RECYCLING

7. Is there currently sufficient landfill space in your state? ___ YES ___ NO

   Will there be sufficient landfill space in the next 5 to 10 years? ___ YES ___ NO

   If NO, in what areas of the state will landfill space be deficient?

   _____

8. Would the reuse of waste materials or by-products help alleviate the problem of insufficient landfill space in some areas of the state? ___ YES ___ NO

   If YES, which waste materials or by-products would be suitable for reuse?

   _____

Thank you for taking the time and effort to respond to this questionnaire. Please indicate your name, address, and telephone number in case any follow-up information is desired. Any other comments you wish to make would be welcomed. Please include a separate letter attached to this questionnaire if you wish to make additional comments. It would also be appreciated if you could include copies of any research reports related to the use of waste materials in your state.

NAME _____ TELEPHONE NUMBER _____

TITLE _____ ADDRESS _____ FAX NUMBER _____

NCHRP PROJECT 20-5
USE OF WASTE MATERIALS AND BY-PRODUCTS
IN HIGHWAY CONSTRUCTION

_____
Name and State DOT

Dear

Thank you very much for responding to the questionnaire sent to you several months ago concerning this project, as well as any other information you may have provided. It would also be of interest to know the extent to which states have developed and are using specifications for highway construction materials containing recycled wastes or by-products. I would very much appreciate it if you could take a little time to indicate which, if any, of the end use applications listed below are being specified in your state. If you are also using specifications and/or special provisions for any other wastes or by-products, please indicate these also.

- ☐ Reclaimed Asphalt Pavement in New or Recycled Asphalt Concrete
- ☐ Reclaimed Concrete Pavement in New Portland Cement Concrete
- ☐ Reclaimed Concrete Pavement in New Asphalt Concrete
- ☐ Fly Ash as Partial Replacement for Portland Cement in Concrete
- ☐ Fly Ash in Lime or Cement Stabilized Aggregate Base Course
- ☐ Fly Ash as Borrow Material for Fill or Embankment Construction
- ☐ Fly Ash with Portland Cement as Flowable Fill or Slurry Backfill
- ☐ Fly Ash as Mineral Filler in Asphalt Concrete Mixtures
- ☐ Bottom Ash as Snow and Ice Control or Anti-Skid Abrasive
- ☐ Blast Furnace Slag as Aggregate in Portland Cement Concrete
- ☐ Blast Furnace Slag as Aggregate in Asphalt Concrete
- ☐ Granulated Blast Furnace Slag as Cement Replacement in Concrete
- ☐ Steel Mill Slag as Aggregate in Asphalt Concrete
- ☐ Shredded Rubber Tires in Asphalt-Rubber for SAMI or Paving Mixes
- ☐ Shredded Rubber Tires in Asphalt-Rubber for Sealing or Seal Coats
- ☐ Shredded Rubber Tires as Aggregate in Asphalt Concrete
- ☐ Chipped Rubber Tires for Fill or Embankment Construction
- ☐ Crushed Glass as Aggregate in Asphalt Concrete
- ☐ Crushed Glass as Aggregate Supplement in Unbound Base Course
- ☐ Recycled Plastic in Delineator, Guide Rail, or Fence Posts

PLEASE INDICATE ANY OTHER SPECIFICATIONS INVOLVING WASTE MATERIALS

_____
_____
_____

PLEASE INDICATE ANY SPECIAL PROVISIONS INVOLVING WASTE MATERIALS

_____
_____
_____

Thank you very much for your prompt attention and return of this information sheet. Please fax this sheet back to me at 215-328-5362. If you wish to include copies of any specifications and/or special provisions, please send them to the undersigned at P.O. Box 422, Springfield, PA 19064.

Sincerely yours,

Robert J. Collins

Robert J. Collins, P.E.

NCHRP PROJECT 20-5
USE OF WASTE MATERIALS AND BY-PRODUCTS
IN HIGHWAY CONSTRUCTION

_____
Name and State DOT

Dear

Once again, sincere thanks for all the information you have previously provided for this project. It would be greatly appreciated if you could be of assistance one last time by supplying some additional information concerning fly ash use in cement and concrete in your state, as a follow-up to the earlier specification questionnaire.

1. How many different ways is fly ash being used in concrete in your state?
   - _____ As a raw material in the manufacture of portland cement.
   - _____ As an ingredient of portland-pozzolan (I-P) blended cement.
   - _____ As a partial replacement for portland cement in ready-mix concrete.

2. Which Class or Classes of fly ash are available in your state?
   _____ Class C _____ Class F _____ Both Class C and Class F

3. If both are available, what percentage of each Class is used in concrete?
   Class C - _____% Class F - _____%

4. Please indicate how fly ash is specified and used in concrete in your state. (If no use, leave blank)

TYPE OF CONCRETE	SPECIFIC APPLICATION	FLY ASH IN SPECIFICATIONS: ALLOWED	FLY ASH IN SPECIFICATIONS: NOT ALLOWED	ACTUAL USE OF FLY ASH: ROUTINE	ACTUAL USE OF FLY ASH: EXPERIMENTAL	ACTUAL USE OF FLY ASH: C or F OR BOTH
Structural	Foundation:	____	____	____	____	____
	Abutments & Piers	____	____	____	____	____
	Retaining Walls	____	____	____	____	____
	Beams & Parapets	____	____	____	____	____
	Bridge Decks	____	____	____	____	____
Paving	Roadway Slabs	____	____	____	____	____
	Concrete Shoulders	____	____	____	____	____
	Roller Compacted	____	____	____	____	____
	Slab Grouting	____	____	____	____	____
Precast	Medial Barriers	____	____	____	____	____
	Proprietary Walls	____	____	____	____	____
	Noise Walls	____	____	____	____	____
	Box Culverts	____	____	____	____	____
	Concrete Piles	____	____	____	____	____
	Inlets & Manholes	____	____	____	____	____
Incidental	Curbs & Sidewalks	____	____	____	____	____
	Divider Islands	____	____	____	____	____
	Channel Linings	____	____	____	____	____
	Headwalls	____	____	____	____	____

5. Are flowable fill mixes being used in your state? _____ Yes _____ No

6. If yes, what are the approximate mix proportions of the flowable fill?
   Lbs. per cubic yard: Fly Ash_____ Cement_____ Sand_____ Water_____

REMARKS: _____

_____

Your prompt attention and return of this final questionnaire is gratefully acknowledged, especially since the report is presently being written. Please fax this sheet back to me as soon as possible at 215-328-5362. It has been a pleasure corresponding with you.

Sincerely yours,

Robert J. Collins

Robert J. Collins

Questionnaire on RAP

NCHRP PROJECT 20-5
USE OF WASTE MATERIALS AND BY-PRODUCTS
IN HIGHWAY CONSTRUCTION

_____
Name and State DOT

Dear

In addition to the enclosed questionnaire concerning the use of RAP, we are also including this second page, which is a questionnaire seeking some additional information on the usage of crumb rubber in hot mix asphalt paving. Please try to take a little bit of time to fill out this questionnaire and return it by fax (preferably along with the RAP questionnaire).

1. Can you estimate the approximate tonnage or number of scrap tires that are discarded within your state each year.
   _____ tons or _____ number of tires _____ unknown

2. Is crumb rubber or granulated rubber from scrap tires currently being recycled into hot-mix asphalt paving or seal coats in your state?
   _____ Yes _____ No _____ Experimental Basis Only

   2A. If yes or experimental, what type of process was used?
   _____ Wet process (asphalt-rubber binder)
   _____ Dry process (crumb rubber aggregate)
   _____ Both wet and dry processes

   2B. Approximately how many projects have used scrap tire rubber?
   _____ Wet process _____ Dry process

   2C. In what types of projects has scrap tire rubber been used?
   _____ Asphalt-rubber wearing surface or friction course (wet)
   _____ Rubberized aggregate wearing surface or friction course (dry)
   _____ Asphalt-rubber seal coat, SAM, or SAMI (wet)
   _____ Asphalt-rubber sealant for bridge decks (wet)

4. Based on your state's experience with scrap tire rubber, how would you rate any of the following applications that you have used?

	SUCCESSFUL		ECONOMICAL		INCONCLUSIVE
	YES	NO	YES	NO	TO DATE
Wearing/Surface Courses (wet)	___	___	___	___	_____
Wearing/Surface Courses (dry)	___	___	___	___	_____
Seal Coat, SAM, or SAMI (wet)	___	___	___	___	_____
Sealant for Bridge Decks (wet)	___	___	___	___	_____

5. In your opinion, how easy or difficult will it be for your state to comply with the ISTEA requirements for recycled tire rubber in hot-mix asphalt?

BY 1994 (5%)		AFTER 1994 (>5%)
_____	Relatively easy	_____
_____	Possible, but not easy	_____
_____	Relatively difficult	_____
_____	Extremely difficult	_____
_____	Impossible	_____

6. If the future use of recycled tire rubber was not mandated by ISTEA, would your state use crumb rubber in hot-mix asphalt in the future?
   _____ Yes _____ No _____ Possibly on Experimental Basis _____ Uncertain

   6A. General comments on the use of crumb rubber in hot-mix asphalt.

   _____

Thank you very much for your continuing cooperation. Would you please return this questionnaire along with the enclosed questionnaire on RAP and fax both of them together as soon as possible to 215-328-5362.

Sincerely yours,

Robert J Collins

Robert J Collins

Questionnaire on Crumb Rubber

NCHRP PROJECT 20-5
USE OF WASTE MATERIALS AND BY-PRODUCTS
IN HIGHWAY CONSTRUCTION

_____
Name and State DOT

Dear

Although a draft report of this project has been submitted to the Transportation Research Board (TRB), we are anxious to obtain some additional information concerning your state's use of RAP in hot-mix asphalt. We would be very grateful if you could take the time to complete and return this questionnaire.

1. Approximate total tonnage of RAP produced per year _____ tons

   1A. Approximate RAP tonnage reused in hot mix per year _____ tons

   1B. Approximate percentage of statewide projects using RAP per year ____%

   1C. Is RAP used in all engineering districts? _____ Yes _____ No

2. What is the maximum percentage of RAP allowed in your state specifications?

   Wearing/Surface courses _____% Binder courses _____% Base courses ____%

3. Can a contractor exceed these percentages with prior approval? ____Yes ____No

4. If yes, what are the maximum allowable percentage limits for RAP?

   Wearing/Surface courses _____% Binder courses _____% Base Courses ____%

5. What is the normal percentage of RAP being used in hot mix in your state?

   Wearing/Surface courses _____% Binder courses _____% Base courses ____%

6. Are cold asphalt recycling or in-place recycling techniques being used on State or Federal aid projects in your state? _____ Yes _____ No

   6A. Approximate RAP tonnage used in such projects per year _____ tons

   6B. What is the normal percentage range of RAP used in such projects?
   Wearing/Surface mixes _____% Binder course _____% Base course _____%

7. Approximately what percentage of the RAP material stockpiled in producers' yards in your state is now being recycled into hot mix asphalt paving during a typical construction season? _____%

8. Are RAP stockpiles in producers' yards growing in your state? ____Yes ____No.

   8A. If yes, which measures do you think would be effective in increasing RAP utilization and controlling the size of future RAP stockpiles?

   _____ Increasing the maximum allowable percentage of RAP
   _____ Allowing RAP use in more paving projects statewide.
   _____ Assuring RAP use in all engineering districts statewide
   _____ Specify and promote RAP use as base and subbase aggregate.
   _____ Provide for bid preferences or economic incentives related to the percentage of RAP to be utilized on specific projects
   _____ Other -- Please describe_____
   _____

Thank you very much for all of your past cooperation. Since we are scheduled to meet with TRB to review the draft report on August 31st, we would greatly appreciate it if you would please fax this questionnaire back as soon as possible to 215-328-5362.

Sincerely yours,

Robert J Collins

Robert J. Collins

THE TRANSPORTATION RESEARCH BOARD is a unit of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. It evolved in 1974 from the Highway Research Board, which was established in 1920. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 270 committees, task forces, and panels composed of more than 3,300 administrators, engineers, social scientists, attorneys, educators, and others concerned with transportation; they serve without compensation. The program is supported by state transportation and highway departments, the modal administrations of the U.S. Department of Transportation, the Association of American Railroads, the National Highway Traffic Safety Administration, and other organizations and individuals interested in the development of transportation.

The National Academy of Sciences is a nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encouraging education and research, and recognizes the superior achievements of engineers. Dr. Robert M. White is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences, by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce Alberts and Dr. Robert M. White are chairman and vice chairman, respectively, of the National Research Council.

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National Cooperative Highway Research Program

TECHNICAL APPENDIX

to NCHRP Synthesis of Highway Practice 199:

Recycling and Use of Waste Materials and By-Products in Highway Construction

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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CHAPTER I

INVENTORY AND CLASSIFICATION OF WASTE MATERIALS

Before discussing the status of waste material and by-product utilization in highway construction and/or maintenance operations, it is important to provide a list of suitable or potentially suitable waste materials that are available. This chapter presents an inventory and classification of non-hazardous waste materials and by-products that have been, or possibly could be, used for such operations. An overall classification of waste materials is presented, categorizing waste materials according to general source as:

- Agricultural
- Domestic
- Industrial
- Mineral

Waste materials or by-products placed in each of these categories are described in terms of origin or process and basic physical and chemical characteristics. Estimated annual quantities and locations for each waste or by-product are given and overall stockpiled quantities are noted, wherever reliable information on such quantities is available. Proven and potential uses for each waste or by-product are discussed, as well as its regulatory status, if applicable. Location maps are provided for some of the most widely occurring waste or by-products.

With changing regulations and the increased need for conserving natural resources, it is more important than ever to be aware of the locations, quantities, and characteristics of available non-hazardous solid wastes. Not only are the number of disposal sites decreasing, but it is also more difficult to meet strict new criteria for sanitary landfills. Within the past year, the U.S. Environmental Protection Agency (EPA) has issued new rules for municipal waste landfills. A total of 32 states now require double liner systems in sanitary landfills (1). These regulations will escalate disposal costs and force the closure of more landfills. This will accelerate the recycling and reuse of solid waste materials.

As a further stimulus for recycling, federal and state legislation has been passed targeting certain waste materials for recovery and reuse. A section in the Resource Conservation and Recovery Act (RCRA) authorizes the U.S. EPA to establish guidelines for federal procurement of items containing a significant percentage of recovered materials (2). Since the construction industry requires enormous quantities of raw materials (earth,

aggregates, etc.), efforts are often directed toward beneficial reuse of solid wastes as construction materials, or as components of products used by the construction industry. Approximately 2 billion tons of construction aggregate (crushed stone or sand and gravel) are produced and sold each year in the United States (3). At least half of this total is consumed on highway and bridge construction. Available quantities of various solid wastes are compared with this annual quantity.

AGRICULTURAL WASTES

According to a U.S. Bureau of Mines study on energy potential from organic wastes (4), over 2 billion tons of agricultural wastes are generated annually in the United States. Although this publication is nearly twenty years old, the basic types and quantities of agricultural wastes are not likely to have changed significantly over the years. The principal types of agricultural wastes are:

- Animal Manure
- Crop Wastes
- Lumber and Wood Wastes
- Miscellaneous Organic Wastes

Each of these types of wastes is briefly discussed.

Animal Manure

Manure production from cattle, hogs, sheep and poultry annually amounts to approximately 1.6 billion tons, based on wet weight. Moisture content of manure is highly variable, depending on the source. Much of the manure is produced from animals raised in confined conditions, such as feedlots, dairies, or hen houses. Most manure, if collected, is not transported over great distances because of the expense involved. Some manure may be processed for fertilizer or refeeding. Some manures may also be converted into compost, or thermally processed to yield oil.

Crop Wastes

Crop wastes consist of field wastes from harvests to milling wastes from grain processing. Over 20 years ago, the total amount of annual crop waste generation was estimated at 550 million tons. However, improved crop harvesting methods and increased waste deposition for erosion prevention have likely resulted in some reduction of the overall amount of crop wastes. Therefore, it is estimated that approximately 400 million tons of such wastes are produced annually. Much of this waste is probably used as animal feed.

Lumber and Wood Wastes

Approximately one-third of the wood harvested in the United States is unused, wasted in the form of logging residues, wood and bark chips, and sawdust, primarily at sawmills. Approximately 20 years ago, logging and wood processing residues amounted to 55 million tons per year. At this time, it is estimated that the annual production of such wastes is probably in the range of 70 million tons per year, with a large proportion being generated in the Pacific Coast states. Where available, some of these wastes can be used as mulch or lightweight fill for the construction or repair of embankments. In all likelihood, some quantities of wood chips and sawdust are already being reused commercially as mulching materials, particle board production, and other industry related applications.

Miscellaneous Organic Wastes

This category of agricultural wastes includes organic waste materials from Federal installations, fermentation residues, and animal carcasses, among other things. A conservative estimate of the amount of such miscellaneous wastes is 30 million tons per year. No specific uses are known or recommended for these wastes.

DOMESTIC WASTES

It is estimated that approximately 200 million tons of domestic wastes are generated annually in the United States, with overall quantities gradually increasing each year. Although this amount is only one-tenth of the annual generation of agricultural waste, its effects are far more pronounced than that of agricultural wastes because domestic wastes are concentrated mainly in populous areas, are more visible, more diverse, and more potentially damaging to the environment. The majority of domestic waste is in the form of household and commercial trash or garbage, which is presently estimated at 185 tons per year (5), or approximately 4 pounds per person per day. Currently, around 75 percent of trash or garbage is deposited in landfills, while 11 percent is recycled and 14 percent is burned (3).

The United States is currently headed for a domestic solid waste disposal crisis, if recent waste management trends are not soon reversed. In 1984, there were a total of nearly 10,500 operating municipal waste landfills in the country. There are at present approximately 6,300 operating landfills, as of the end of 1990, down over 1,000 from 1989 (6), and more and more landfills are expected to reach capacity, or otherwise be closed in the next 5 to 10 years. By the year 2000, the National Solid Waste Management Association (NSWMA) estimates that projected landfill closing, even with newly constructed disposal sites, will reduce

the number of operating landfills to approximately 2,150 (6). As a result, landfill capacity will be reduced between 50 and 60 percent.

To combat this problem, increased emphasis must be placed on reducing the volume of domestic waste to be landfilled. This can be done primarily by recycling and thermal reduction or incineration, and to a lesser extent by source reduction. Since 1960, the annual amount of material collected has nearly quadrupled and many states have adopted aggressive recycling programs. At least 32 states now have comprehensive recycling laws (7). Separation of recyclable materials is normally handled through curbside collection programs or at central processing plants, referred to as materials recovery facilities (MRF). Over the past year, the number of materials recovery facilities has doubled to a total of 92 plants operating in 24 states (8). Recycled materials that are normally separated and reused include paper, metal, glass, and plastics. Recycled glass and plastics are of some interest to the highway construction industry.

Another form of recycling, composting, is gaining increasing popularity in this country. There are now over 1,500 composting operations in at least 40 states. Compost is being produced from sewage sludge, yard waste, or municipal solid waste and, in some cases, combinations of these materials. The U.S. Environmental Protection Agency (EPA) estimates that the amount of composted yard waste will increase from 500,000 tons in 1988 to 9.5 million tons in 1995 (8).

At one time, incineration was a common means of managing municipal solid waste (MSW) in many localities, mostly densely populated areas. With the advent of clean air regulations, many of the old batch type incinerator plants in the country were forced to close due to air emission violations. Spurred in part by an energy crisis, thermal reduction facilities have staged a comeback in the form of resource and energy recovery plants, equipped with modern state-of-the-art emission control devices. There are now nearly 150 MSW thermal reduction facilities operating in the United States (9). Nearly 100 additional facilities are in various stages of planning, permitting, or construction. The EPA estimates that by the year 2000, there may be nearly 300 such plants that will have the capacity to handle approximately one-fourth of the nation's domestic waste. What to do with the ash from these plants is a hotly debated concern at this time.

One factor that may have a negative impact on the number of MSW incinerators that are placed into operation in the future is the air emissions from such facilities. The EPA is currently studying the impact of municipal waste burning on air quality and the resultant incidence of respiratory diseases in humans. If any adverse impacts are indicated from such a study, EPA may consider stricter air emission requirements for MSW incinerators.

- Incinerator Ash
- Sewage Sludge
- Scrap Tires
- Compost
- Glass
- Plastics
- Used Oil
- Waste Paper

Each of these types of domestic wastes is discussed in the sections that follow. A separate synthesis report has been prepared on the generation, collection, and potential reuse of roadway litter (10). Therefore, there is no discussion of roadway litter in this volume.

Incinerator Ash

There are currently 148 thermal reduction facilities with a capacity of at least 50 tons of solid waste per day in operation in the United States (11). These facilities operate in 36 states and the District of Columbia. The locations of these plants are shown in Figure 1. The breakdown of the types of facilities now in operation is as follows:

- 62 Mass Burn Waste-to-Energy
- 24 Refuse Derived Fuel Waste-to-Energy
- 18 Conventional Incinerators
- 34 Mass Burn Modular Incinerators

In addition, there are at least 20 other facilities, including 10 modular incinerators, which operate at a capacity less than 50 tons per day, which were not included in the above total. All told, it is now estimated that these facilities have the capacity to burn approximately 28.6 million tons per year of municipal solid waste (MSW). Assuming that the residue remaining after burning is approximately 30 percent by weight of the incoming refuse, this results in the generation of 8.6 million tons of incinerator ash or residue. Approximately 90 percent of this ash is bottom ash, with the remainder being fly ash.

The characteristics of incinerator ash, particularly the bottom ash, are influenced by several factors, including the extent of upfront processing, the design of the plant's grate system, and the operation of the plant. Upfront processing, involving either separation of recyclables or preparation of refuse derived fuel, can significantly reduce the amount of non-combustibles in the waste stream, resulting in a different ash

FIGURE 1

LOCATIONS OF OPERATING MUNICIPAL INCINERATOR PLANTS

from that produced in a conventional mass burn incinerator. If agitation is applied to the refuse during burning (as with a rotary kiln, reciprocating grate, or rocking grate), the resultant ash is ordinarily more well burned than if it were put through a plant with a traveling grate. Careful plant operation, consisting primarily of maintaining a steady, high combustion temperature (1400° to 1500°F minimum), also results in a more well burned ash than if the temperature were permitted to fluctuate. Grate speed is also a factor, with longer residence time producing a better burnout. Time, temperature, and turbulence are the keys to optimizing combustion efficiency and volume reduction by incineration.

Although well burned incinerator ash or residue may have once been considered a candidate highway construction material, especially bottom ash, in today's regulatory climate it is considered at best a "special waste" and at worst a hazardous waste. The main concerns associated with incinerator ash are heavy metal concentrations (mainly lead and cadmium), especially in fly ash fraction. At present, most operating thermal facilities combine fly ash and bottom ash for disposal in monofills. Leachate analyses of selected incinerator ash grab samples indicates that most fly ash samples exceeded regulatory limits for lead and cadmium, while the majority of combined ash samples did not exceed such limits (12).

Regulation of incinerator ash disposal is presently confused by the interpretation of RCRA Section 3001(i), which excludes certain wastes from regulation under Subtitle C (hazardous waste) (2). Amendments to RCRA exclude all household wastes from the hazardous waste classification and state that facilities burning MSW do not manage hazardous wastes if burning only non-hazardous household wastes. However, EPA is also considering an option that if incinerator ash fails a toxicity test, it must be managed as a hazardous waste (13). There are at least two law suits now being appealed, one in Illinois and one in New York state, concerning whether or not MSW ash is to be considered hazardous.

Some 10 to 15 years ago, there were a number of documented attempts to utilize incinerator ash or residue as a construction material. Regulatory indecision on the status of this material, along with a lack of public understanding or acceptance of the material, have stymied most efforts at beneficial reuse. The material, when properly processed, is potentially usable when blended with conventional aggregate in asphalt base mixes, stabilized with portland cement for base course construction, vitrified into a synthetic aggregate product, or used as a component of cement stabilized reef blocks.

Sewage Sludge

An estimated total of 8 million tons of dry solids per year of sewage sludge are being generated by more than 15,000 municipal wastewater treatment plants throughout the country (14). This estimate is based on a generation rate of 0.2 pounds of solids per person per day (15) and an assumption that roughly 80 percent of the total population resides in areas serviced by sanitary sewers and sewage treatment facilities. Now that ocean disposal of sewage sludge has been banned by EPA, as of January, 1991, options for sludge handling include land application, composting, incineration, landfilling, and beneficial reuse. At the present time, about 40 percent of municipal sewage sludge is land applied or composted and marketed. Roughly 40 percent is codisposed with MSW in sanitary landfills and about 20 percent is presently incinerated (16).

Sewage sludge, prior to dewatering, is a slurry ranging from 3 to 6 percent solids content. Following dewatering, the resultant sludge cake can have a solids content ranging from 18 to 24 percent. Sewage sludge consists mainly of organics such as nitrogen and phosphorous, but may also contain contaminants taken from the wastewater. In November, 1992, the EPA adopted final regulations for sewage sludge handling and disposal options. These regulations apply to over 5,300 treatment facilities and will address national pollutant limits of 27 sludge contaminants for land application, monofills or codisposal, incineration, and distribution and marketing of sludge products. The new regulations recognize three basic methods of sludge use and disposal: land application, surface disposal, and incineration.

There are presently approximately 282 sewage sludge incinerators operating at over 150 plants in the United States, according to EPA (17). The majority of these sludge incinerators, about 70 percent, are multiple hearth facilities. The bulk of the remainder are fluidized bed combustors. In total, these sludge incinerators generate somewhere between 500,000 and 1 million tons of sludge ash annually (18). The sludge ash is a dry powder as it leaves the incinerator, but can either be disposed of in a moistened form in a landfill or slurried into ponds.

Both the dewatered sewage sludge and the ash from sludge incinerators are prospective candidates for beneficial reuse in highway construction. Land application, composting, and fertilizer production are the principal uses for sewage sludge at this time. Sludge ash has potential as an asphalt filler, as well as in the production of bricks and concrete blocks.

Scrap Tires

A total of approximately 280 million tires are discarded each year in the United States, or about one tire for each person. Roughly 45 million of these tires are either reused or retreaded, and so are not included in the total number of tire discards. This leaves roughly 235 million discarded tires annually, which works out to approximately 2 million tons of scrap rubber (19). Although this is only 1 percent of the total domestic waste production of 200 million tons annually, discarded tires represent one of the most troublesome solid waste disposal problems. Tires do not compact well in landfills, they tend to float to the surface, they hold water which aids in the propogation of disease vectors, and they catch on fire easily and can burn for extended time periods. Recognizing these problems, at least 30 states have now enacted legislation regulating the disposal of tires (19).

Over 80 percent of the discarded tires each year are landfilled. Nearly 10 percent are recovered and used as fuel. About 2 percent of discarded tires are ground into crumb rubber and used in asphalt rubber. Another 2 percent are used in other new products such as floor mats, carpet backing, hoses, etc. or in artificial reefs (19). It has been estimated that there may be as many as 2 to 3 billion discarded tires stockpiled around the country.

Mobile equipment has been developed to shred tires into chips or to slit tire sidewalls from treads. Companies have also been created to grind tires into crumb rubber. Since steel belted radial tires now account for more than 90 percent of new tire sales, the recyclability of these tires has been complicated compared to the bias ply tire. Not counting the retread industry, there are currently 18 crumb rubber generating facilities in the United States (20). Figure 2 shows the locations of these crumb rubber facilities.

Aside from retreading, tires are most frequently recycled as a fuel source. Tire chips have also been used to construct fills and embankments and for highway safety barriers. Tire sidewalls have been utilized for embankment reinforcement. Whole tires have been burned as fuel or used to build retaining walls. They have even been used to assist in the construction of earth homes in the Southwest (21).

A separate synthesis report has been prepared on the recycling and uses of scrap tires in highway construction (22). This synthesis report discusses the composition and processing of tires and summarizes legislative issues related to tire disposal and reuse. The report contains a detailed description of the use of scrap tire rubber in asphalt binders and also discusses other highway uses,such as geotechnical applications. Environmental, as well as health and safety issues, are also addressed.

FIGURE 2

LOCATIONS OF CRUMB RUBBER FACILITIES

Compost

Compost refers to the biological decomposition of organic wastes under controlled conditions. Composting is an aerobic process that occurs at elevated temperatures. It yields an end product that is relatively stable and can be applied to the soil. Biological decomposition is carried out by micro-organisms which break down complex organic substances into carbon dioxide, water, and compost residue. Composting takes place when there is a plentiful supply of oxygen, provided by regular aeration (23).

Compost can be produced from a variety of organic materials. In the United States, compost is produced from sewage sludge, yard wastes, or municipal solid waste (MSW) and paper mill sludges. However, other organic wastes such as agricultural and food processing wastes can also be processed into compost. Sometimes, more than one waste source is combined during the composting operation. This is referred to as co-composting. Bulking agents such as wood chips may also be added to the pile during composting.

There are three basic techniques for producing compost:

- Windrow
- Aerated Static Pile
- In-Vessel

In windrowing, the material to be composted is placed on a pad in a pile up to 4 or 5 feet high and the pile is periodically turned over by a windrow turning machine to achieve aeration. In an aerated static pile, forced air is supplied to the pile from pipes extending beneath the pad. In-vessel composting is accomplished in an enclosed digester for up to 7 days. Once the compost has been produced, it is then screened or sized to comply with market requirements. EPA criteria for compost materials involves pathogen control, pH, heavy metal content, carbon to nitrogen (C/N) ratio, and waterholding capacity (24).

At the present time, there are approximately 1400 yard waste (leaves, cuttings, and/or grass) composting operations in the United States (8) as well as 133 sewage sludge compost facilities (25), and 18 MSW compost operations (26). The estimated total compost produced each year from these facilities is probably on the order of 2 to 3 million tons, perhaps even more, owning to the rather limited information on the volume of yard wastes currently being handled. As recently as 1988, only 0.5 million tons of compost was recycled.

Composts and/or co-compost materials can be and are used for mulching, soil amendment, fertilizers, and erosion control. These uses have also included highway construction and/or maintenance operations. Mature, properly produced compost should be considered more of a potential resource than a waste material.

Glass

According to the National Solid Waste Management Association (NSWMA), approximately 12.5 million tons of glass were included in the 185 million tons of household waste discarded annually. Waste glass in the form of beverage and food containers now constitutes about 7 percent by weight of domestic waste (5) and is slowly declining. In 1988, a total of 1.5 million tons of glass (roughly 12 percent of all glass discarded) was recycled (27). The principal use of waste glass is as cullet for glass manufacturing. In order to be acceptable as cullet, waste glass should be color sorted and free of contaminants. Waste glass has also been incorporated into wall panels and tiles.

The composition of glass consists mainly of silica or sand, but also contains predetermined amounts of limestone and soda ash, which are incorporated in order to impart uniform quality and color. There are three basic types of glass that are manufactured commercially in this country. These are borosilicate, soda-lime, and lead glass. Approximately 90 percent of the glass produced is soda-lime glass (28).

In highway construction, waste glass has potential applicability as a fine aggregate in unbound base courses, pipe bedding and as a partial replacement for aggregate in asphalt paving mixes. The use of finely crushed waste glass as a substitute for up to 15 percent of the aggregate in asphalt paving is often referred to as "glasphalt." For more than twenty years, there have been occasional installations of "glasphalt" mixes. Finely crushed glass could also conceivably be used as glass beads in highway line striping. However, the total amount of recovered glass on a national basis is relatively small, especially when compared with the overall quantity of aggregate (crushed stone or sand and gravel) produced annually throughout the United States.

Plastics

NSWMA figures indicate that the total amount of plastics in the household waste stream amounts to 14.4 million tons annually, which represents 8 percent by weight of the total domestic waste, but 20 percent of the volume (5). Plastics are used in many different forms, including containers, packaging, wrapping, construction materials, and electronics. There are basically six types of plastics used by U.S. industry to produce the majority of these various plastic products. These resin types, ranked according to volume of sales, are:

- Low-density polyethylene (LDPE)
- Polyvinyl chloride (PVC)
- High density polyethylene (HDPE)
- Polypropylene (PP)
- Polystyrene (PS)
- Polyethylene terephthalate (PET)

LDPE is used primarily to make plastic wrapping film and to manufacture plastic trash bags. PVC is used to make pipes, siding, wall covering and flooring materials. HDPE is used to make one gallon milk jugs, containers for motor oil and detergent,and toys and housewares. PP is commonly found in battery casings, luggage, and appliance cabinets. PS is used to make the foam that is fashioned into egg cartons, food trays, plastic plates and cups. PET is used primarily for 2 liter soft drink bottles, but is also used in photographic film (29).

Plastic resin suppliers routinely recycle resin that fails to meet specifications by reprocessing it, blending it, or burning it for energy. Although plastic factories reuse 75 percent of the scrap left over from their operations, recovering plastics from the market place poses more difficult challenges. At this time, about 30 percent of PET soft drink bottles are being recycled. The recycling rate for HDPE milk jugs has risen from 1.5 percent in 1989 to 7 percent in 1990. Supermarket chains have started recycling plastic grocery sacks, but very little other LDPE film is currently being collected (29).

Recycled high density polyethylene (HDPE) has been used to produce remolded plastic lumber for wall panels, fence and sign posts, picnic tables, traffic cones, and delineators. Low-density polyethylene (LDPE) has also been recycled and incorporated as a modifier in asphalt paving mixes. Recycled polyethylene terephthalate (PET) bottles are primarily fed to a grinder, washed and used as fiberfill for products such as pillows and ski jackets (30). PET bottles can also provide an alternative resin source for use in geotextile manufacturing. At least one manufacturer of geotextiles uses recycled PET in the production of their fabric products.

Used Oil

According to EPA figures, some 2.6 billion gallons of lubricating oil were sold in the United States in 1988. This resulted in the generation of approximately 1.4 billion gallons of used oil, of which about 800 million gallons were handled through the used oil management system (31). About 180 million gallons of used motor oil and 390 million gallons of waste oil from businesses are discarded or poured down sewers each year. To put these figures in perspective, this combined amount of used oil is 57 times greater than the Exxon Valdiz oil spill. At this time, only 10 percent of used motor oil is being recycled (27).

Approximately 90 percent of reclaimed oil is burned as a fuel, but a market also exists for industrial uses such as cutting oils and hydraulic fluids. Asphalt plants are among the users of reclaimed oil as fuel. Relatively small amounts of used oil are reused as motor oil in automobiles and trucks (31), although some state transportation agencies indicate that used motor oil is being recycled for this purpose in state vehicles.

One problem in dealing with the recycling used oil is the variation in state regulations or the handling of this material. Many states have no regulations at all, while in a few states (California is a prime example), waste engine oil is considered a hazardous waste. EPA is presently considering a wide range of used oil issues before issuing regulations (31).

Waste Paper

Statistics from the National Solid Waste Management Association of the composition of household waste indicate that approximately 72 million tons of paper and paperboard are discarded annually. This constitutes roughly 40 percent by weight of the domestic solid waste stream (5). Waste paper consists of a number of products, including newsprint, office paper, books and magazines, paper bags, paper plates and cups, cardboard boxes, and junk mail.

Figures available from NSWMA indicate that a total of 10.5 million tons of cardboard boxes, 4.4 million tons of newspapers, and 3.1 million tons of other paper products (including office paper, books and magazines, and junk mail) were recycled during 1988 (27). At that time, approximately one-third of all newsprint was reported as being recycled. However, some areas of the country have experienced an oversupply of newsprint since then. Aside from cardboard boxes and newspapers, approximately 8 percent of all other waste paper was being recycled at the time of this survey.

Recycled newsprint is reused in newspaper as well as the production of other paper products. There is a limit, however, to the percentage of recycled paper vs. virgin wood pulp than can be used in newspapers and other products. A number of states have adopted mandatory separation and recycling goals for recovered newspapers. Other recycled paper products are primarily targeted for producing paper, cardboard, and related materials. As far as highway construction and maintenance operations are concerned, shredded waste paper has been successfully used as a mulching material.

INDUSTRIAL WASTES

Annual generation of non-hazardous industrial wastes in the United States involves between 250 and 300 million tons of materials, not counting the production and disposal of dredge spoils. Not included in this category are the wastes and by-products resulting from mining and mineral processing activities. Industrial wastes include, but are not necessarily limited to, the following materials:

- Coal ash by-products
- Advanced SO2 control by-products
- Sulfate waste
- Construction and demolition debris
- Iron and steel slags
- Non-ferrous slags
- Cement and lime kiln dusts
- Reclaimed asphalt pavement
- Recycled concrete pavement
- Foundry wastes
- Silica fume
- Roofing shingle waste
- Lime waste
- Paper mill sludge
- Petroleum contaminated soils
- Dredge spoils

Each of these wastes or by-product sources is discussed in some detail. The discussions include a description of each waste or by-product, amounts generated and utilized, availability and locations, and most practical applications, if any.

Coal Ash By-Products

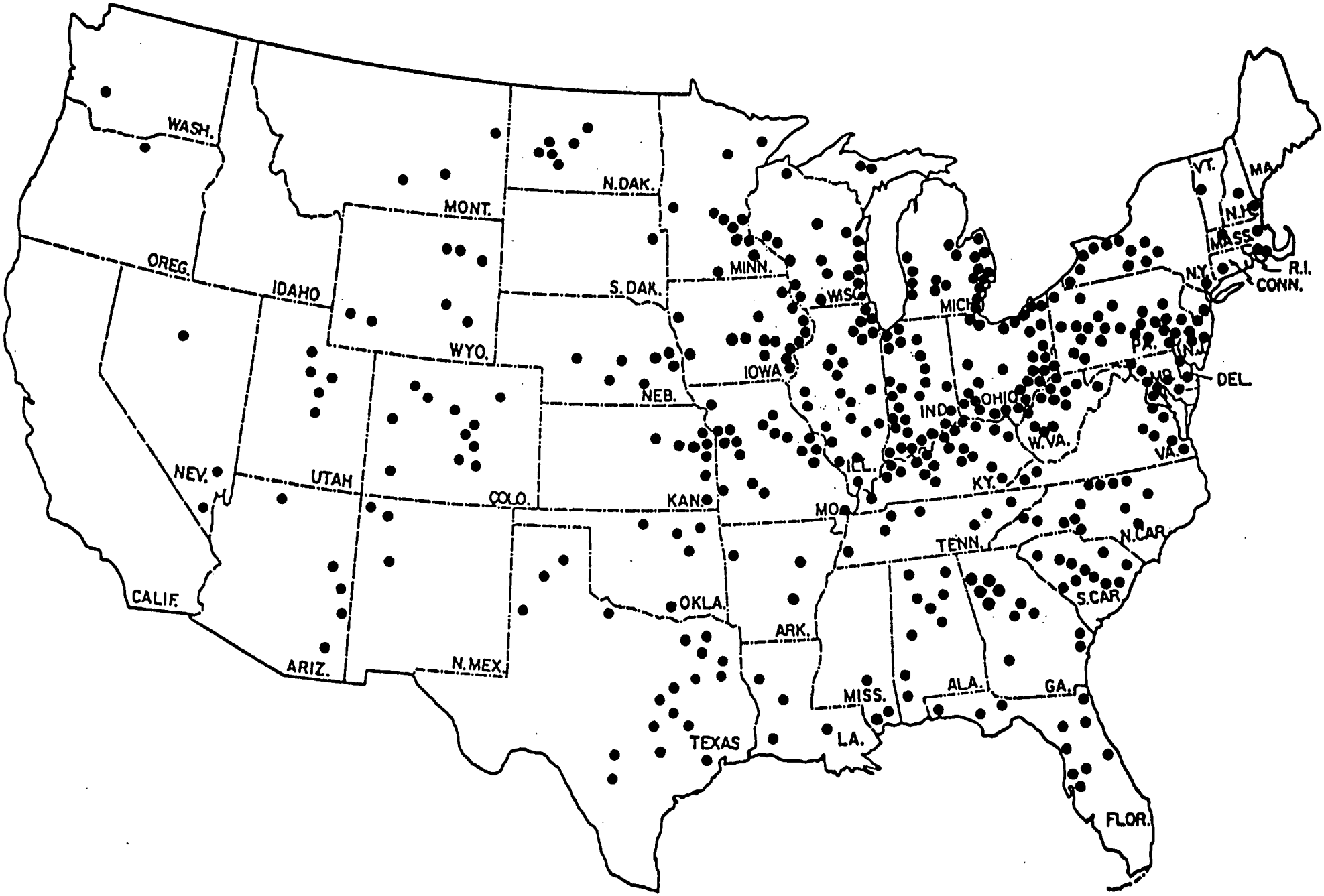
The burning of coal is responsible for nearly 60 percent of all the electrical energy produced in the United States. During 1988, approximately 700 million tons of coal were burned at electric utility generation plants (31). There are presently almost 420 such coal-fired power plants located in 45 states (32). Figure 3 shows the locations of these plants, most of which burn pulverized coal to generate steam and electricity.

The by-products resulting from the coal combustion cycle at electric utility plants are referred to as coal ash or power plant ash. These by-products are produced in three forms: fly ash, bottom ash, and boiler slag. Fly ash is the fine-grained, powdery particulate material which is collected from furnace flue gases, usually by electrostatic precipitators. Bottom ash is the granular, sand size material which collects at the bottom of a pulverized coal furnace. Boiler slag (sometimes referred to as "black beauty") is the coarse, hard, glassy material which leaves the furnace as molten slag from either a pulverized coal slag-tap boiler or a cyclone boiler.

When pulverized coal is burned in a dry bottom boiler, about 80 percent of the ash in the coal leaves the furnace entrained in the flue gas. When pulverized coal is burned in a slag-tap or wet bottom boiler, as much as 50 percent of the ash in the coal may be retained as slag in the furnace, with the other 50 percent entrained in the flue gas. In a cyclone furnace, 70 to 80 percent of the ash is retained as slag and only 20 to 30 percent is entrained in the flue gas (33).

FIGURE 3

LOCATIONS OF COAL FIRED POWER PLANTS



The relative amounts of fly ash and bottom ash (or boiler slag) that are produced at a power plant are determined mainly by the design and operation of the boiler units, as well as the characteristics of the coal being burned. Although fly ash and bottom ash (or boiler slag) are collected separately, these materials may be, and often are, mixed together prior to or during disposal at many power plants.

Coal ash characteristics are influenced by the techniques used at the power plant for handling, storage, and disposal. Ash handling and storage techniques are related to power plant design, as well as utility practice, regulatory considerations, and available land at the plant site. Ash handling and storage is accomplished using either dry, conditioned (less than 25 to 30 percent moisture), or wet (greater than 30 percent) methods.

Dry methods involve short-term (less than a week) storage of fly ash in hoppers or silos. Dry fly ash can be discharged through gates or conveyed pneumatically into or out of enclosed transport vehicles. Dry handling of fly ash is necessary for supplying ash in the ready-mix concrete market or as a component of blended cement. Conditioned fly ash results from the addition of controlled amounts of water to prevent dusting and facilitate stockpiling in large quantities. Wet handling of ash involved adding large quantities of water to the ash to produce a slurry, which enables the ash (fly ash and/or bottom ash) to be transported by pipeline to settling ponds or lagoons for disposal and possible reuse.

At the present time, approximately two-thirds of all coal ash currently being produced is handled dry (S. Tyson, American Coal Ash Association. Private Communication). At many power plants, fly ash and bottom ash are collected and disposed of together, although a number of plants employ more than one means of ash handling and storage.

According to the latest coal ash production statistics (34), a total of 71.9 million tons of coal ash was produced in 1989. This included 53.4 million tons of fly ash, 14.2 million tons of bottom ash, and 4.3 million tons of boiler slag. During the last 15 years, the overall amount of coal ash produced in the United States has remained relatively constant, fluctuating between 60 and 75 million tons per year.

At the present time, there are only five states which do not have any operating coal-burning power plants. These are California, Hawaii, Idaho, Maine, and Rhode Island. States which produce the most coal ash annually, based on number of coal-fired power plants and total utility coal burned, are Ohio, Texas, Pennsylvania, West Virginia, Indiana, Illinois, North Carolina, and Kentucky.

Power plant ash, especially fly ash, is often classified according to the type of coal from which the ash was derived. The American Society for Testing and Materials (ASTM) has a standard specification C618, "Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete" (35). Fly ash is considered a pozzolan, which is defined as a siliceous, or aluminous and siliceous, material which is itself chemically inert, but, when in a finely divided form and in the presence of water, will react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties (35). Fly ash in the ASTM C618 specification is divided into two classes:

Class F - Fly ash normally produced from burning anthracite or bituminous coal. This class of fly ash has pozzolanic properties (35).

Class C - Fly ash normally produced from burning lignite or sub-bituminous coal (35). In addition to having pozzolanic properties, many Class C fly ashes also have hydraulic or cementitious properties.

The main difference between Class F and Class C fly ash is in the amount of total calcium oxide present. In Class F ashes, the total calcium is normally in the 5 to 8 percent range, with an upper limit of 12 percent. In Class C ashes, total calcium oxide contents are often in the 25 to 30 percent range. For this reason, Class F fly ash is sometimes referred to as "low lime" ash, while Class C fly ash is often referred to as "high lime" ash. Another difference is color, which is an indicator of carbon content. Class F fly ash is usually gray in color, indicating higher carbon content that Class C fly ash, which is normally a tan or buff color (36). Many sources of Class C ash exhibit rapid setting behavior shortly after the addition of water.

Lignite and sub-bituminous coal deposits are located west of the Mississippi River and, in general, most of the Class C ash is produced in power plants west of the Mississippi. However, some sub-bituminous coal is hauled to power plants east of the Mississippi River as well, so there are some states east of the Mississippi that also produce Class C ash. Illinois produces more Class C ash than any other state east of the Mississippi. Class C ash is also being produced in Indiana, Ohio, and Michigan.

There are a number of states west of the Mississippi that produce both Class F and Class C ashes. These states include, but may not be limited to, Arizona, Colorado, Iowa, Kansas, Missouri, Nebraska, New Mexico, South Dakota, and Texas. Generally, some type of coal ash is available in every state, with the exception of Hawaii.

The principal uses of fly ash are in cement and concrete products, structural fills and embankments, road bases and subbases, grouting, asphalt and other fillers. The principal uses of bottom ash and/or boiler slag are in structural fills, snow and ice control, blasting grit, and road bases or subbases.

Overall, approximately 25 percent of all coal ash is utilized annually (34), which means that 75 percent must still be disposed of each year. In 1989, a total of 17.5 million tons of coal ash was utilized, including approximately 10 million tons of fly ash, 5 million tons of bottom ash, and 2.5 million tons of boiler slag (34). At present, only 19 percent of all fly ash being produced annually is being used, compared to 34 percent of all bottom ash and 59 percent of all boiler slag (34). Despite the many proven uses for coal ash, there is obviously a need to improve the utilization percentages for these materials. Technical considerations relative to a number of coal ash applications are discussed in some detail in Chapter Two of this volume.

Advanced SO_2 Control By-Products

Clean air regulations have resulted in greater efforts and expenditures being applied to the cleanup of air emissions. This is especially true of emissions from the burning of fossil fuels for power generation, particularly coal emissions. Although a number of coal-burning electric utility plants are equipped with flue gas desulfurization (FGD) devices, mainly in the form of wet scrubbers, the Clean Air Act has mandated that an even greater number of such plants must also be retrofitted with FGD scrubbers within the next several years in order to continue operating.

Locations of existing and planned FGD scrubber units are shown in Figure 4. There are presently 152 operating scrubbers located in 28 states. In addition to wet scrubbing, control of sulfur dioxide (SO_2) emissions from coal burning can be realized by one or more of the following emerging technologies:

- Advanced coal cleaning
- Fluidized bed combustion
- Limestone (or sodium) furnace injection
- Spray drying (dry scrubbing)

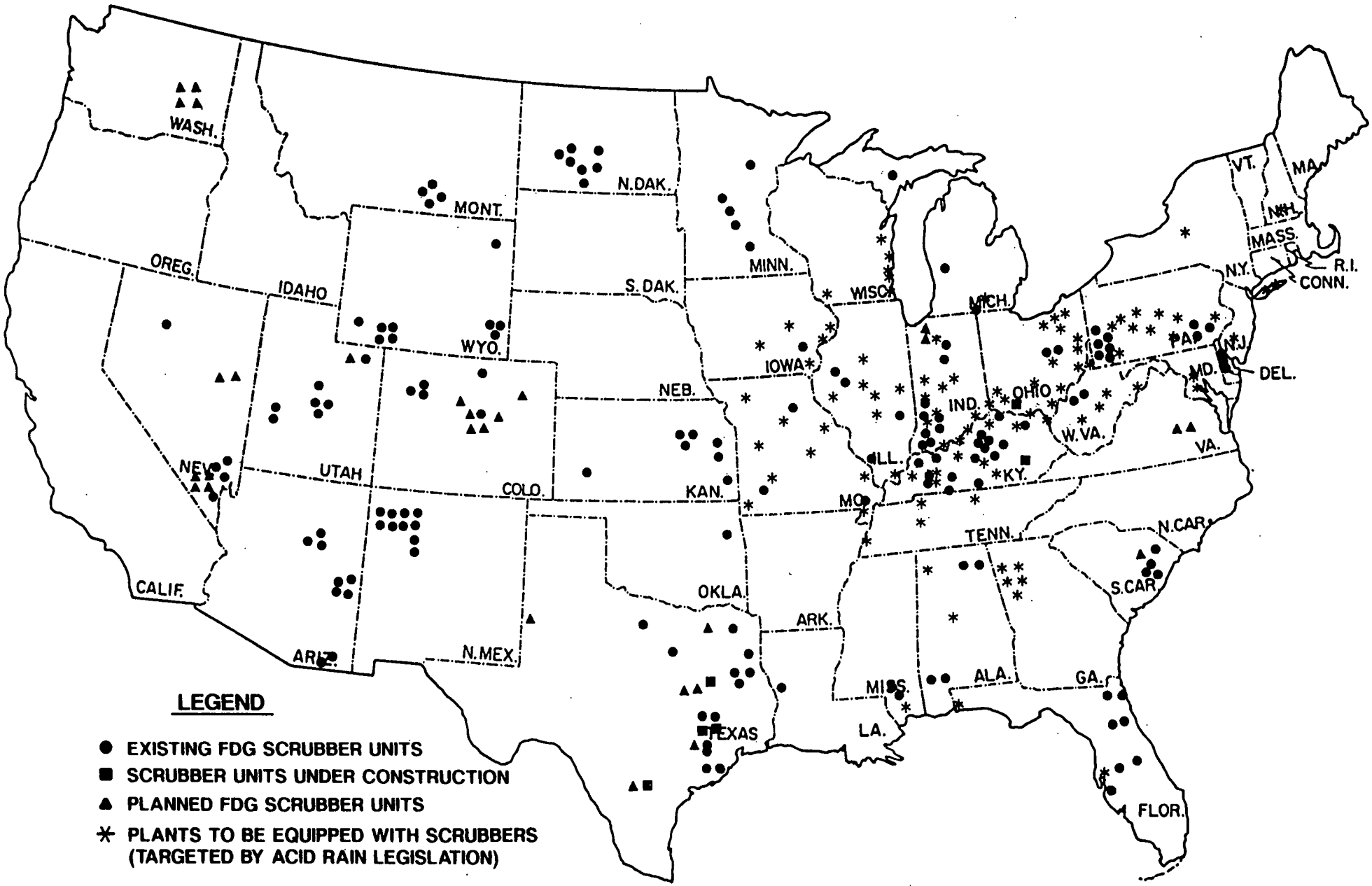
Each of these emerging technologies for SO_2 control, and the resultant by products, are discussed in the following paragraphs.

<u>Advanced Coal Cleaning</u>

Advanced coal cleaning is a pre-combustion process to reduce the sulfur content of coal by chemically removing some of the sulfur and mineral impurities that are not normally removed by conventional physical coal cleaning. Conventional coal cleaning

FIGURE 4

LOCATIONS OF EXISTING AND PLANNED FGD SCRUBBER UNITS



is accomplished at coal preparation plants. There are at this time approximately 620 coal preparation plants located in 21 states (37). These activities produce coarse coal refuse and fine coal slurry, both of which are described in the following section of this chapter under mineral wastes.

Since advanced coal cleaning technology is still under development, there are presently no commercially operating advanced coal cleaning plants. However, when such plants are constructed, they are likely to be located primarily at power plant sites. The resultant wastes from advanced coal cleaning processes are expected to consist of sulfate or sulfite based slurries or sludges.

Fluidized Bed Combustion

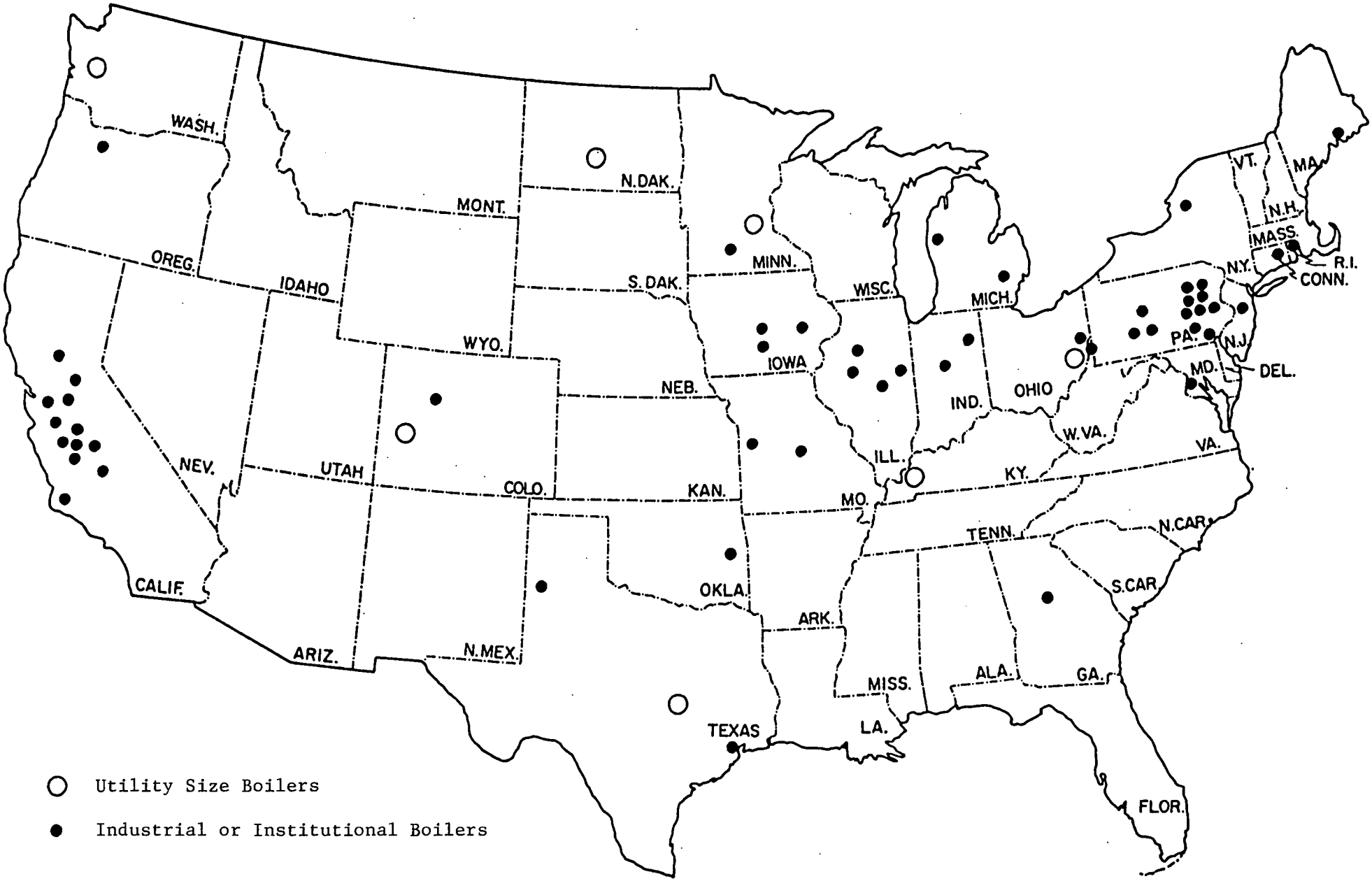
Fluidized bed combustion involves the burning of coal (and possibly other combustible materials) in a bed along with a sorbent material, such as limestone. The crushed coal and limestone are mixed together and suspended in the bed by an upward flow of combustion air. The coal burns in the bed while the limestone is calcined to form lime at temperatures ranging from 1500° to 1800°F., approximately 40 to 50% lower than temperatures that normally exist in conventional coal-fired boilers. During combustion, SO_2, NO_2 and other acid gases react with and are absorbed by the limestone sorbent, thereby reducing emissions. Turbulent mixing and burning of the fuel and sorbent enhances heat generation, fluidizes the fuel and sorbent, and minimizes plant emissions (38).

There are presently 60 operating fluidized bed combustion boilers, including 7 utility boiler units, 4 institutional boilers, and 49 industrial coal-fired boilers. Of these,59 units are atmospheric and one is a pressurized fluidized bed boiler, located at the Tidd Station in Brilliant, Ohio. Fluidized bed combustion boilers are located in 22 different states. Figure 5 shows the locations of operating fluidized bed combustion boilers, most of which are relatively small cogeneration facilities.

There are two types of fluidized bed boiler systems: 1) bubbling beds and 2) circulating beds. In bubbling beds, fuel combustion and desulfurization take place in a shallow limestone bed agitated by air injection at low velocities. Circulating bed systems involve higher velocity air jets which blow the coal-limestone mix out of the combustion chamber, through a cyclone filter, and back into the boiler. The mix is recirculated many times per hour, increasing residence time and improving combustion efficiency (39). The majority of operating fluidized bed boilers are circulating bed systems.

FIGURE 5

LOCATIONS OF COAL FIRED FLUIDIZED BED COMBUSTION FACILITIES



Fluidized bed combustion (FBC) systems generate at least two different by-products. The spent sorbent or bed material is referred to as FBC residue or bed ash. It is a granular material containing substantial amounts of calcium compounds, including sulfates. A precipitation or baghouse fly ash is also collected, which is generally high in carbon content. In circulating bed systems, a recycle char material is collected in the cyclone, which may or may not be combined with the fly ash or the FBC residue (39). The bed ash or FBC residue usually comprises the majority of the waste stream from a fluidized bed boiler, unless the coal is finely ground or pulverized prior to burning. The bed ash is also the most usable portion of the waste stream because it is usually very reactive, unless a fuel other than coal is burned in the bed.

Limestone (or Sodium) Furnace Injection

In this type of system, a dry sorbent material is injected directly into the furnace of a pulverized coal boiler. The sorbent is usually a pulverized calcium-based material, such a limestone or hydrated lime, but may also be sodium-based, such as naturally occurring sodium carbonate or bicarbonate. The SO_2 in the flue gas reacts with the sorbent to form either calcium sulfate or sodium sulfate, which along with the fly ash, is collected as a dry particulate in an electrostatic precipitator or baghouse. The limestone furnace injection process results in a fine powdery by-product that is chemically similar to fluidized bed combustion residue. The sodium furnace injection process also results in a very fine-grained by-product, although the chemistry is quite different from the calcium-based SO_2 control by-products (38).

Spray Dryer (Dry Scrubbing)

There are presently at least 10 coal-fired electric utility power plants with operating lime-based spray dryer systems. Figure 6 shows the locations of these power plants, all of which are located west of the Mississippi River. A spray dryer system can generate significant quantities of by-product. It is estimated that a 500 megawatt generating station equipped with a lime-based spray dryer burning coal with a 10 percent ash and a 1 percent sulfur content will generate approximately 185,000 tons of combined fly ash and spray dryer by-product annually (39).

Sulfate Waste

Calcium sulfate is generated as a by-product or a waste material from several different industrial processes. The principal source of sulfate waste in the United States is the wet scrubbing of flue gases from coal burning power plants to remove sulfur dioxide from stack emissions. The resultant calcium

FIGURE 6

LOCATIONS OF OPERATING CALCIUM SPRAY DRYER SYSTEMS

sulfate slurry is referred to as flue gas desulfurization (FGD) sludge. There are currently 152 utility coal-fired boiler units equipped with wet scrubbing systems. These units are in operation at 88 power plants located in 28 different states (40). Recent figures indicate that approximately 15 million tons of FGD sludge are generated annually (34).

In addition to existing FGD scrubbing systems, there are 7 other scrubbing units under construction at 6 power plants in either Kentucky, Ohio, or Texas. There are also 31 other scrubbing units in the planning stages, plus 108 coal-fired power plants that have been targeted for the installation of new FGD scrubbers by the Clean Air Act, in order to reduce emissions to combat acid rain (41). Figure 4 shows the location of the existing and planned FGD scrubber units.

FGD scrubber sludge normally occurs as a semi-solid or sludge, with a solids content in the range of 35 to 50 percent. Chemically, the sludge can be either calcium sulfate or calcium sulfite, depending on whether lime or limestone is used as the sorbent in the scrubber. Most FGD sludges are calcium sulfate resulting from lime scrubbing. Calcium sulfite sludges are much more difficult to dewater than calcium sulfate sludges.

A second source of sulfate waste is acid mine drainage treatment sludge from the neutralization of acidic mine waters at bituminous coal mining locations primarily in West Virginia and Western Pennsylvania. Lime or limestone is added to acidic mine water to elevate the pH and assist in meting discharge permit requirements. The resultant sludge is mainly calcium sulfate mixed with iron and aluminum hydroxides (42). The exact number and location of these neutralization plants is not known, but it is possible that an overall total of several million tons of acid mine drainage treatment sludge could be produced annually.

Other sources of sulfate waste are from plants which produce phosphoric acid and hydrofluoric acid. In these plants, sulfuric acid is reacted with a calcium containing material to form new acid and calcium sulfate. The waste from phosphoric acid facilities is referred to as phosphogypsum. This is essentially a mineral waste and is, therefore, discussed in the following section under mineral wastes. Hydrofluoric acid by-product is produced in a dry form at 15 different plant locations in 10 different states (42). The overall quantity of hydrofluoric acid by-product generated at these plants is probably less than 1 million tons per year.

Construction And Demolition Debris

Although precise quantity figures are not readily available for construction and demolition (C&D) debris, the overall amount of these wastes may comprise up to 20 to 25 percent of the total municipal solid waste stream. This leads to a conservative estimate of at least 20 to 30 million tons per year of C&D debris, perhaps even higher. Construction and demolition debris consists of a variety of materials, including wood, concrete, drywall, plaster, insulation, roofing, tile, glass, cardboard, and various metals (43), which must be separated in order to effectively recycle certain of these components.

Construction and demolition debris has traditionally been accepted and processed at demolition debris landfills. Because the debris is bulky, difficult to compact, and basically inert, demolition debris landfills have not been tightly regulated and have not been required to install liners and leachate collection systems like those required at sanitary landfills. As a consequence, the tipping fees at demolition debris landfills have been considerably lower than those of sanitary landfills.

However, some recent studies have indicated that C&D debris may not be as benign as once believed. Some building debris may contain asbestos insulation, lead-based paint, or lumber treated with questionable preservatives or even carcinogenic materials such as creosote (43). This is now leading to tougher regulations and higher tipping fees for demolition debris landfills in some states. This has also led to an increase in the number of transfer stations or materials recovery facilities (MRF) that specialize in the separation of C&D debris, with only the non-recyclable debris being landfilled. Recycling rates at a typical MRF may be as high as 50 percent.

Of principal interest to the highway construction industry is that portion of C&D debris which can be reclaimed, crushed and processed into aggregate. This is being done on a regular basis at numerous processing locations around the country by recovering and recycling concrete, blocks, brick, ceramics, and even asphalt, for use mainly as a road base aggregate. In order to effectively market crushed C&D debris as aggregate, however, the resultant processed material must be effectively separated so that deleterious components (such as wood, drywall, plastic, etc.) are not present in the crushed product.

The wooden fraction of C&D debris is also being separated, shredded, and reclaimed for use as mulching material for landscaping or blended with dewatered sewage sludge in the production of compost. When recycling the wooden fraction of C&D debris, care must be taken to separate metal pieces (such as nails or bolts) from the wood prior to reuse.

Iron And Steel Slags

Pig iron is produced by heating iron ore, coke, and limestone to temperatures of 2700°F. in iron blast furnaces. Blast furnace slag is a by-product of pig iron production. Blast furnace slag is defined as "The non-metallic by-product consisting essentially of silicates and alumina silicates of lime and other bases, which is developed simultaneously with iron in a blast furnace." The slag is discharged from the blast furnace in the form of molten lava (44).

There are basically three types of blast furnace slag, which are characterized by the method of cooling the molten slag. These slag types are: 1) air-cooled; 2) granulated; and 3) expanded. Air-cooled slag is dumped into pits and allowed to solidify gradually, under atmospheric conditions, resulting in large chunks that can later be crushed to size. Granulated slag is cooled by sudden immersion in water, resulting in a fine sand-sized material. Expanded slag is the cellular product which is formed when molten slag is cooled by the application of a limited quantity of water, less than that required for granulation, resulting mainly in coarse gravel size pieces. The basic chemistry for all three slag types is the same, consisting of oxides of silica, alumina, calcium, and magnesium, along with other minor elements (45). Of the three types of blast furnace slag, air-cooled is the most common, comprising approximately 90 percent of total production (46).

Steel production involves a process that is somewhat different from the production of iron in a blast furnace. Steel production is a batch process, whereas the reduction of iron ore to pig iron is a continuous operation. Steel slag is formed as lime flux reacts with molten iron ore, scrap metal, or other ingredients in the steel furnace at melting temperatures in the 2800°F. range. During the process, part of the liquid metal becomes entrapped in the slag. The molten slag flows from the furnace to a pit area where it solidifies by air cooling. Because steel making is a batch process, a non-uniform slag material is produced. Metallics are removed from the slag by magnetic separation (47).

Steel slag consists essentially of a fused mixture of oxides and silicates, mainly calcium, iron, and silica, including a substantial amount of unslaked lime (CaO) and magnesium oxide (MgO). These unreacted oxides, when hydrated in the presence of water, can be responsible for volume increases. Steel slags are heavier than blast furnace slags and most normal weight aggregates, with an average unit weight of 125 pounds per cubic foot.

There are three basic types of steel furnaces (open hearth, basic oxygen, and electric arc), which produce three different types of steel slags. The basic chemistry of the slags from these three furnace types is similar, although sometimes variable and unpredictable (47). At the present time, approximately half of all currently operating steel furnaces are electric arc furnaces, which are primarily fed by scrap metal. Many of the older open hearth type furnaces have ceased operations in the last ten years. However, many of the older steel slag banks contain open hearth slags.

Production of iron and steel slags is directly related to the production of iron and steel, with consumption of these slags dependent on supply and demand in the construction industry, which is the principal market for these slags. During 1989, a total of 15.5 million tons of blast furnace slag and 7.4 million tons of steel slag were sold or used in the United States (47). The respective quantities of iron and steel slags used have been essentially the same over the previous five years, despite the fact that a number of iron and steel producers have reduced production during that time period. Much of the slag that is sold is processed from slag accumulations, so declining slag production is not expected to have a negative impact on the availability of these slags in the foreseeable future. The main concern with processing slag from existing banks is that blast furnace slag and steel slag are co-mingled. Figure 7 shows the locations where blast furnace slag and/or steel slag are produced.

Principal uses for air-cooled blast furnace slag are as aggregate in road bases, concrete, and asphalt paving, as well as fill material. Steel slag, provided it has been properly aged in moistened stockpiles, can be used as a road base aggregate. Granulated blast furnace slag has been used for road base and soil conditioning, and is finely ground for use as slag cement. Expanded blast furnace slag is sold as an aggregate for lightweight concrete. Steel slag has also been successfully used as an asphalt paving aggregate, fill material, railroad ballast, and for snow and ice control. Non-highway uses for blast furnace slag include the production of mineral wool, roofing shingles, and glass manufacture. The principal non-highway use for steel slag is as a raw feed material for blast furnaces (46).

Non-Ferrous Slags

Non-ferrous slags are by-products from the thermal processing of copper, lead, zinc, nickel, and phosphate ores. Approximately 10 million tons of non-ferrous slags are produced annually at ore smelting and roasting facilities throughout the United States. There are 36 primary metal smelter operations located in

FIGURE 7

LOCATIONS OF BLAST FURNACE AND STEEL SLAGS

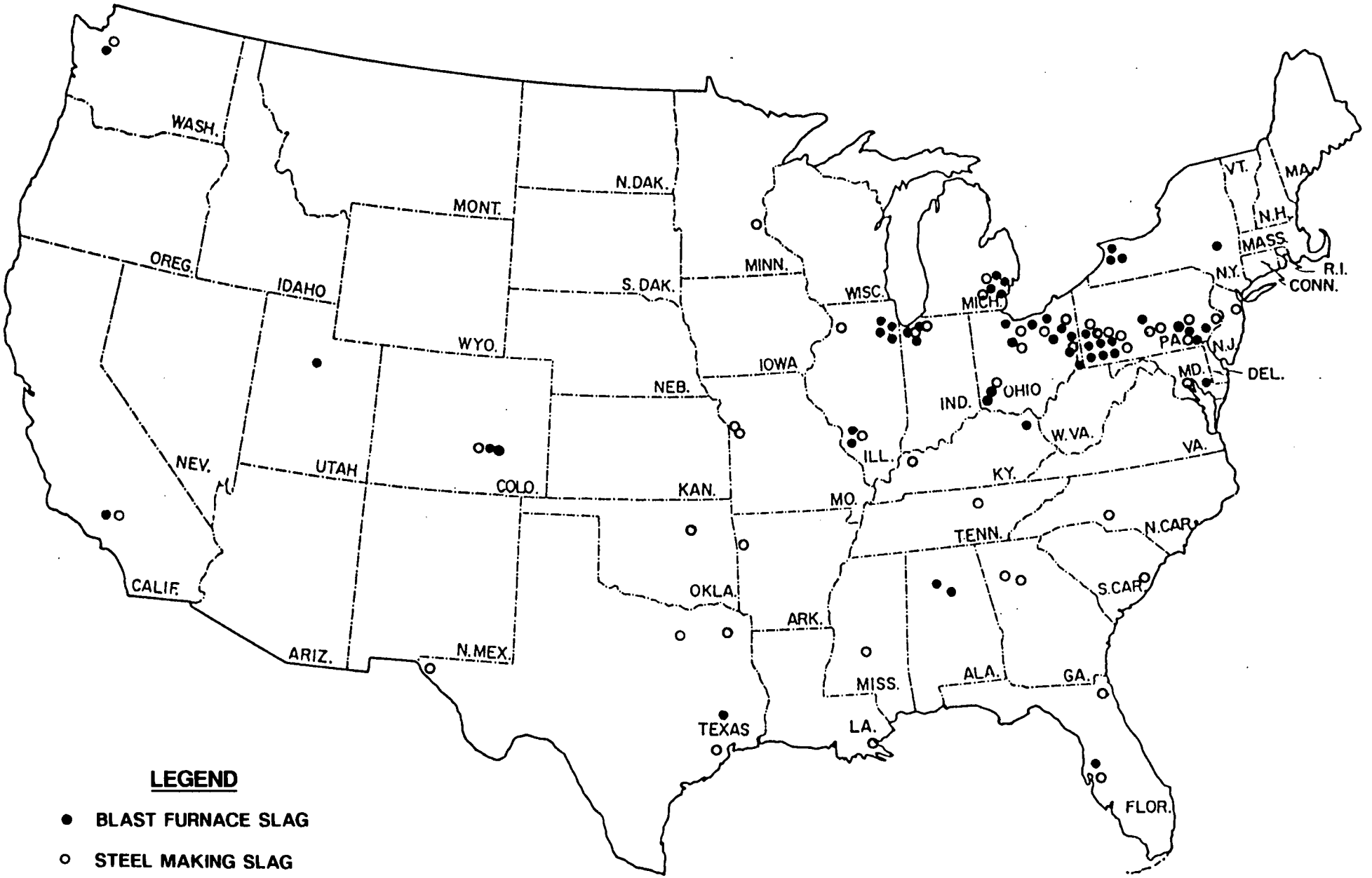
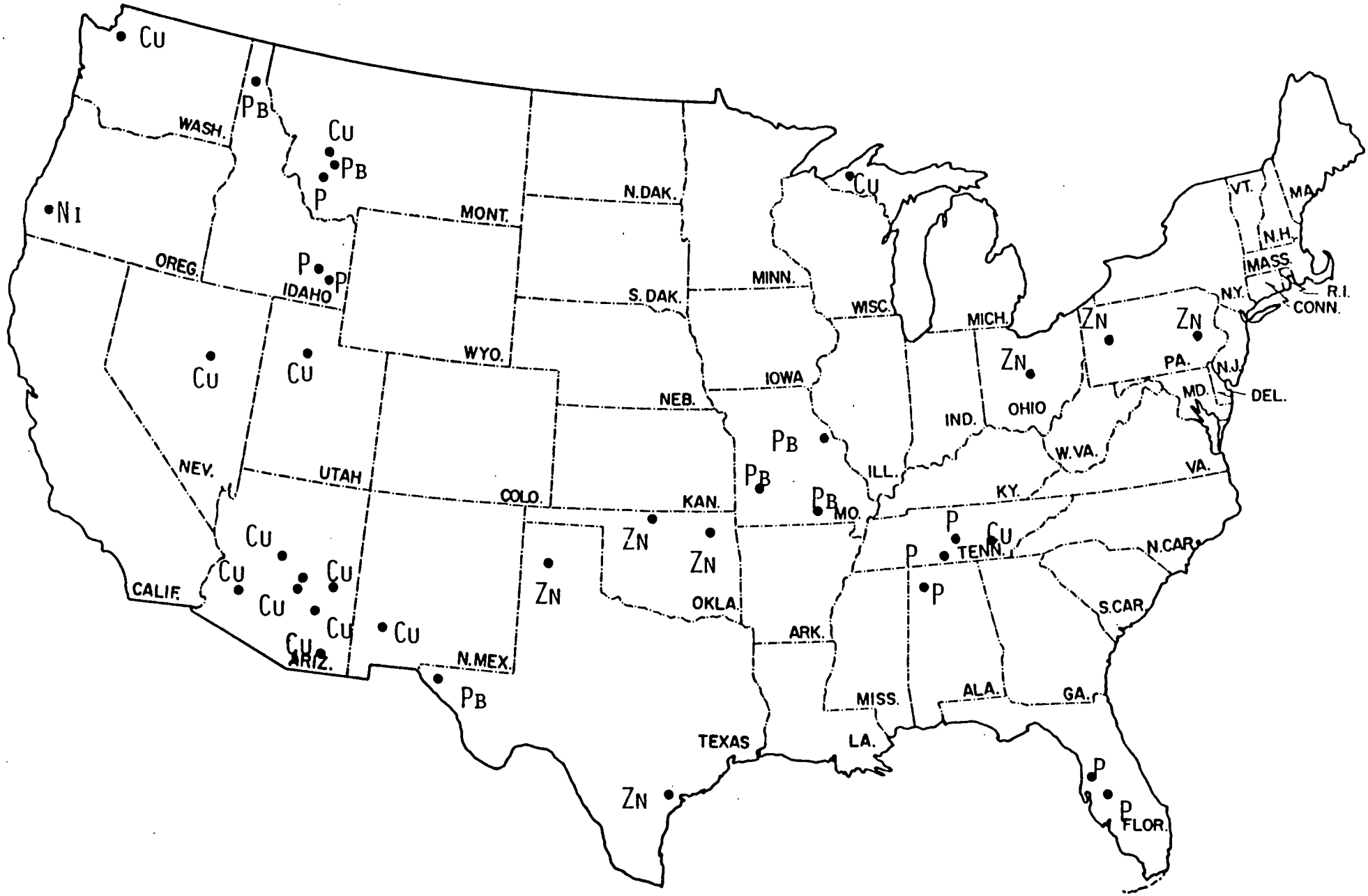


FIGURE 8

LOCATIONS OF NON-FERROUS SMELTER SLAGS



17 different states, mostly west of the Mississippi River. Figure 8 shows the locations of these operations and the type of ore processed at each location. In addition to annual production of non-ferrous slags, there are locations where huge accumulations of these slags have been stockpiled.

The largest quantities of non-ferrous slags are the copper slags and the phosphate slags. Total annual production of each of these slags is estimated at approximately 4 million tons per year. Annual quantities of lead, zinc, and nickel slags all are estimated to range from 0.5 to 1.0 million tons per year. There are 15 copper smelters, most of which are in the southwest, mainly in Arizona. There are 8 phosphate roasting facilities located in four different states (Florida, Idaho, Montana and Tennessee). There are 5 lead smelters, 7 zinc smelters, and 1 nickel smelter. Three lead smelters are located in Missouri, plus one each in Idaho and Montana. Zinc smelters operate in Ohio, Oklahoma, Pennsylvania, and Texas. The lone nickel smelter location is in Oregon.

Non-ferrous slags are produced in either an air-cooled or a granulated form, depending on the particular method employed for cooling the slag at a given location. Copper, lead, and zinc slags are produced both as air-cooled and granulated slags. Almost all of the phosphate slag is air-cooled. Nickel slag is produced in a granulated form. As a rule, all of these slags consist of particles with an extremely high hardness, particularly the phosphate slags.

Although the chemical composition of these slags varies, the copper, lead, and zinc slags can be characterized as ferrous silicates, while the slags from phosphate and nickel furnaces are calcium or magnesium silicates. Copper, lead, and zinc slags also exhibit some calcium oxide content. All non-ferrous slags also contain some concentration of the metals in the ores from which they were produced. The copper, lead, and zinc slags are usually black or dark gray in color, regardless of whether they are air-cooled or granulated. Phosphate slags are usually a light gray color, somewhat resembling blast furnace slags. Granulated nickel slag is also dark gray in color (48).

Cement And Lime Kiln Dusts

Portland cement is produced at a total of 119 cement plants, located in 38 different states. The cement industry produces a total of approximately 78 to 80 million tons of cement clinker annually, using either the wet process or the dry process (49). As a by-product of cement production, an estimated total of 20 million tons of cement kiln dust are generated and collected annually. Approximately 60 percent of freshly produced cement kiln dust is recycled, either by returning the dust back into the

front end of the kiln as a raw feed material (i.e., alkali levels are sufficiently low); insufflating or blowing the dust back into the kiln; or intergrinding the dust with the cement clinker (50).

This leaves approximately 8 million tons of cement kiln dust to either be disposed of in landfills or reused in some way. In addition, there are many more millions of tons of stockpiled dusts. Besides its use as an agricultural liming material, cement kiln dust has also been used as a stabilizing agent for municipal sewage sludge, industrial waste sludges, road base aggregates, and clayey soils. There has also been limited use of cement kiln dust as a mineral filler in asphalt paving and as a fill material.

Cement kiln dusts are fine, powdery materials with a high specific surface, whose chemical composition may be quite variable, depending on the raw feed materials in the kiln, the type of dust collection system, and the location within the system where the dust is collected. Generally, dry process dust is more fine grained and contains higher levels of free calcium oxide than wet process kiln dust. Also, upstream dust particles usually contain more reactive calcium oxide, while the downstream dust particles contain more alkalis. There are also significant compositional differences between the total dust collected at a cement plant and the separated dust from that same plant (J.P. Nicholson, N-Viro Energy Systems, Ltd. Private Communication).

Kiln dusts collected during normal kiln operations have been found to be reasonably consistent, while the dusts collected during kiln upset periods (start up, shut down, change in kiln feed or fuel) are usually much more variable. Furthermore, the characteristics of aged or stockpiled kiln dusts, are more variable and inconsistent than those of fresh kiln dusts, and are also not usually as reactive as the fresh dusts. Moreover, stockpiled kiln dusts could possibly be contaminated with foreign matter (51).

At the present time, there are at least 7 cement plants that burn hazardous waste as a primary kiln fuel for the production of cement clinker. There are also 31 other cement plants that burned hazardous waste as an alternate kiln fuel during 1990 (52). A total of 51 cement plants have now applied to the U.S. Environmental Protection Agency for interim status in order to burn hazardous waste in their cement kilns. Prospective users of cement kiln dust may wish to inquire from a potential supplier of dust whether or not that plant is using hazardous waste as a kiln fuel.

Total lime production in the United States is currently around 17 million tons per year, produced at 71 commercial lime plants located in 29 states (53). There is an estimated total of from 2 to 4 million tons per year of lime kiln dust generated by

the commercial lime industry (K. Guttschick, National Lime Association. Private Communication). The majority of the lime kiln dust is produced from rotary kilns with very little dust available from vertical kiln operations. Most lime kiln dust is disposed of in landfills, although some dust is being used for agricultural liming or as a reagent in waste stabilization. Lime kiln dust is also potentially usable as a mineral filler, fill material, or in soil or road base stabilization.

Lime kiln dusts are physically similar to cement kiln dusts, insofar as they are very fine grained, powdery materials with a high surface area. Chemically, lime kiln dusts may be very different from one plant to another, depending largely on whether the plant is producing lime from high calcium or dolomitic limestone. Dusts from the production of high calcium lime have a higher calcium content and lower magnesium content than dusts from the production of dolomitic lime. Also, some high calcium dusts contain some free lime (CaO) and may be very reactive when mixed with water, whereas most dolomitic dusts are usually not very reactive when mixed with water.

Figure 9 shows the locations of operating portland cement and commercial lime plants throughout the United States. Nearly all of the cement plants and many of the lime plants generate sizable quantities of kiln dust which may be available for reuse.

Reclaimed Asphalt Pavement

Since the early to mid 1970's, asphalt pavement recycling has proceeded from an experimental concept to a fairly common practice, at least among highway agencies. Over the years, pavement milling and reclaiming equipment has been developed, used in the field, and refined. Techniques for recycling asphalt pavements have similarly advanced and the ensuing technology transfer has resulted in some universally accepted approaches and methods for reclaiming asphalt pavements.

Asphalt paving recycling can essentially be performed in one of four ways:

- Hot
- Cold
- Hot in-place
- Cold in-place

FIGURE 9

LOCATIONS OF OPERATING CEMENT AND LIME PLANTS

Each type involves its own sequence of equipment and construction techniques, but all four approaches to asphalt pavement recycling require an initial step of milling or removing the existing asphalt paving material to a specified depth. Depending on the recycling technique employed, the milled paving material can be reclaimed by either mixing it with new binder and placing it back on the road, or by returning it to a stockpile to be later incorporated into a paving mix.

The proper recycling technique or process to be used for a particular project involves evaluating the nature of the distress for that pavement, the potential recyclability of the existing asphalt paving material, and the comparative costs involved for the appropriate rehabilitation alternatives. If an existing pavement is suitable for recycling, the technique or process selected should be the one most appropriate for that pavement.

Although precise quantity figures for reclaimed asphalt pavement (RAP) are not readily available, it is estimated that approximately 100 million tons of asphalt paving material are currently being milled annually (M.R. Krissoff, Asphalt Recycling and Reclaiming Association. Private Communication). At the present time, not all of this milled material is being recycled; some of it still is being disposed of in landfills. Much of the milled asphalt is returned to contractors or asphalt producers' yards where it is stockpiled as RAP for future use in hot or cold recycling mixes. When stockpiled for such purposes, the milled material is not a waste, but a resource, no different from any other source of aggregate (crushed stone, sand and gravel, or slag).

Surveys of RAP usage among state highway agencies indicate that growing stockpiles of RAP are not considered a problem in most states. Current estimates are that only about 20 percent of the 100 million tons of milled asphalt taken up annually is recycled into hot mix that same year (M.R. Krissoff. Private Communication). Given that there are more than 2 million miles of roads in the United States with over 90 percent of the mileage in asphalt paving, the quantities of RAP being used today are only a small percentage of what could potentially be used by highway agencies at all levels (state, county, and municipal).

Reclaimed Concrete Pavement

As with reclaimed asphalt pavement, the recycling of existing portland cement concrete pavement and the reuse of the crushed pavement as aggregate is an effective and economical rehabilitation option for deteriorated concrete roadways. Again, the development of improved equipment for breaking slabs, removing reinforcing steel from the broken concrete, and crushing and sizing the broken concrete into aggregate has accelerated the

growth of concrete pavement recycling. In addition to equipment advances, much has been learned through laboratory studies and field trials concerning the suitability of various size fractions of reclaimed concrete pavement in new concrete or as a base course aggregate.

Depending on the type of pavement breaker used, the percentage of the existing concrete pavement that can be recovered and reused can range from 60 to 90 percent. Use of drop hammer or guillotine type breakers usually results in being able to recover and reuse up to 90 percent of the existing pavement concrete, whereas the use of vibrating resonant breaking machines, which pulverize the existing pavement, result in a higher percentage of fines, thus reducing the amount of recoverable concrete to approximately 60 percent (M. Knutson, American Concrete Pavement Association. Private Communication).

Reclaimed concrete pavement has been successfully recycled into aggregate that has been reused in new concrete pavements, although, generally speaking, recycled coarse aggregate (material larger than 3/8 inch) is more suitable than recycled fine aggregate (material finer than 3/8 inch). This is because of the residual cement that usually remains in the finer material. When recycled fine aggregates are reused in concrete, they are generally limited to about 30 percent of the fine aggregate or sand portion of the mixture (54).

Reclaimed concrete pavement is a useful and versatile source of aggregates. Besides recycling of RCP as coarse aggregate in portland cement concrete, reclaimed concrete pavement has also been used as fill or embankment material, as base or subbase aggregate, as riprap or drainage stone, as an aggregate in asphalt base and binder mixes, as a chip seal aggregate, and as a component of cement treated base courses.

Precise estimates of the quantity of concrete pavements that are recycled annually do not exist. The American Concrete Pavement Association (ACPA) has indicated that approximately 200 miles of concrete pavement are currently being recycled each year in the United States (M. Knutson. Private Communication). Most of this pavement is probably an average of four lanes in width. A rough calculation of a one mile length of two lane (24 foot wide) concrete pavement 10 inches thick indicates that there is approximately 8,000 tons of paving material in that one mile length. Using a recovery factor of 75 percent, approximately 6,000 tons of reclaimed concrete can be recycled from every mile of concrete pavement two lanes wide.

Therefore, if 200 miles of two lane concrete pavement are being recycled annually, these figures indicate that 2.4 million tons of reclaimed concrete are being reused. Because of increasing disposal costs and a deteriorating infrastructure, especially

in densely populated areas, it is expected that the overall amount of concrete pavement that will be recycled will continue to increase in the future.

Foundry Waste

Foundries are metal working shops where castings or molded metal products are fabricated by pouring molten metal into dies or molds. Metals commonly used include iron, steel, aluminum, lead, zinc, magnesium, brass, and bronze. There are approximately 2,300 active foundry operations located throughout the United States, but concentrated mainly in and around large industrialized population centers where steel-making furnaces are situated (G. Mosher, American Foundrymen's Society. Private Communication).

The principal types of foundry wastes include:

- Furnace dust
- Arc furnace dust
- Sand residue

Furnace dust and arc furnace dust are similar chemically and physically, each being fine powdery materials comprised mainly of iron and silica, with small concentration of other trace metals, such as copper, lead, nickel, and zinc. The main difference is color. Furnace dusts are rust brown in color, while arc furnace dusts have a black coloring. All furnace dusts, because of metal concentrations, are usually handled and disposed of as hazardous wastes. Sand residues are somewhat more granular siliceous materials with some alumina and carbon content, as well as trace metal concentrations similar to those of the furnace dusts. Although there are no official overall tonnage figures for the total amount of foundry waste currently being generated, it is believed that there is probably a total of 10 to 15 million tons of foundry waste that are being produced annually in this country (G. Mosher. Private Communication). The majority of this tonnage is in the form of foundry sand.

Foundry dusts, because of their fine particle sizing, can be pelletized and fired into synthetic aggregate materials or used as grog in the production of structural clay products such as brick, tile or pipe (55). The presence of trace metals in most dusts may cause them to be classified as hazardous and would generally preclude their use of these dusts as fill material. The sand residue has been used in some states as a fill material, pipe bedding material, and as a fine aggregate in asphalt paving mixtures. Foundry sand is also being used as a feed material for portland cement production in some areas.

Silica Fume

Condensed silica fume or microsilica is a by-product of the manufacture of silicon and ferrosilicon alloys. During the reduction process to obtain the alloy, furnace gases are driven off that consist primarily of silicon monoxide, which is oxidized in air to form silicon dioxide in the form of extremely fine spherical particles, which are then collected in baghouses. Silica fume particles are 10 to 20 times finer than fly ash and are very pozzolanic because of their high silica content and specific surface area (56).

Silica fume has been used as a partial replacement or supplement for portland cement in concrete, especially in bridge decks, parking garages, and other surfaces subjected to deicing salts and freeze-thaw cycles. Silica fume is available commercially in two forms: 1) as a powder or 2) as an aqueous dispersion. Silica fume is produced at fifteen different alloy furnace locations in eight different states. The locations of these plants are shown in Figure 10. There are four plants in Alabama, three in Ohio, and two each in Oregon and West Virginia (3). The overall amount of condensed silica fume produced in the United States is relatively small, probably less than 50,000 tons per year.

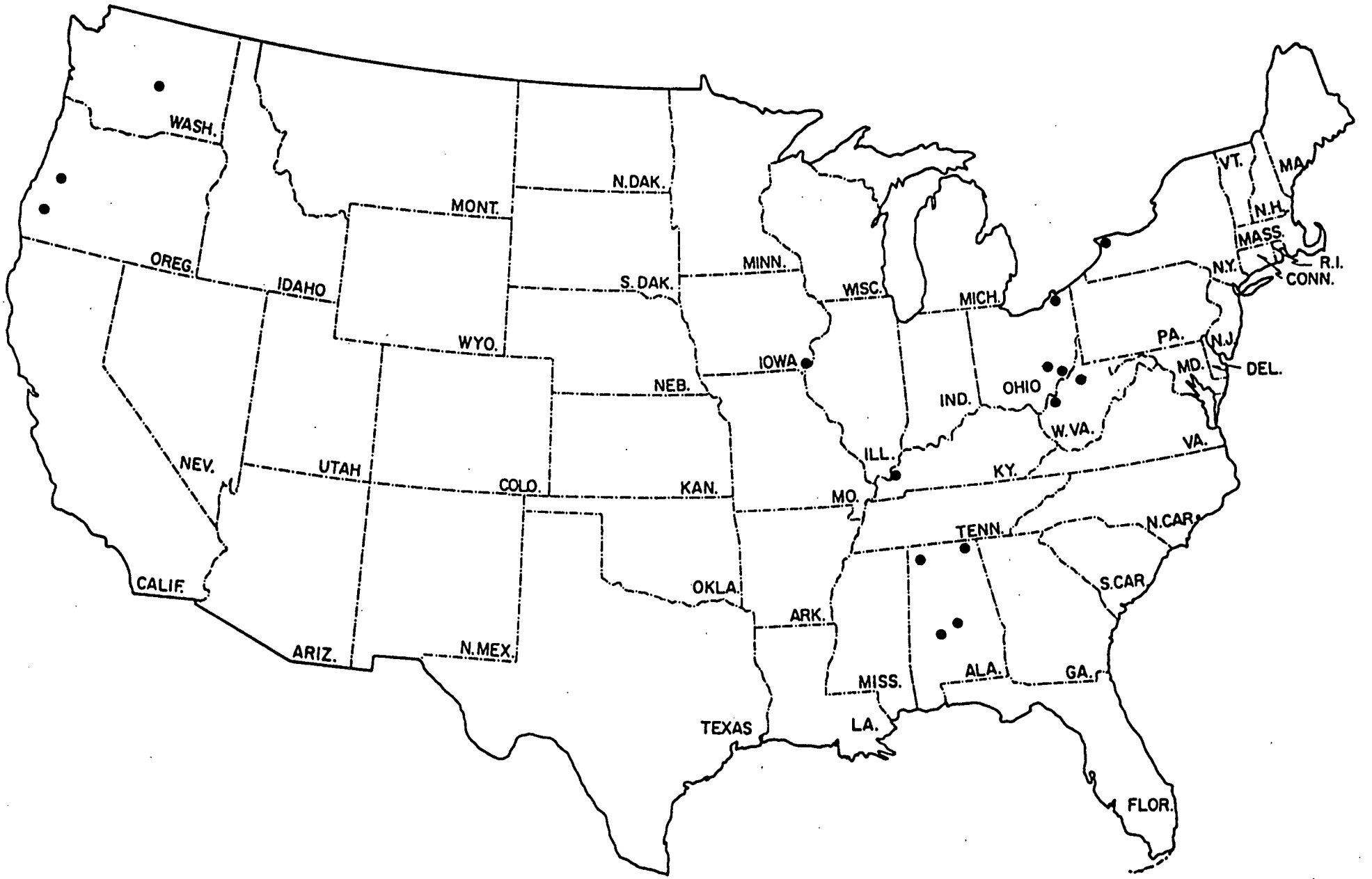
Roofing Shingle Waste

Approximately 9 million tons of roofing shingle waste are generated annually as scrap and leftover materials at shingle manufacturing operations. The amount of roofing shingle waste from construction and demolition debris, if it were separated, would undoubtedly add several million more tons to this total. The waste consists of shingle fragments and tabs, and contains asphaltic binder materials as well as fine aggregate in the form of granules.

A number of successful attempts have been made to reuse roofing shingle waste as a component of asphalt paving materials, either as part of hot mix asphalt, or as the major constituent of cold patching material (57). Suitable asphalt mixes have been designed in the laboratory and produced in the field. Roofing shingle waste is being recycled into asphalt patching material in some major metropolitan areas where disposal costs are high and there is a steady demand for pavement patching. Roofing shingle waste is also recyclable to some extent within the shingle manufacturing process.

FIGURE 10

LOCATIONS OF SILICON AND FERROSILICON PLANTS



Paper Mill Sludge

Most of the waste material generated by the pulp and paper industry is in the form of inorganic sludges of relatively low solids content (5 to 15 percent) that are composed mainly of silica and alumina. These sludges are clay-like in appearance and tend to dewater gradually over time. The dewatered sludges are fibrous in texture, relatively lightweight, but still retain a significant moisture content. Although paper mills are distributed throughout the country, many operations are concentrated in the South.

In addition to inorganic sludges, the paper industry also generates process waste in the form of a spent sulphite liquor, which is actually calcium ligno-sulfuric acid. These liquors contain some wood cementing materials from the paper making process and have been used successfully as a dust palliative. Research has also indicated that the addition of lignins to soils decreases permeability and binds soil particles together (58).

Petroleum Contaminated Soils

Promulgation of underground storage tank regulations by the U.S. EPA has created a sizeable increase in remediation efforts for leaking storage tanks. These regulations provide cleanup standards for removal of petroleum contaminated soil in the vicinity of leaking tanks as a protective public health measure to eliminate potential sources of groundwater pollution. Nationally, there are probably tens of thousands of oil, gasoline, or kerosene spills or leaks that occur every year nationally. It is estimated that at least 25 percent of all underground oil and gasoline storage tanks that are at least two years old show some signs of leakage. Furthermore, each leaking tank also results in an estimated 30 to 50 cubic yards of petroleum contaminated soil (59).

Petroleum contaminated soils can vary from clays and silty clays to sands and gravels, but most tank backfills tend to be more granular in particle sizing. It is the granular soils (sands and gravels) that are the most suited to recycling. There are at least two practical construction-related alternatives to disposal of petroleum contaminated soils, which can be very costly. One is to treat the contaminated soil with portland cement in sufficient quantity to reduce leachate to acceptable levels, and use the cement-treated soil as a stabilized base material. Another is to use the contaminated soil as a fine aggregate source in asphalt paving mixtures. Hydrocarbon contamination is removed as the soil is processed in a hot mix asphalt plant.

The main sources of contamination are total petroleum hydrocarbons (TPH) and benzene, toluene, ethylbenzene, and xylene (BTEX). Different state environmental agencies have different acceptable levels of TPH and BTEX concentrations, above which some remediation action must be undertaken. Action levels for TPH in soil generally range from 50 to 100 parts per million for most states, although at least two states have action levels of 500 parts per million. Action levels for BTEX are sometimes compound specific, but total BTEX action levels, while more variable than those of TPH, most often are in the range of 10 to 20 parts per million. However, there are a few states which have total BTEX action levels as high as 100 parts per million (60).

Dredge Spoils

The excavated or dredged sediment materials from waterway maintenance dredging operations are sometimes referred to as dredge spoils. The majority of this dredging work is either performed by or administered by the U.S. Army Corps of Engineers, which is responsible for maintaining 22,000 miles of navigable waterways, plus hundreds of harbors, throughout the United States. The nature of the dredge spoils depends on the physical and chemical characteristics of the sediments being dredged, which probably encompasses the spectrum of materials from clays through gravels. For engineering purposes, dredge spoils may be divided into three classifications: 1) coarse grained; 2) fine grained; and 3) organic. Furthermore, some fine grained or organic sediments may be contaminated as a result of previous discharges into certain waterways.

The total volume of dredged material handled in a year is not precisely known, but probably involves several hundred million tons annually. Much of this material is still disposed of in open water, despite the fact that water quality may be adversely affected. The remainder of the dredged material is disposed of on land by pumping into designated disposal areas, where the materials may dewater to a more compactible consistency over time. Despite having a variable composition, dredge spoils must be located within an economical transportation distance to be considered for potential use.

Very little prior use has been made of dredged materials for construction purposes, except for the occasional recovery and reuse of the more coarse grained materials as fill material. Although less than 5 percent of all dredge spoils are actually contaminated, state environmental agencies typically require a water quality certification in order to permit dredged materials to be disposed of at a particular location (W. Martin, U.S. Army Corps of Engineers. Private Communication).

MINERAL WASTES

The volume of waste materials produced from the extraction and refining of minerals and ores in this country is staggering. It is estimated that approximately 1.8 billion tons of mineral processing wastes are generated in the United States each year. In addition to these huge volumes of material, there are literally mountains of solid waste accumulations from past mining activities that are visible throughout many parts of the country. Overall, there are probably more than 30 billion tons of mining and milling wastes scattered across much of America as barren piles that mar the natural beauty of the land (61).

These wastes cover hillsides, fill valleys, and are impounded behind huge dikes on fairly level terrain. Large mineral waste piles are not only eyesores, but they often occupy land that could be valuable for other purposes. In addition, mineral wastes may be a detriment environmentally, being a source of dust on dry, windy days, and causing silt and chemicals to be washed into nearby streams and rivers during rainy periods.

Mineral processing wastes can be further classified into one of the following categories:

- Waste rock
- Mill tailings
- Coal refuse
- Washery rejects
- Phosphogypsum

Each of these mineral processing wastes is described in some detail in the following paragraphs.

Waste Rock

The coarse, crushed or blocky material removed during mining and containing little or no mineral value is referred to as waste rock. The greatest amounts of waste rock are produced from surface mining operations, such as open-pit copper, phosphate, uranium, and iron ore or taconite mines. In many open-pit mines, the overburden material, consisting of soil and rock, is excavated and disposed of in a mine waste dump,along with waste rock from the mine. A large part of the material in many waste dumps is overburden. Waste rock can vary in size from boulders down to gravel and can be reduced to a desired gradation by normal crushing and sizing.

Because waste rock from mining operations is often derived from similar rock formations to those from which crushed stone products are mined, some waste rock has been used as a construction material when it occurs in locations that are reasonably

accessible. Unfortunately, many of the largest open-pit mines are in remote areas, far removed from markets where construction materials are needed. At this time, it is estimated that approximately 1 billion tons of waste rock, including overburden, is generated by the mining industry in the United States each year. Although some waste rock piles have been crushed and used as construction aggregate, the overwhelming majority of these materials are simply stockpiled. Some copper and uranium mining operations do recover residual ores from the crushing and acid leaching of waste rock piles which have an economically recoverable amount of ore present (62).

Mill Tailings

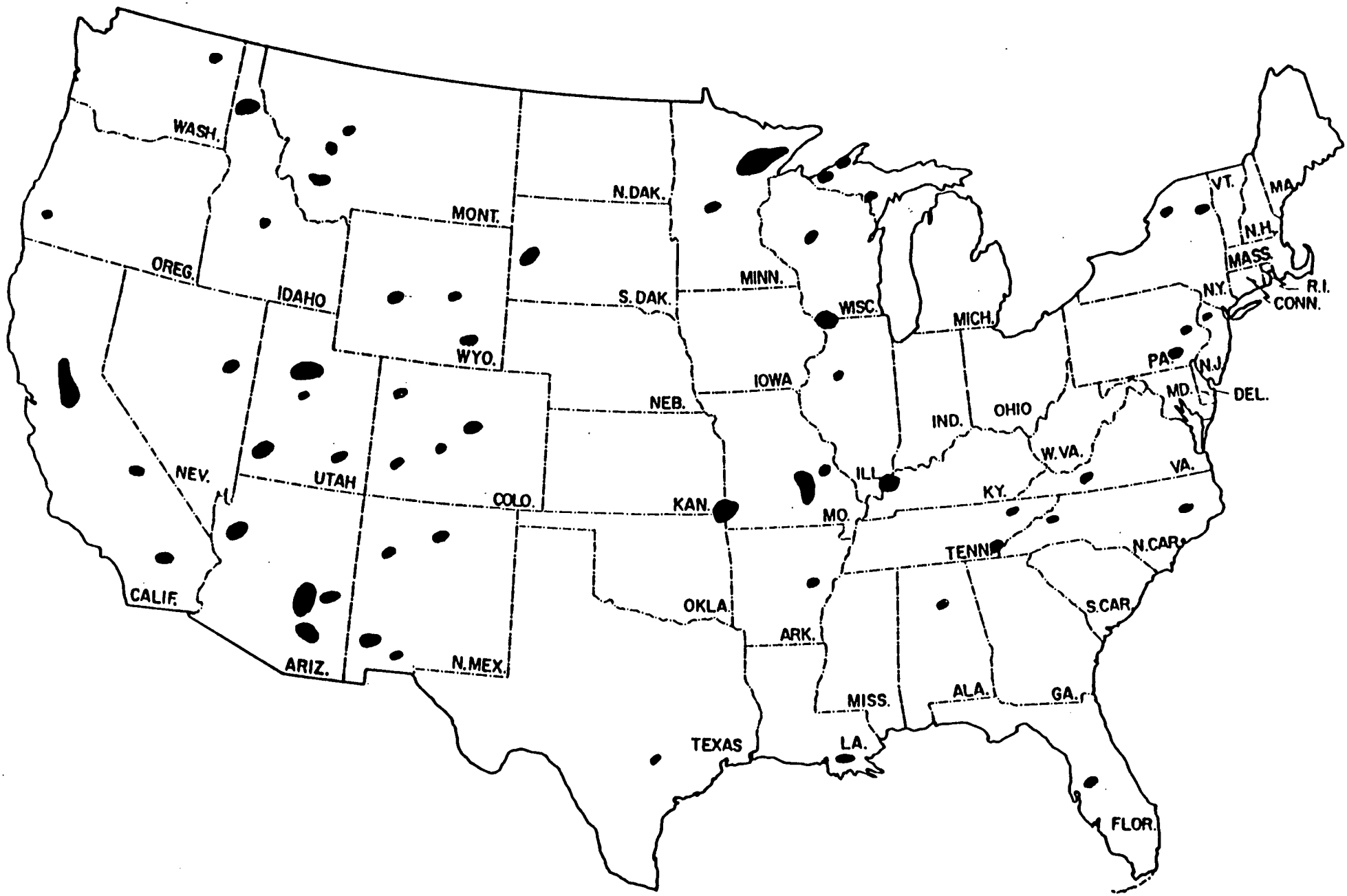
Mill tailings are the finely graded waste products generated in the process of concentrating an ore. The basic mineral processing techniques involve milling or crushing the ore and separating it from its impurities by a variety of washing, sink-float, or mechanical methods. The resultant material left after the separation and refinement of the ore is referred to as tailings. Typically, the tailings are sand to silt-clay size materials that are disposed of as a slurry by pumping into large ponds. Dikes built for containment of tailings are normally constructed of waste rock and coarse tailings. The tailings are basically finely crushed rocks and their mineralogical compositions correspond to those of the parent rocks from which the ores were derived.

The overall quantities, physical characteristics, and chemical composition of mill tailings are determined by the relative amount of ore present in the parent rock and the mineral processing techniques used to separate and recover the ore. It is estimated that the mining industry in the United States is currently producing approximately 500 million tons per year of mill tailings. The largest amounts of tailings are generated as a by-product of the mining and milling of copper, iron and taconite, lead, zinc, and uranium. Other mineral processing operations that generate sizeable amounts of tailings are gold, silver, molybdenum, feldspar, fluorspar, and phosphate. Figure 11 shows the locations of the principal sources of mining and mineral processing wastes, including waste rock and mill tailings.

Mill tailings from copper, iron and taconite, lead, zinc, gold, molybdenum, and phosphate ore processing have all been successfully used at one time or another as road construction materials. These materials have been utilized by local and state highway agencies, as well as by the mining companies themselves, mainly as fill materials, but also in base courses and in asphalt paving mixes (62).

FIGURE 11

PRINCIPAL LOCATIONS OF MINING AND MINERAL PROCESSING WASTES



The chemical composition and leaching characteristics of tailings sources must be determined before any decision can be made concerning the potential usefulness of these materials. Some tailings, especially those derived from sulfide-based ore bodies, do contain relatively high concentrations of leachable trace metals which could be of environmental concern. Because of residual radioactivity, prior attempts to reuse uranium mill tailings proved unsuccessful.

Coal Refuse

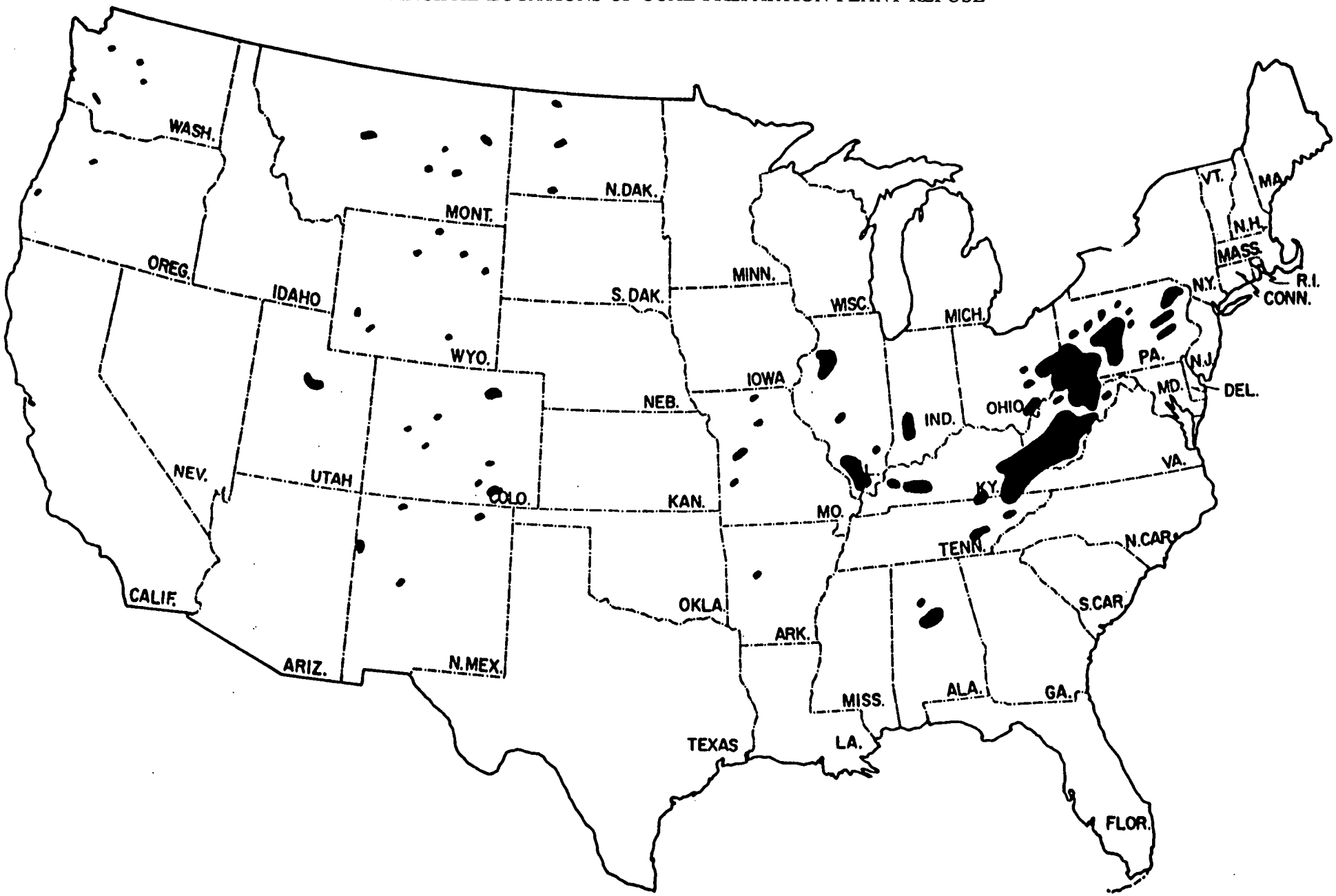
Approximately 800 million tons of coal are mined each year in the United States. The majority of this coal is bituminous coal, much of it requiring cleaning or preparation to separate impurities from the coal prior to shipment and burning. Coal cleaning is accomplished at coal preparation plants, using a variety of washing and gravity or media separation techniques. There are presently at least 620 coal preparation plants operating in 21 different coal producing states. The unwanted mineral matter separated from the coal in coal preparation plants is referred to as coal refuse. It is estimated that approximately half of all coal is cleaned and prepared, with roughly 30 percent of the raw coal separated as refuse. Therefore, the total estimated annual quantity of refuse generated by coal preparation plants in this country is approximately 120 million tons per year. It is further estimated that total accumulations of coal refuse in this country are probably in the range of 3 to 4 billion tons (62). Figure 12 shows the principal locations of coal preparation plant refuse.

Coal refuse can be further classified as either coarse or fine, with the dividing size usually being the No. 4 sieve. The amount of coarse refuse produced is about 70 to 80 percent by weight of total coal refuse. Coarse coal refuse is a dark gray granular material composed largely of slate or shale particles with some intermixed coal, sandstone, and clay. These materials are disposed of in large banks, sometimes referred to as culm banks or gob piles. The remaining 20 to 30 percent is a silt or slurry material that is sluiced into impoundments or holding ponds. Fine coal refuse is more uniformly graded than coarse coal refuse, being a fine sand or silty size material. Because of refinements in coal preparation techniques, some of the older coal refuse slurry impoundments have higher coal content, making them potential sources of low grade fuel.

Coal refuse banks are a highly visible reminder of past coal mining activities across many areas of the United States, particularly in the Appalachian region. These banks, while being aesthetically unattractive, also present the disadvantages of contributing to air and water pollution through spontaneous combustion, airborne particulates, and acid mine drainage. Many

FIGURE 12

PRINCIPAL LOCATIONS OF COAL PREPARTION PLANT REFUSE



of these large heaps of coal-derived material are situated relatively close to, and sometimes actually in, populated areas. In such locations, refuse banks usurp valuable land, although establishing the ownership of some of the older piles can sometimes be a difficult, time-consuming, and costly task. This is particularly the case with abandoned or so-called "orphan" spoil banks (62).

Over the years, most coal mining states have enacted strict legislation regulating disposal and ultimate land reclamation activities at active coal mining operations. As a result of improved practices, most coal refuse disposal areas are now being operated as controlled fill sites. Some abandoned refuse banks are also being reclaimed in an effort to restore the land to some useful purpose. Coarse coal refuse is being utilized to some extent as a fuel source in fluidized bed combustion boilers and has been sporadically used to construct embankments or fills. Despite efforts to rectify the inadequacies of past coal mining disposal practices, there are still hundreds of millions of tons of coarse coal refuse that are potentially available for reclamation and reuse, either as an auxiliary fuel source or as an alternative construction material.

Washery Rejects

This category of mineral wastes deals essentially with the by-products of two industries: the phosphate industry and the aluminum industry. The predominant wastes generated by these two mineral industries are classified as washery rejects because these wastes are disposed of in a slurry form and tend to remain in this form indefinitely. This is in contrast to mill tailings and fine coal refuse, which are also initially disposed of as slurries, but ultimately experience some drying and become solid or semi-solid materials.

The benefication of phosphatic clay and rock deposits by washing and flotation results in the generation of sand tailings and phosphate slimes. Phosphate slimes are colloidal materials,mostly less than one micron in diameter, that are disposed of in huge ponds at solids contents ranging from 2 to 6 percent. Due to their colloidal particle size, settlement rates are extremely slow. Even after many years of settlement, solids contents seldom exceed 20 percent. Huge volumes of these slimes, often mixed with sand tailings to assist settlement, are generated in central Florida, and to a lesser extent in North Carolina and Tennessee. It is estimated that in excess of 100 million wet tons of clay-bearing slimes must be disposed of annually by the phosphate industry (62). The problem of dewatering is by far the biggest deterrent to recovery and possible utilization of these materials. Because of this problem, there are no reported uses for phosphate slimes at this time.

The extraction of alumina from bauxite ores also produces clay-like by-products, which are disposed of in a slurry form at approximately 20 percent solids. These materials are referred to as alumina muds. After many years of settling, these muds approach a solids content of 50 percent. High annual rainfall will retard the dewatering process. Depending on the basic type of alumina extraction process used, the resultant by-product may be a red mud or a brown mud. Approximately 90 percent of the alumina by-product currently being generated is red mud.

A total of approximately 5 million tons per year of alumina muds are being generated. These muds are produced at alumina refining plants located mainly in Louisiana, Texas, Arkansas, and Alabama. The particle size distribution of alumina muds is in the clay range. Those muds are composed of compounds of silica, alumina, iron and soda ash. There are very few reported uses for alumina muds due to instability and handling difficulties at comparatively low solids contents (62).

Phosphogypsum

Phosphogypsum is a by-product gypsum material generated from the manufacture of phosphoric acid fertilizers by the wet process. About 5.5 tons of phosphogypsum are generated for every ton of phosphoric acid that is produced. Phosphogypsum occurs as a sand-sized material that is disposed of in large stacks, predominantly in the central Florida phosphate region. There is some residual radioactivity in phosphate rock deposits which remains in the phosphogypsum by-product and has caused some serious environmental concerns. Average radium concentrations in phosphogypsum are in the range of 18 to 24 pico curies per gram (63).

The research and use of phosphogypsum has been curtailed since December, 1989 due to a ruling by the U.S. Environmental Protection Agency (EPA) that declared the material to be hazardous due to its residual radiation (64). Prior to that time, phosphogypsum had been successfully used in a series of experimental projects in Florida and Texas as a cement-stabilized base material, as a component of roller compacted concrete base and subbase mixtures, and as a pipe bedding material.

WASTES FROM HIGHWAY MAINTENANCE OPERATIONS

Although the scope of this synthesis does not include highway litter, some non-hazardous wastes from highway construction and/or maintenance operations do fall within the overall scope of this synthesis. Some of these waste materials that are generated by the highway industry are difficult to categorize. Reclaimed asphalt pavements (RAP) and reclaimed concrete pavements (RCP) have already been included as industrial wastes, since they are generated and used by highway paving contractors. However, other highway-generated wastes (such as used guide rail, old bridge girders, pavement grinding residue, and spent blasting abrasives) are often stored in highway maintenance yards or disposed of wherever possible. Such wastes are the responsibility of the highway industry and there are numerous examples of the innovative recycling of certain of these materials. However, other wastes from maintenance operations (such as old paints and spent solvents) may be hazardous and must be disposed of properly. Any potentially hazardous materials should be avoided in highway construction.

VOLUME 2

CHAPTER TWO

WASTE MATERIAL USE IN HIGHWAY CONSTRUCTION

The purpose of Volume 2 is to provide further discussion and additional details concerning the use of certain waste materials and by-products in selected highway construction applications, over and above the information presented in the Volume 1 synthesis report. For each selected application, only those waste materials or by-products which have been most frequently used are discussed. The following highway applications are addressed in this order in Volume 2:

- Embankments
- Soil stabilization
- Bases and subbases
- Concrete
- Asphalt paving

The use of one or more waste materials or by-products are discussed for each of these five applications. Each waste material and/or by-product is discussed by first providing a general background concerning how that particular material came to be used in a selected application, in what proportions, over what period of time, and any special technical considerations or concerns associated with such use. Most of the general background information for each material has been derived from the technical literature. Following the general background, the discussion of each material will focus on the current practice among the various states for using that material in the selected application. Information on current practice for various waste materials and by-products is based mainly on the responses from the state highway agency questionnaires, supplemented by selected reports from the technical literature.

COAL ASH AS EMBANKMENT MATERIAL

General Background

The use of coal ash, or pulverized fuel ash, as a structural fill or embankment material was pioneered in Great Britain, where ash is required to be bid as an alternate borrow material on roadway fill projects in all areas where it is available. There has been a fairly limited use of coal ash, mainly fly ash, as a structural fill or embankment material in the United States, despite the comparatively large quantities of ash that are being

generated and are available in many areas. This is probably due in part to a general availability of suitable earth borrow material, plus a lack of familiarity with fly ash and some of its unique engineering properties by many engineers and contractors.

Fly ash has a relatively low unit weight, even after compaction, which is particularly advantageous when constructing an embankment on top of soft or weak subgrade soils. Lowering the unit weight results in substantially reduced settlements. Fly ash is essentially a silty material which compacts well over a fairly wide range of moisture content. However, compaction should be achieved at or below the optimum moisture content. Well compacted fly ash embankments develop shear strength that is comparable to that of normal borrow materials used in earthwork operations. Compacted fly ash has low permeability, comparable to clay or silty clay soils, so that fly ash embankments are relatively impervious (65). When fly ash is stockpiled and delivered to the job site at the proper moisture content, it does not create any more dust than conventional soil borrow materials.

Because fly ash is essentially a silty material, it is frost susceptible. To protect against the possibility of frost heave in a fly ash embankment, the fly ash should be kept below depths normally expected for frost penetration, or fly ash within the frost zone should be stabilized with lime or cement to prevent frost damage. Fly ash may also be subject to the capillary rise of water. An effective means of preventing capillary rise in fly ash embankments and fills is the placement of a drainage layer of granular material at the base of the embankment or fill. The drainage layer is normally 2 to 3 feet in thickness and should extend at least 18 inches above the seasonal high groundwater elevation (65). Fly ash is fairly erodible, so side slopes should be covered with 2 to 3 feet of natural soil during construction to minimize erosion. As a caution, fly ash may be subject to liquefaction and should not be used for construction of embankments or fills in areas of known seismic activity (66).

To construct embankments or fills with fly ash, it is not necessary to use a high quality fly ash, such as that specified for use as a cement replacement by ASTM C618, or as in a stabilized road base mixture by ASTM C593. It is not really that important what the ignition loss characteristics of the ash are when it is to be used for embankment construction. Conditioned ash is preferred for this type of application, but ponded ashes can be reclaimed, dried to the proper range of moisture content, and used as compacted fill. Coal ash is a non-hazardous by-product of coal combustion. Although its leachate characteristics should be determined prior to use, monitoring wells do not need to be installed unless the water table is extremely close to the ground surface.

Current Practice

A review of the technical literature, together with responses from state highway agency questionnaires, indicates that at least 10 states have constructed embankments using fly ash, mainly Class F ash. These states are Arizona, Delaware, Illinois, Massachusetts, Minnesota, Missouri, Ohio, Pennsylvania, West Virginia, and Wisconsin. The use of fly ash as an embankment or structural backfill material in each of these states is discussed further in the following paragraphs. In addition, at least four states (Arkansas, Missouri, Pennsylvania, and South Carolina) have investigated the use of bottom ash as a fill material.

Arizona

In 1980, approximately 61,000 cubic yards of fly ash from the Arizona Public Service Company's Cholla plant were used to construct an embankment for the south approach of the Interstate 40 bypass around Joseph City. The bridge for the Westover Cross road traversed the flood plain of the Little Colorado River, underlain by deposits of loose, saturated silty sand. Because of concerns for excessive settlement from the planned 30 foot high embankment, fly ash from the nearby power plant was selected for use as a lightweight fill material. The fly ash was obtained from a lagoon on power plant property, after having first been removed from the lagoon at 40 percent moisture and spread on the ground to dry as necessary prior to compaction.

The maximum dry density of the ponded ash averaged 85 pounds per cubic foot at an optimum moisture content of between 25 and 30 percent. The ash was spread in 8 inch loose lifts with a rubber tired dozer and compacted with a steel wheeled roller in the static mode. The rate of construction of the embankment was specified not to exceed 2 feet of compacted thickness per day or a maximum of 5 feet in any week. The embankment was instrumented to monitor vertical and horizontal movements during construction. The slopes of the embankment were stabilized by the addition of 10 percent quicklime by dry weight of fly ash, plus sufficient water to assure adequate mixing and slaking of the quicklime. No topsoil was spread over the slopes and little erosion has resulted (67).

Delaware

During June, 1987, approximately 8,300 cubic yards of landfilled fly ash from Delmarva Power and Light Company's Edge Moor power plant was used to construct two new interchange ramps at Interstate 495 and Edgemoor Road in Wilmington. Fly ash was placed in 12 inch loose layers and compacted with a smooth drum vibratory roller. The depth of the fly ash embankment ranged from 4 to 16 feet over a length of 450 feet. All fly ash was able to meet or exceed Delaware Department of Transportation (DEL DOT) compaction requirements.

Construction and post-construction monitoring for the fly ash embankment was sponsored by the Electric Power Research Institute (EPRI). Four groundwater monitoring wells were installed in the vicinity of the ash fill site. Quarterly samples were obtained from each of these wells, beginning in January, 1987, and analyzed over a three-year time period. No changes in groundwater quality were observed over those three years. Elevation readings were taken periodically on three pairs of settlement plates (two in the fly ash and one in the granular borrow) for two years after construction of the fill and negligible settlements were observed. Two permeate collection pans were installed beneath the fly ash fill, but no leachate was recovered from either location throughout the entire monitoring period (68). Based on the experience gained on this project, DEL DOT used over 250,000 tons of fly ash for embankment construction on a section of the new State Route 1 Bypass around Dover during the 1992 construction season.

Illinois

In 1972, the Illinois Department of Transportation utilized 246,000 cubic yards of fly ash from Commonwealth Edison's Waukegan power plant to construct an embankment for the Melvin E. Amstutz Expressway in Waukegan, 40 miles north of Chicago. The fly ash embankment was constructed in six inch lifts to an overall depth of 3 to 4 feet over a length of 7500 feet between Greenwood Avenue and Grand Avenue. In addition, fly ash was used to construct ramp fills at these two interchanges, where embankment heights reached a maximum of 28 feet.

Prior to construction, two feet of swampy soils were removed and the fly ash fill was underlain by two feet of porous granular backfill. Compaction was achieved with a vibratory single drum 10 ton roller. An 8 foot thick envelope of cohesive soil was placed on the side slopes of the embankment for erosion protection and support of vegetation. Some dusting problems were encountered when using dry ash from the silos, but these problems were quickly alleviated when stockpiled ash was delivered to the job site. Instrumentation was installed to measure settlement, frost depth, and capillary rise, but no evidence of any problems was observed (69).

Massachusetts

According to a compilation of high volume fly ash utilization projects, 5,000 cubic yards of ash were utilized in 1978 by the Massachusetts Department of Transportation to build an embankment for the John Scott Boulevard in Norton (70). No further information is available concerning the details of this project.

Minnesota

During 1971, the Minnesota Department of Transportation used 50,000 cubic yards of fly ash as common borrow material to construct embankments adjacent to a new bridge over the Chicago, Milwaukee, St. Paul, and Pacific railroad tracks in St. Paul. The fly ash was obtained from Northern States Power Company's High Bridge plant. The fly ash had a maximum dry density of 85.7 pounds per cubic foot at an optimum moisture content of 27 percent, compared with dry density values ranging from 110 to 125 pounds per cubic foot for sandy borrow. The lower density of the fly ash allowed for up to 40 percent more legal yardage of fly ash to be hauled per truck trip, reducing the cost of trucking. Compaction of the fly ash was achieved rather easily because of the relatively high amount of moisture in the fly ash compared to that of the sandy borrow (71).

Another fly ash embankment project in Minnesota was constructed in 1979. It involved the placement of 350,000 cubic yards of fly ash for the construction of an embankment for State Route 13 in Eagan, about 10 miles south of St. Paul (70). No further information is available concerning this installation.

Missouri

Approximately 140,000 cubic yards of ponded fly ash from Kansas City Power and Light Company's Hawthorne station were used in the construction of the north approach fill to the Route 9 ASB bridge over the Missouri River in Kansas City. The ash, which was not self-hardening, was initially delivered to the site in July, 1982 at moisture contents averaging 50 percent. Time spent on the job site drying the fly ash back to its optimum moisture content of 37 percent delayed construction of the embankment. During construction, it was decided instead to dry the ash at the power plant and deliver it to the site at the desired moisture content. Work on the 600 foot long embankment, which had a maximum height of 35 feet, was completed in September, 1983. The 2:1 side slopes of the fly ash fill were covered with several feet of sandy soil and a sand cap was placed on top of the fly ash fill (72).

Ohio

There are at least three known fly ash embankment projects that have been completed thus far by the Ohio Department of Transportation. In the first of these projects, nearly 6,000 tons of conditioned fly ash from Ohio Edison Company's Burger Station were placed as backfill behind the abutments of a new concrete bridge over the CONRAIL railroad at the intersection of Routes 7 and 148 near Powhatan Point. The fly ash was placed in 12 inch loose lifts to a maximum height of 27 feet and extended longitudinally about 80 feet wide at the base. The fly ash was

compacted to attain at least 95 percent of a standard Proctor density. Work commenced in the Fall of 1979, proceeded through the Winter, and was completed in the Spring of 1980. Little or no settlement has been observed in the fill since it has been opened to traffic (73).

The other two ash embankment projects involved the use of 30,000 tons of fly ash for an Interstate 480 embankment in Avon near Cleveland during 1981 and 27,000 tons of fly ash as embankment material for U.S. Route 35 in Gallia County during 1983 (70). No further information is available concerning either of these projects.

Pennsylvania

Approximately 255,000 cubic yards or 353,000 tons of coal combustion by-products were used to construct a 1,490 foot long embankment fill along a section of Interstate 279 in Pittsburgh. The average width of the embankment is 210 feet at the base with an average depth of 50 feet. Approximately 320,000 tons of ponded fly ash from Duquesne Light Company's Cheswick station were removed from the emergency ash pond, dewatered to the desired moisture content, and transported 17 miles to the project site. Also, about 30,000 tons of ash from Cheswick's dry storage silos were delivered, as well as 2,200 tons of stabilized lime-fly ash - SO_2 scrubber sludge (Poz-O-Tec) from Duquesne Light Company's Elrama Station (74).

Construction of the ash embankment began during late October, 1987 and was completed in mid-June, 1988. The fill is underlain by a 12 inch thick stone underdrain enclosed in a geotextile fabric and a 32 inch protective soil cover. Ash was placed in 8 inch loose layers compacted with a 20 ton vibratory pad foot roller. Construction and post-construction monitoring were sponsored by the Electric Power Research Institute. No adverse environmental impacts were observed. Actual settlements were less than predicted, with slightly more than one inch of measured settlement within the ash fill. Total construction cost savings of $200,000 were realized from the use of coal ash by-products. These cost savings were divided evenly between the Pennsylvania Department of Transportation and the project contractor (74).

West Virginia

There are at least two known projects in West Virginia in which fly ash was used for embankment construction purposes. The first instance occurred in 1971, when the West Virginia Highway Department's maintenance forces used 5,000 tons of fly ash to repair a portion of U.S. Route 250 near Fairmont that had been undermined by a landslide. Conditioned fly ash from Allegheny Power System's Fort Martin Station was placed in 9 inch layers at 19 percent moisture content and compacted to 98 percent of

standard Proctor density using a rubber-tired vibratory roller. Because of poor subsurface drainage in the area, a 3 foot thick crushed stone drainage layer was placed beneath the fill (75).

The second project involved the placement of approximately 20,000 cubic yards of fly ash on a section of County Route 60/12, about 5 miles east of Charleston, during the 1976 construction season. This project, known as the Malden "S" curve, consisted of an 1,100 foot realignment to eliminate a dangerous curve in the roadway. Fly ash from American Electric Power Service Company's Kanawha River plant was supplied to the West Virginia Department of Highways on an experimental basis for this project. A 4-foot blanket of bottom ash was placed beneath the fly ash for drainage and to prevent capillary saturation at the base of the fly ash. The fly ash was spread in 12 inch loose lifts and compacted to a minimum of 95 percent of standard Proctor density using a 20 ton self-propelled smooth drum vibratory roller. A two foot soil cover was placed on the side slopes. A crushed stone base was placed directly on top of the fly ash. Deflection measurements taken periodically after reopening the road to traffic indicate that the fly ash embankment provided stable support for the overlying pavement (76).

Wisconsin

The first fly ash embankment constructed by the Wisconsin Department of Transportation involved 120,000 tons of ash for a roadway in Milwaukee. Specifics of this project are not known, but since that first project, approximately 300,000 cubic yards of fly ash have been utilized by Wisconsin DOT as an embankment material. The state requires that the fly ash be encapsulated with clay and that monitoring wells be installed and sampled for each ash fill project. Within the next two years, Wisconsin DOT has plans to use another 100,000 cubic yards of fly ash for embankment construction (C.N. Laughter, Wisconsin Department of Transportation. Private Communication).

MINING WASTES AS EMBANKMENT MATERIAL

General Background

Mining and processing of minerals and coal involve the excavation and handling of large volumes of material. Depending on the percentage of ore in a parent rock formation, or the quality of a coal seam, a considerable amount of waste material may result from ore concentration or coal preparation processes. Huge quantities of by-products are generated and disposed of as a result of mining operations. Over time, significant accumulations of waste rock, mill tailings, and/or coarse coal refuse have resulted from these activities.

These mining and mineral processing wastes are rock-like or earthen in nature and, as such, are prospective candidates for use as construction materials. From time to time, some large piles of mining wastes have been recovered, processed and reused in the construction of highway embankments. Ordinarily, such instances of mining waste reuse occur only when a highway construction project requiring a substantial amount of borrow material is located reasonably close to a source of mining or mineral processing waste. In addition, ownership of the waste pile must be determined and the proper amount of sampling and testing of the waste material must be completed. The project must be designed to include the use of the waste material, provisions for its use must be incorporated into the construction, and the proper approvals and/or permits must be applied for and obtained. As part of the permit process, the environmental characteristics and potential impacts of the waste material must be identified and addressed.

Mining and mineral processing wastes considered potentially suitable for the construction of embankments include waste rock, mill tailings, and coarse coal refuse. Possible advantages to using these by-products in the construction of embankments, in cases where the material properties are suitable for such use, are prospective cost savings, environmental improvement, conservation of natural resources, and land reclamation. These possible advantages need to be balanced by an awareness of the chemical and mineralogical composition of the particular by-product being evaluated and the potential environmental consequences, if any, associated with its use as an embankment material. Of particular concern are the possible leaching of metals into the ground water, runoff into nearby waterways, dusting potential, and any measurable levels of radiation that may be associated with the placement of the by-product into a permanent embankment.

Current Practice

A review of the technical literature, together with unpublished information and responses to state highway agency questionnaires indicates that there are at least 16 different states which at one time or another have made use of mining or mineral processing wastes as embankment construction materials. Three states (Arkansas, Illinois, and Missouri) have also indicated in their questionnaire responses that they have utilized quarry wastes as fill material. Further discussion of the usage of mining wastes in these various states is provided in the following paragraphs.

The State Materials Engineer for the Alaska Department of Transportation has indicted in response to a questionnaire that mine tailings in the Fairbanks area are commonly used as crushed rock and in the construction of embankments (K.C. Lowney, Alaska Department of Transportation. Private Communication). No further details concerning such use have been provided.

California

Millions of cubic yards of dredge and hydraulic tailings from past gold mining activities exist in areas of central California as piles or ponds of sand and gravel, many of which are processed and sold as commercial aggregates for highway construction. While being marketed primarily for use in concrete and asphalt, some of these tailings have undoubtedly also been used as embankment material (T.E. Gay, Jr., California Division of Mines and Geology. Private Communication).

Colorado

It is also possible that gold tailings have been used in the past as a fill material on some Colorado highways. Some material from old coal mine dumps has been utilized as fill for state and county roads, although little or no use is now being made of coal wastes for highway construction purposes (A.E. Deborski, Colorado Division of Mines. Private Communication).

Idaho

In 1963, over one million cubic yards of tailing materials from lead-zinc-silver mining in the Couer d'Alene mining district of northern Idaho were used to construct embankments for a four mile section of Interstate 90 near Kellogg. The tailings reportedly compacted and presented no unusual construction or handling problems (77). In addition, gold dredge tailings were used as a fill material for a forest service road along the Yankee Fork of the Salmon River in Custer County (R.N. Appling, Jr., U.S. Bureau of Mines. Private Communication).

Illinois

A portion of Interstate 57 in Franklin County was constructed on an embankment of coal refuse. Several refuse piles were located within the corridor of the roadway and the refuse material was used as fill rather than being removed and stockpiled at another site (M.E. Byers, Illinois Department of Transportation. Private Communication).

Indiana

Some 15 to 20 years ago, the Indiana State Highway Commission constructed two interstate highways through coal strip mine areas. By undercutting and carefully selecting the backfill material from the mine strippings, the overburden was able to be used as an embankment material for constructing these two roadways (C.F. Hotter, Indiana State Highway Commission. Private Communication).

Michigan

Waste rock from copper mining operations in Ontonogan County was used in the construction of embankments for U.S. Route 45 near Military Hills during 1963. In all, some 460,000 cubic yards of this material was used. In addition, approximately 250,000 tons of waste rock from iron mining operations was utilized to construct an embankment on U.S. Route 2 between Ironwood and Bessemer in Gogebic County. Some 60,000 cubic yards of copper stamp sands were used as embankment and backfill material on U.S. Route 41 in the Houghton area (K.E. Allemeir, Michigan Department of Transportation. Private Communication).

Minnesota

There are reports that taconite tailings have been used as an alternate to sand and gravel for embankment fill, where these tailings are available in the Iron Range (R.M. Conner, Minnesota Department of Highways. Private Communication). No specific locations or quantities were divulged for such use.

Missouri

According to the questionnaire response from the Missouri Highway and Transportation Department, waste rock from mining operations has been evaluated as fill material (W.L. Trimm, Missouri Highway and Transportation Department. Private Communication). No further details were made available.

New York

Response to the state DOT questionnaire indicates that the New York Department of Transportation has used waste rock as stone fill on a regular basis with very good performance to date (W.B. Brule, New York State Department of Transportation. Private Communication). No further information is available in terms of where and from what mining operations the waste rock was obtained, or in how many projects the stone fill has actually been used.

North Carolina

Tailings from feldspar production in the Spruce Pine district of western North Carolina have been used as fill material, although it is not clear whether the material has been used in highway construction (B. Robinson, The Feldspar Corporation. Private Communication). About 100,000 tons of phosphogypsum were reportedly used as fill and base material for a road crossing a swampy area (R.S. Chamness, Texasgulf, Inc. Private Communication).

Ohio

In eastern Ohio, coal refuse has been accepted for use in embankments for many years, provided the refuse materials conform to the weight, compaction, and other requirements of the state specifications. Coal refuse is considered as a random material in these specifications (J.C. Dixon, Ohio Department of Transportation. Private Communication). No specific locations have been indicated where embankments of coal refuse were constructed on either the state or local road system.

Pennsylvania

There are at least four known highway embankments in Pennsylvania that have been constructed using coal refuse materials. Three of these embankments were built using anthracite refuse, while the fourth involved the use of bituminous coal refuse. Some information is provided on each of these projects.

More than 1.5 million cubic yards of anthracite coal refuse were used in a portion of an embankment for the Cross Valley Expressway near Wilkes-Barre. This embankment is part of the western approach to a bridge which crosses the Susquehanna River between Forty Fort and Kingston. The embankment is 2,344 feet in length with a maximum width of 475 feet and a maximum height of 57 feet. The refuse was obtained from the Breacher bank 27 miles west of the project after the bank was first cleaned to remove its residual coal content. A four foot thick soil cover was placed on all berms and the top of the embankment was covered with 2 feet of soil and 2 feet of incinerated refuse (red dog). Compaction was attained more easily than anticipated, even though some work was performed during winter (78).

Anthracite coal refuse was also used to construct embankments 40 to 50 feet high for two sections of Interstate 81 near Hazleton. The refuse was placed and compacted in five foot lifts and the outside slopes were covered with ten feet of soil (79).

Approximately 190,000 cubic yards of coarse bituminous coal refuse were used during 1974 to construct an embankment on a section of relocated U.S. Route 219 near Ebensburg in Cambria County. The refuse was obtained from the Revloc bank about 2,000

feet away from the right of way line. A 12 foot soil cover was placed around the refuse on the side slopes, with a 5 foot soil cover on top. The refuse was also kept at least 5 feet away from contact with any concrete structures. Compaction was achieved by means of a steel wheeled vibratory roller. Normally, two passes with the roller was enough to achieve at lest 95 percent of standard Proctor density. The use of coarse coal refuse was a definite advantage during wet weather periods and resulted in an overall cost savings of nearly $50,000 on the project (80).

South Dakota

The state highway agency questionnaire from South Dakota indicates that mine tailings have been used as embankment borrow and have provided good performance (D. Anderson, South Dakota Department of Transportation. Private Communication). According to a previous survey conducted by Purdue University, South Dakota has reported using 75,000 tons of gold mine tailings annually as a subgrade or embankment material (81).

Utah

More than 5.5 million tons of classified copper mill tailings have been used to construct highway embankments in Utah. The most outstanding single example of such use is the utilization of 3.3 million tons of tailings to construct embankments along six miles of Interstate 215 West of Salt Lake City (82). Only the classified portion of tailings from Kennecott Copper Company's Magna operation was used for this project. After classification, the coarser fraction of these tailings consist of sand sized material with a maximum of 20 percent passing a 200 mesh size (D.R. Cummings, Kennecott Copper Company. Private Communication).

Washington

Carbonate waste rock from lead-zinc mining in the Metaline Falls area has been used in a variety of applications, including as a miscellaneous fill material by the county road department (L.M. Kinney, Bunker Hill Company. Private Communication).

SCRAP TIRES IN EMBANKMENTS AND RETAINING WALLS

Scrap tires have been used in the construction of fills or roadway embankments in at least two different ways. Tire sidewalls have been used as soil reinforcement for embankments and tire chips have been used as a lightweight fill material. The scrap tire chips can either be used by themselves or blended with soil during construction. In each case, the scrap tires require some mechanical processing prior to use. Whole scrap tires are

also used in the construction of retaining walls. The scrap tires are stacked on top of each other and are clipped together and filled with borrow soil or concrete.

Scrap tire sidewalls were used in California to reinforce embankments in the construction of a tied-back timber retaining wall. The scrap tires provided additional reinforcement by being attached to the anchor bars using a cross-arm assembly. The scrap tire sidewalls were spaced at close horizontal intervals along the length of each anchor bar in order to provide an additional safety factor against pullout. Besides enhancing the reinforcement of the embankment, the sidewalls provided the additional benefits of reduced wall construction cost and significantly less volume of borrow material due to steeper side slopes. Scrap tire sidewalls also possess high tensile strength and are not biodegradable. Another benefit to reinforcement with scrap tire sidewalls is additional resistance to seismic loading (83).

The use of scrap tire chips as a lightweight fill material is particularly advantageous in soft soil conditions or in areas of recurring landslides, where overburden pressures or driving forces need to be minimized. Depending on the size of the chips and the manner in which they are placed and compacted, their unit weight in place may be only 20 to 30 percent of that of conventional soil after compaction. If tire chips are blended with soil, the unit weight of the blended material will increase as the percentage of soil in the blend increases. The use of scrap tire chips without soil requires placing a geotextile below and above the tire chips in order to provide the proper degree of containment for the chips. Several feet of cover soil must also be placed on top and outside of the tire chips. Placement of tire chips as fill materials is generally not recommended below the water table, although it seems environmentally acceptable.

The advantages of using scrap tire chips to construct embankments in soft areas are a dramatic reduction in the dead weight of the fill, the relative ease of compaction of the chips, and the ability to use large amounts of scrap tires. Approximately 40 scrap automobile tires will fit into one cubic yard of embankment after being shredded into chips. The experience gained from using scrap tire chips in a number of projects and monitoring their performance indicates that short-term settlements are reasonable and long-term consolidation after initial loading is negligible.

The main disadvantages to the possible use of tire chips as an embankment construction material are the potentially high costs for obtaining the chips (particularly if transportation costs are high), the need to use tracked instead of rubber tired vehicles to spread and compact the chips (due to pieces of steel belt in the chips), and the possible need to provide an indemni-

There is a U.S. patent (84) on the use of scrap tire chips in various layer configurations as a roadway mat or embankment material. Although the patent on using scrap tire chips as fill mentions the use of interconnected whole tires as a roadway mat, the patent does not specifically address using whole scrap tires for construction of retaining walls. Wall heights using whole tires should probably be limited to 10 feet.

Whole scrap tires have not been widely used to any great extent to construct retaining walls. However, the principal advantages of using whole tires for such an application are the savings in cost over conventional retaining wall systems and an opportunity to use a fairly large number of scrap tires, especially truck tires.

Current Practice

A review of the technical literature and response to state highway agency questionnaires indicates that at least 7 states have utilized scrap tires for the construction of embankments and/or retaining walls. These states are California, Colorado, Minnesota, North Carolina, Oregon, Vermont and Wisconsin. Scrap tire usage in each of these sevem states is discussed in some detail in the following paragraphs. At least two other states (Indiana and Louisiana) have conducted limited research into embankment or subgrade uses for scrap tires.

California

In 1976, the California Department of Transportation (Caltrans) constructed a scrap tire reinforced embankment within a 300-foot long section of CA-236 about 15 miles north of Santa Cruz. The section of road required a slide correction on a sidehill in a densely wooded area. Embankment heights in the affected area were reconstructed to depths of 40 to 50 feet. Tire sidewalls in each layer were interconnected by means of metal tire clips. Tire layers were installed every two feet vertically within the reconstructed embankment. Prior to construction, it was determined that tire reinforcement permitted building the embankment with a steeper slope (1/2:1), thus saving approximately 90,000 cubic yards of embankment material that would have been needed for conventional 1:1 side slopes (83). This embankment was located in the area affected by the 1989 Loma Prieta earthquake. However, Caltrans engineers did not observe any damage to this embankment as a result of the earthquake (R. Prysock, California Department of Transportation. Private Communication).

In 1981, Caltrans also developed a retaining wall system for soil reinforcement that incorporated the use of scrap automobile tire sidewalls and discarded railroad ties. The scrap tire anchored wall system used No. 5 steel reinforcing bars as tied-back anchors for vertical timbers made from the railroad ties

In 1981, Caltrans also developed a retaining wall system for soil reinforcement that incorporated the use of scrap automobile tire sidewalls and discarded railroad ties. The scrap tire anchored wall system used No. 5 steel reinforcing bars as tied-back anchors for vertical timbers made from the railroad ties placed on 4 foot centers. Scrap tire sidewalls, with treads discarded, added reinforcement by gripping the anchors through the restraining action of a metal cross-arm welded to the anchor bar. It was determined that this system develops high traction forces within the embankment through cohesion and the frictional resistance in the compacted soil. The tire-anchored system was used on at least two different road construction projects.

The first project using this system was a road widening on CA-203 at Mammoth Lakes. Two timber walls were constructed with a total length of approximately 750 feet and wall heights that varied from 3 to 12 feet. Four vertical rows of tire sidewalls were placed behind much of the timber walls. The system provided a factor of safety of 10 against pullout of the anchor bars (85). The cost of the timber walls were about half the cost of conventional concrete retaining walls. There is at least one other retaining wall project of this type that involved a 21 foot high timber wall in the Big Basin area.

Colorado

In early 1992, the Colorado Department of Highways began construction of a 10,800 cubic yard embankment on a new section of Interstate 76 extension west of Denver. Part of the embankment traversed a section of a sanitary landfill being operated by the City and County of Denver. A tire chip embankment was built within this section in an area with dimensions 300 feet long by an average of 110 feet wide by 3 feet deep. In total, some 400,000 to 450,000 scrap tires were used in this embankment. The tire chips are to be covered with a geotextile then overlaid with three feet of compacted earth. An additional two feet of earth surcharge were placed and will be later removed, in order to maximize potential settlement. The embankment will also be monitored with slope inclinometers at the bottom and top to further evaluate settlements (B. Gilmore, Colorado Department of Transportation. Private Communication).

Minnesota

In 1989, the Benton County, Minnesota Highway Department used shredded automobile tires to reconstruct an embankment traversing a swampy area underlain with peat and mulch. The original road (Highway 21) across the swamp was stable, but subsequent efforts to raise the grade above the rising water level caused an embankment failure. The entire embankment was excavated to within 6 inches above the level of the marsh. A geotextile was placed on the surface of the excavated area.

Shredded tire chips (approximately 8 inches square, maximum 12 inch length) were placed directly on the fabric in 2 foot lifts, compacted with a bulldozer, and brought up to within 3-1/2 feet of the top of subgrade elevation. Additional fabric was also installed on top of the shredded tire chips. The overall length of the embankment section was 250 feet. Approximately 52,000 tires were shredded and used in this embankment. The compacted unit weight of the tire chips is estimated at 550 pounds per cubic yard, compared to about 2,800 pounds per cubic yard for gravel fill (86).

North Carolina

During the 1991 construction season, the North Carolina Department of Transportation widened a 2.18 mile long segment of State Route 54 in Carrboro, Orange County. This project received experimental funds from the Federal Highway Administration (FHWA) to incorporate a variety of recycled materials in the construction. Among those recycled materials were whole scrap tires and shredded tire chips.

An estimated total of 2,500 42-inch diameter scrap truck tires were used in the construction of a tire retaining wall. The wall was constructed by excavating and shoring the desired area, placing and filling the scrap tires, and securing all adjacent tires by means of 1/2 inch diameter steel tire clips. The overall length of the tire retaining wall was approximately 350 feet. The height of the wall ranged from 4 to 10 feet (M. Whitmill, North Carolina Department of Transportation. Private Communication).

Shredded tire chips were mixed with soil within two embankment sections on the project. One section was 500 feet long, the other section 300 feet long. Tire chips ranged in size from one to three inches. The tire chips were mixed with the soil at a ratio between 10 and 40 percent by volume of the soil. On the average, about 25 percent by volume of the embankment material consisted of tire chips. The total volume of the embankment is estimated at 5,000 cubic yards. Approximately 64,000 14-inch diameter scrap tires were used in the construction of this embankment (87).

Oregon

The Oregon Department of Transportation used shredded scrap tires as a lightweight fill material on a slide correction project on State Highway 35, approximately 25 miles west of Roseburg. This project was undertaken during 1990 and was funded in part by the Federal Highway Administration (FHWA) as an experimental project. Approximately 8,500 cubic yards of earth were removed from a 600 foot long section of the roadway and replaced with 5,800 tons of tire chips, derived from shredding

approximately 580,000 tires. A drainage blanket was placed beneath the shredded tire embankment to prevent the tire chips from becoming submerged. Tire chips were compacted in 3 foot lifts using a D-8 dozer. The maximum depth of the tire chip embankment was 8 feet. Geotextile was installed beneath and on top of the shredded tires. A 3-foot soil cap was placed above the tire fill.

Tire chips were obtained from three different vendors. The chips varied somewhat in size, as well as loose density, which ranged from 24 to 33 pounds per cubic foot. The compacted density of the various size chips, prior to loading with soil and pavement, was approximately 45 pounds per cubic foot. The embankment was constructed in two stages in order to maintain traffic. The fill area was constructed to an elevation 12 inches higher than the design elevation in order to allow for anticipated settlement under traffic. Data from settlement plates indicated that the thickest portion of the shredded tire fill was compressed a total of 20 inches, with 16 inches of settlement observed during the placement of the soil cap (88).

Vermont

Tire chips were used as embankment fill and subgrade material on a research project in Vermont with acceptable results. No further information on this use was provided (R. Frascoia, Vermont Agency of Transportation. Private Communication).

Wisconsin

A shredded scrap tire test embankment was built in 1990 on a landfill haul road under the general supervision of the University of Wisconsin-Madison. This test embankment involved a total of 8 test sections, each 20 feet in length, 6 feet high, and with a crest width at the top of 16 feet to allow the passage of large trash trucks. Two of the test sections were control sections, in which on-site sandy soils were used. The other six test sections incorporated three different tire chip sources of different sizes with variations in placement conditions. A geotextile was placed under and on top of the tire chip test sections before placement of the subbase.

One test section involved alternate 12 inch thick layers of tire chips and soil. Another test section involved a 50:50 mixture by volume of tire chips and soil. Two test sections involved all tire chips with 3 feet of soil cover. Another two test sections involved all tire chips with only 1 foot of soil cover. Traffic, consisting of 60 to 100 trash trucks (22 tons average) per day, was allowed on the test embankment in June, 1990. Periodic regrading and filling of potholes with crushed stone was necessary. A survey of settlements in each test section was performed during the first 5 months of traffic.

The largest settlements were observed in the test section with the alternate layers of tire chips and soil. The lowest settlements were observed in the test sections with 3 feet of soil cover (89).

Related Scrap Tire Uses

In addition to using scrap tires in embankments and retaining wall applications, there are also two other examples of related highway construction uses for scrap tires. In each example, the application involves whole scrap tires. The Colorado Department of Highways has made use of whole scrap tires fastened together to form a rock fall barrier along a section of Interstate 70 in Glenwood Canyon, east of Glenwood Springs (B. Gilmore. Private Communication).

The Connecticut Department of Transportation constructed a crash barrier system consisting of one to four tires filled with sand. These scrap tires were supported on the bottom section of a 55 gallon drum and covered with 6 mil polyethylene. The system was placed in a gore area separating state Routes 2 and 17 and contained a total of 29 different modules (90).

WOOD WASTE IN EMBANKMENTS

General Background

Wood waste can be classified into sawdust, chips or fibers, chunks, and brush wood. Chips or fibers are frequently used as a mulch material and are well suited for that purpose. The principal advantage to using wood waste in embankment construction is the very low unit weight or density of these materials, even when they are wet. Dry unit weights can be as low as 14 pounds per cubic foot, with wet unit weights, even after saturation, usually in the 40 to 50 pounds per cubic foot range. Because wood wastes are usually disposed of, they are often available at little or no cost, aside from the cost of transport. Wood wastes are generally easy to compact and the particles interact with each other, resulting in good lateral stability.

Although there is some concern regarding the long term decomposition of wood waste in an embankment, it has usually been found that sealing the outer edges of the fill effectively eliminates changes in moisture content within the wood waste, thus retarding decomposition of the fill. Sealing of the outer edges of the fill also is a practical approach in alleviating the threat of spontaneous combustion within the wood waste. This is similar to the techniques used to combat possible spontaneous combustion in coal waste embankments.

Generally, fluctuations in the moisture content of wood waste in an embankment or structural fill are more detrimental than placing the wood waste in a saturated condition. As long as the exterior (top and sides) of the fill is sealed, the moisture content within the fill will remain basically unchanged and the wood waste will decompose at a very slow rate. Therefore, it should be considered acceptable construction practice to be able to construct wood waste embankments above as well as below the water table.

Current Practice

A review of technical literature, together with responses from the state highway agency questionnaires, indicates that some form of wood waste has been used in at least six states to construct or repair embankments. These states are Alaska, Idaho, North Carolina, Washington, Wisconsin and Wyoming. It is likely that there are also some other states, in which logging and/or lumber processing are vital industries, that have at one time or another used some type of wood waste as a lightweight fill material in embankments or for landslide repair.

Alaska

During the mid 1980's, the Alaska Department of Transportation rebuilt a segment of two-lane highway between Fairbanks and Anchorage that had been settling under its own weight, at the rate of about a foot annually over a 10 year time period. The affected portion of the embankment was about 750 feet long and was originally 30 feet high. The top half of the embankment was removed and replaced with 21,000 cubic yards of greenwood chips. The rebuilt section was 130 feet wide at the base, 44 feet wide at the top and 14 feet high.

The Department of Transportation specified wood chips smaller than 6 inches in size, evenly graded in a uniform dense fill. The fill was placed in two 6 inch layers and then compacted using a bulldozer. As weight was applied to the embankment, the wood chips tended to interlock at an angle, bridging any voids. The chips were topped with a crushed aggregate to keep oxygen out of the wood. The sides of the embankment were capped with a dense silt rock fill. The embankment was then loaded with 30 inches of rock fill. A 12 inch thick paving base course and 2 inches of hot-mix asphalt were placed in the Spring of 1987 (91).

Idaho

In 1987, a major reconstruction of a 3200 foot long runway at the Benewah County Airport involved the excavation and removal of up to 3.5 feet of crushed rock ballast and up to 8 feet of highly organic subgrade soil overlying an unknown thickness of peaty silt-clay floodplain deposits. The reconstruction work

involved replacement of these materials with compacted light-weight wood fiber fill 8.6 feet thick covered with 12 inches of compacted well graded granular material, in an effort to minimize settlements that had previously exceeded 2 feet in some locations.

The dry unit weight of the wood fiber fill ranged from 13 to 14 pounds per cubic foot. Because of the capacity of the wood fibers to absorb water, the compacted wet unit weight after soaking and draining averaged 52 pounds per cubic foot at an optimum moisture content of 260 percent. The wood fiber fill was placed in 12 inch loose layers and each layer was compacted with a minimum of two passes of a dozer or crawler tractor equivalent in weight to a Caterpillar D-7. No further densification of each layer was observed after more than two passes were applied (92).

Since the groundwater table was 4 feet below grade, the wood fiber fill was placed both above and below the water table. Development of anaerobic conditions within the wood fiber fill were achieved by sealing the surfaces of the fill with at least 12 inches of well compacted and well graded granular soil. The maximum observed settlement of the runway after 32 months of use following reconstruction was 0.53 feet, which was considered an acceptable level. The compressibility and creep behavior of the wood fiber particles used in this project were found to be comparable to those usually observed for fine grained soils (92).

North Carolina

During 1986, the North Carolina Department of Transportation chose a failing slope site about 60 miles east of Asheville on State Route 126 for a demonstration of soil bioengineering systems. Soil bioengineering systems involve the use of live plant cuttings, in conjunction with inert structural materials such as stone or wood, to stabilize earth slopes and act as barriers to surface erosion. The cuttings function as soil reinforcement and in time roots permeate the soil, increasing its shear strength and resistance to sliding. In addition to mechanical reinforcement, the stems or cuttings act as lateral drains, intercepting groundwater seepage along the loose outer edges of compacted fills (93).

The soil bioengineering systems employed at the Route 126 project site included live staking, rooted plants, cut and fill brushlayers, and live fascines (bundled live branches). Much of the work was performed by hand with the aid of chain saws. Nearly 8,800 bundles of brushlayers were placed in the slopes of the 870 foot long embankment, along with 7,000 live stakes, 3,000 rooted plants and over 400 live fascines. Maximum fill heights ranged from 25 to 60 feet. Selected fill brushlayers in the toe area were further reinforced by placing a 6.5 foot wide layer of geogrid. From this demonstration, it was concluded that soil

bioengineering is an excellent way to repair shallow landslides, soil sloughing, and slope erosion problems, especially in areas where access with heavy equipment is difficult (93).

Washington

During 1972, a serious landslide occurred on U.S. Route 101 south of Cosmopolis, in which 1-1/2 miles of the 2-lane highway slid diagonally downward some 40 feet, forcing the closure of a 250 foot long section of the road. Because the area experiences unusually heavy rainfall, the use of locally available sawdust was chosen as an all-weather lightweight fill material for the repairs. A total of 3,650 cubic yards of sawdust were delivered to the project site by Weyerhaeuser Timber Company free of charge. The only specification requirement for the sawdust was that it be 100 percent wood fibers with no particle exceeding 6 inches in its maximum dimension (94).

The sawdust consisted of three varieties: planer chips, bark chips, and hog fuel. Planer chips and bark chips are both by-products from the Weyerhaeuser sawmill, while hog fuel is pulverized bark stripped from logs by high pressure water at the Weyerhaeuser pulp mill. The sawdust materials were placed in 12 inch lifts to a total depth of 10 feet and compacted by construction equipment. No water was required during placement. The compacted sawdust has a unit weight of 36 pounds per cubic foot. To keep air from decomposing or deteriorating the sawdust, an emulsified asphalt sealer was sprayed on the 1:1 fill slope at the rate of 1.3 gallons per square yard. Class B gravel base was placed directly on top of the compacted sawdust in two 6 inch lifts, then topped with an asphalt base and wearing surface. The sawdust was found to be very workable fill material which reduced the driving forces for a potential landslide by approximately 70 percent (94).

The Washington Department of Transportation has used sawdust and wood chips in a total of at least 14 embankment projects since 1972. Wood waste is used as a lightweight fill material in special situations such as landslide repairs and the need for lightweight fills to traverse soft soil areas. According to the state DOT questionnaire, the overall performance of sawdust and wood chips has been very successful (K. Anderson, Washington Department of Transportation. Private Communication).

During 1991, the Washington Department of Transportation undertook an evaluation of the existing condition and overall performance of the 14 different locations where wood waste fills have been used in embankment construction. The performance of each of the wood waste fills was evaluated based on the quality of the wood fibre material, the quality of the effluent from the fill (where available), and the condition of the pavement in the area of the fill. Over half of the wood fibre samples were found

to be fresh or nearly fresh and none were completely decomposed. In all but one case the condition of the pavement above the wood waste fills surpassed that of the pavement in the surrounding area. Generally, water samples taken from the vicinity of the wood waste fills were found to be clean and pure, with no leachate problems identified. Based on these findings, the Department has concluded that fills or embankments constructed of wood waste (sawdust or wood fibres) have an expected service of 50 years or more (95).

Wisconsin

Researchers at the U.S. Forest Service Experiment Station in Houghton, Michigan developed a machine called a woodchunker. This machine is capable of processing whole trees having a base diameter of from 9 to 12 inches. Wood chunks from this machine range in size from 1/4 inch up to 6 inches, with an average diameter of 3 inches. The chunks vary in size and shape depending on the nature of the trunk, limb or twig that is processed. The mixture of varying sizes and shapes provides a great deal of interlock between particles, which results in high frictional strength. The major advantage of these chunks over conventional soil borrow materials is their light unit weight (about 20 pounds per cubic foot) compared to that of sand and gravel (about 120 pounds per cubic foot). This low unit weight greatly reduces induced stresses on weak roadbed soils.

A cooperative field demonstration with accompanying laboratory research was arranged between the Forest Service, Michigan Technological University, and the Chequamegon National Forest in Wisconsin. A 650 foot long test road was constructed across a muskeg bog overlying a thick peat deposit on Forest Road 481 at Hayward. The muskeg thickness varied to a maximum thickness of 18 feet. The test road consisted of two sections -- one with 30 inches of wood chunks, the other with 14 inches of wood chunks enveloped in a geotextile and overlaid with 12 inches of native granular soil. At 25 ton truck was driven across the road for a total of 100 passes. One pothole developed in the 30 inch section, which was satisfactorily repaired. No other distress or settlement was observed in the roadway (96).

Wyoming

According to the state DOT questionnaire response, Wyoming is another state like Washington, which has used wood chips as a lightweight fill material for repairing landslide areas. The wood chips are used in locations where they are available and repairs are needed. The use of wood chips for landslide repairs in Wyoming is considered very successful (R. Harvey, Wyoming Department of Transportation. Private Communication).

FLY ASH IN SOIL STABILIZATION

General Background

Stabilization is a technique for upgrading the engineering properties of soils for pavement construction. Improvements in load bearing capacity or resistance to moisture can be provided by admixing chemical reactants or aggregates, or by compactive effort. Besides improving the characteristics of marginal subgrade soils, stabilization is a construction technique that helps to reduce road building costs while conserving raw materials. Generally, in-place stabilization of locally occurring soils becomes more cost effective as the price for traditional subgrade replacement materials (crushed stone or sand and gravel) increases. In addition to saving the cost of the aggregate, including its transportation cost, further cost savings are realized through avoidance of excavation, loading, hauling, and disposal of the subgrade soil that was instead stabilized (97).

Stabilization measures can improve the properties of an unsuitable soil for engineering applications by:

- Improving inherent soil properties, such as decreasing the plasticicity index or volumetric shrinkage and/or swelling.
- Cementing individual soil grains to increase strength and durability characteristics.
- Reduce soil moisture content to a more workable range to facilitate spreading and compaction.

Chemical stabilizers traditionally used for such purposes include cement, lime, lime-fly ash, bituminous materials and chemicals such as calcium or sodium chloride (98). Normally, cement stabilization is used where coarse-grained soils are involved. With fine-grained soils, it is well known that the addition of lime or lime-fly ash to clays, silts, and even fine to medium sands, has a beneficial stabilization effect (99). Class C fly ash has also proven to be an effective stabilizer for a variety of soil types, including some fine-grained soils.

Because no one stabilization reagent works best for all soils, the purpose of the soil modification or the function of the stabilized layer is an important consideration. Stabilizer reagent selection depends to a large extent on what one desires to accomplish. In order to dry wet subgrades or borrow materials, lime is frequently applied in small doses (2 percent by weight) in order to provide a suitable working platform for constructing the remainder of the pavement structure. Fly ash and kiln dust have also been used for improving the workability of wet subgrade soils. Once a soil's workability has been increased, other stabilization reagents can be used. In fact,

combinations of stabilization reagents are often used successfully (97).

In the stabilization of coarse-grained soils, fly ash is used with lime and/or portland cement as a pozzolan to improve the strength development of the soil-binder mixture and to cement the individual soil particles together in a stable mass. In the stabilization of coarse-grained soils, early strength is a prime consideration. The increasing availability of Class C ash has resulted in growing interest in the possible use of Class C fly ash alone for soil modification or stabilization.

In the stabilization of fine-grained soils, lime has traditionally been used to raise the pH and modify or improve the inherent properties of the soil. Initially, lime causes a cation exchange or a flocculation-agglomeration reaction to occur, which reduces the plasticity characteristics and moisture content of the soil. This is then followed by a pozzolanic reaction between the calcium and magnesium ions in the lime and the alumina and silica ions in the soil. The use of fly ash, usually Class F fly ash, in combination with lime serves to further enhance both of these reactions, particularly long term strength development from the pozzolanic reaction (100).

Much of the lime or lime-fly ash stabilization in the United States is concerned with improving the properties of expansive clay soils, that is, soils that exhibit significant volume changes as their moisture contents change. The majority of the expansive clay soils in this country are found in western states (particularly arid or semi-arid regions), although some problem clay soils are also found in the southeastern states along the Mississippi River. There are thirteen states that have at some time actively sponsored research on swelling clay soils. All of these states (with the exception of California) are ash-producing states, and most produce predominantly Class C ash.

When using Class C fly ash alone in soil stabilization, there are some differences in behavior compared to traditional lime stabilization. Although the plasticity of soils stabilized with Class C fly ash is not reduced as significantly as when hydrated lime is used, the Class C ash nevertheless reduces the swelling of the stabilized soils to within acceptable limits (M. Mings, Walter N. Handy Company. Private Communication). The main difference in construction techniques is that soil stabilized with Class C fly ash must be compacted within one to two hours after mixing, compared to a normal "mellowing" period of 24 hours for lime or lime-fly ash stabilized soil (G. Ferguson, Terracon Consultants. Private Communication).

Regardless of whether Class C or Class F ash is being considered, each source of fly ash should be separately evaluated, although, in general, less lime is needed for stabilization

of fine-grained soils with Class C fly ash than with Class F fly ash. When using highly reactive or high free lime Class C fly ash, no supplemental lime is needed for stabilization.

Recognizing the need to effect a pozzolanic reaction in fine-grained soils, as opposed to a cementitious reaction in coarse-grained soils, a study of the possible use of Class C fly ash in the stabilization of fine-grained soils was performed in 1981 at Texas A&M University. In this study, it was discovered that, even though Class C fly ashes are characteristically high in CaO content (sometimes 30 percent or more), most of the calcium is in a combined form with silicates and aluminates and very little calcium (usually 2 to 4 percent) exists in a free oxide form. Class C fly ash reacts in the presence of water more like portland cement and is ordinarily not recommended for use alone in stabilization of clay type soils. Instead, it is recommended that Class C fly ash be combined with lime to allow pozzolanic reactions to develop in fine-grained soils (101).

Despite these recommendations, Class C or self-cementing fly ash has been used for more than 10 years in the midwest for a variety of soil stabilization applications. These applications have included use as a drying agent to facilitate soil compaction; treatment of expansive clay soils to reduce shrink-swell potential; and stabilization of subgrade soils to improve subgrade support capacity and allow a reduction in pavement thickness. Class C fly ash has successfully stabilized a number of different soil types, not just expansive clays. Soil temperatures as low as 45°F. had no detrimental effects on compressive strengths of Class C ash amended soils, but below 40° F. a pronounced reduction in strength development occurs. For best results, initial compaction should be undertaken within 10 minutes after adding the fly ash. Final compaction must be achieved within 2 hours. Generally, Class C fly ash stabilization of fine grained soils is approximately half the cost of lime stabilization (102).

Current Practice

At least 10 states have utilized coal ash in soil stabilization, as indicated either from a review of the technical literature or from responses to state highway agency questionnaires. A brief discussion of the experiences and evaluation of performance of fly ash in each of these states is provided in the following paragraphs.

Alabama

The earliest indication of fly ash use as a soil stabilizer dates back to 1960, when a mixture of 5 percent lime and 15 percent Class F fly ash were used to stabilize a mixed sandy clay subgrade as part of an 8 mile road construction project between Gorgas and Parrish (103). In their questionnaire response, the Alabama Department of Transportation characterizes the relative success of fly ash as good when used as a stabilizing material.

Arizona

The Arizona Department of Transportation, in their response to the state highway agency questionnaire, notes that fly ash has been used as a soil stabilization admixture and that its performance has been very successful. No further details of this application were provided.

Georgia

The Georgia Department of Transportation has used coal ash for subgrade stabilization. According to the state highway agency questionnaire, this application has been successful and is acceptable for further use.

Kansas

All fly ash soil stabilization work in Kansas has been with Class C ash. The Kansas Department of Transportation reports acceptable performance on soil stabilization projects using Class C fly ash. A considerable amount of Class C ash soil stabilization has also been performed on county and local roads, as well as private work involving access roads and parking lots.

Kentucky

The Kentucky Department of Transportation has indicated in their questionnaire response that fly ash has been investigated for use in subgrade stabilization and has been judged to be potentially acceptable. Fly ash use in Kentucky involves Class F ash. There was no indication from the questionnaire response that fly ash has been used for soil stabilization purposes on any construction projects.

Minnesota

The Minnesota Department of Transportation has also indicated in their questionnaire response that power plant ash, probably Class C ash, was investigated for possible use as a stabilizer. To date, the findings from this investigation are inconclusive.

Mississippi

During 1983, a 7.5 mile long lime-fly ash soil stabilization project was completed as part of the Federal Highway Administration (FHWA) Demonstration Project No. 59. A Class F fly ash was used to stabilize A-2, A-3, and A-4 soil types in proportions consisting of 1 part lime to 4 parts fly ash (B. Stroud, Mississippi Department of Highways. Private Communication). The Mississippi Department of Highways did not indicate the use of fly ash for soil stabilization in their questionnaire response.

North Dakota

Over 10 years ago, a combination of 3 percent lignite fly ash and 3 percent lime was used to stabilize an A-7 subgrade soil along portions of Interstate Route 29 in eastern North Dakota (O.E. Manz, University of North Dakota. Private Communication). In their questionnaire response, the North Dakota Department of Transportation indicates only that fly ash has been used as a concrete additive.

Oklahoma

In 1983, over four miles of weathered shale subgrade was stabilized using 25 percent Class C fly ash to reduce the plasticity index of the shale and improve its compressive strength and modulus of rupture (104). The Oklahoma Department of Transportation has noted in their questionnaire that Class C ash is acceptable as a soil stabilizer and is now being used routinely.

Texas

During 1979, a total of seven experimental lime-fly ash soil stabilization projects were constructed in Texas. These projects were placed in a number of different areas of the state, using four different sources of Class C fly ash. At each project site, several test sections were involved, each one having a different lime-fly ash ratio (105).

FLY ASH IN STABILIZED BASES AND SUBBASES

General Background

One of the most promising applications for the use of fly ash in transportation construction is in the use of stabilized base course mixtures. Such mixtures can consist of lime-fly ash-aggregate (LFA); lime-cement-fly ash-aggregate (LCFA); or cement-fly ash-aggregate (CFA). These mixtures are blends of commercial lime (and/or cement), fly ash, and mineral aggregates, combined with water in the proper proportions and compacted to form a dense, stable mass.

Stabilized fly ash base course mixtures may also involve the substitution of kiln dusts from cement or lime production in place of lime or cement. An investigation of kiln dust-fly ash-aggregate base course compositions, jointly sponsored by the U.S. Department of Energy and the U.S. Department of Transportation, has concluded that kiln dusts from the production of cement or lime can be substituted for hydrated lime in LFA or LCFA bases and still produce an acceptable base or subbase from the standpoint of strength and durability (106).

Mix Proportions

The relative proportions of lime and/or cement (or kiln dust), fly ash, and aggregate in pozzolanic mixtures varies depending on the materials used and their characteristics, as well as the design criteria to be met. Typically, LFA mixtures contain from 2-1/2 to 4 percent lime and from 10 to 25 percent fly ash. Similar mix proportions are used in CFA mixes. In some cases, small quantities (from 0.5 to 1.5 percent) of Type I portland cement have also been added to LFA mixtures during late season construction in order to accelerate the initial strength gain of the mix. Lime to fly ash ratios in the range of 1:3 to 1:5 are most commonly used in LFA base. In kiln dust-fly ash-aggregate bases, the kiln dust to fly ash ratio ranges from 2:1 to 1:1, depending on the chemistry of the kiln dust (107).

Engineering Properties

The most important engineering properties of fly ash base and subbase mixtures are:

- Compressive Strength - The most widely used criterion for the acceptability of fly ash stabilized base materials is compressive strength. Compressive strength development is time and temperature dependent. As a general rule, the higher the compressive strength, within limits, the better is the quality of the stabilized material, provided excessive early strengths (comparable to concrete) are not developed. The key to developing compressive strength is achieving maximum density of the mix.

- Durability - The durability of fly ash stabilized base mixtures is the single property which most affects its performance in the field. Durability refers to the ability of a material to maintain its structural integrity under the in-service environmental conditions to which it is exposed. Cyclic freezing and thawing is the major durability factor that must be considered when evaluating stabilized base mixtures.

- Autogenous Healing - One of the most unique characteristics of stabilized base course compositions is their inherent ability to heal or recement cracks within the material by means of a self-generating mechanism. This phenomenon is referred to as autogenous healing and results from a continuing pozzolanic reaction (107).

- Pavement Thickness Design Considerations - Thickness design of pavements with stabilized base course mixtures is based on the structural layer equivalency concepts developed from the AASHTO Road Test, as well as recognized structural design methods. A majority of states still make use of structural layer coefficients in pavement design (107). Using pavement structural layer coefficients also allows engineers to compare the costs of alternative pavement design types. More recently, development of mechanistic thickness design methods also take into account the design flexural strength of the different pavement layers when computing the required thickness of the base course (108).

- Late Season Construction and Cutoff Dates

Durability is the most important single property related to the performance of fly ash stabilized base course materials, particularly resistance to cyclic freezing and thawing. Unless a pozzolanic base material is able to develop a certain level of cementing action and resultant strength, it will be unable to withstand the disruptive forces associated with the initial winter freeze-thaw cycle. Since cementing action and strength development are time and temperature dependent, it is believed that material placed beyond a certain period during the construction season may be unable to develop the strength and durability needed for freeze-thaw resistance.

Analysis of weather data and correlation of air and pavement temperature variations have enabled state transportation agencies to determine a reasonable date beyond which stabilized fly ash base will probably not develop sufficient strength and durability to resist freezing and thawing until the following Spring. This date is referred to as a construction cutoff date. In many of the northern states, a cutoff date during the month of September has been established.

Class F vs. Class C Ash in Stabilized Base

Until the last 10 to 15 years, most of the pozzolanic base projects involved the use of Class F or bituminous coal fly ash. However, a considerable amount of stabilized base and subbase material has now been placed using Class C fly ash from the burning of lignite or sub-bituminous coals.

As mentioned previously, Class C fly ash has some unique physical and chemical properties which distinguish it from Class F fly ash. Not the least of these properties is its self-hardening characteristics. When using a Class C fly ash in fly ash mixtures, certain precautions must be taken to prevent flash setting or the base mix will rapidly set up and will not even be able to be discharged from a truck.

Several measures have been used to counteract the flash setting of Class C ash in fly ash stabilized base mixtures:

- The Class C fly ash may be initially conditioned with relatively low (10 to 15 percent) amounts of water in a conditioning plant, stockpiled for one to three months, run back through a crusher to reduce agglomerations, and then used (J. Pound, American Fly Ash Company. Private Communication).

- A retarder, such as gypsum, or certain commercial retarding admixtures, may be added to the LFA mix in low percentages at the blending plant. It has been found that the addition of 1 percent gypsum does not adversely affect the overall strength development of the mix, but simply retards the flash set (109).

- Low percentages of water, sufficient to retard dusting can be added at the plant, with the additional water required for proper compaction added at the site prior to compaction.

One additional precaution concerning the use of Class C fly ash in stabilized base mixtures is that delays between placement and compaction of the material in the field are almost always accompanied by a significant decrease in the overall strength of the base mix, unless a retarder is used. Therefore, pozzolanic base mixes containing Class C ash should be compacted in the field as soon as possible after placement (109).

Stabilized Base Performance Concerns

One of the main concerns with using fly ash stabilized bases, as expressed by some materials engineers at the state and federal level, is the development of random cracking within the base course layer. The development of cracks is a problem that is not unique only to fly ash stabilized bases, but which also occurs with many other types of base and surfacing materials, especially soil-cement. The problem with base course crack development is that the cracks eventually reflect into the overlying asphalt layers, resulting in surface cracks that must be sealed to prevent water entry. Crack development in fly ash stabilized bases is usually more thermal or shrinkage related, as opposed to structural, and can be fairly effectively controlled on a roadway by saw cutting through the bituminous overlay and into the stabilized base layer at regular transverse intervals

(perhaps every 20 to 30 feet), then sealing the saw cut joints with a hot poured asphalt sealant.

Pavement Recycling

In the past, it has been accepted procedure to remove old pavement materials, haul them to a dump site, and bring in all new materials to construct a new pavement structure. However, it has been determined that pavements can be recycled, both asphalt and concrete pavements, as well as the base and subbase materials that support them. In fact, subsequent sections of Volume 2 provide further discussion of the recycling of each of these types of pavements. This section discusses the in-place recycling of existing roads and streets, regardless of what type of pavement material is involved, into a new stabilized base in which fly ash is used as a stabilization reagent. Pavement recycling into stabilized base materials represents an opportunity to utilize significant quantities of fly ash, especially at the local, county, or municipal level.

The primary reason to recycle existing pavements is economics. It is frequently cheaper to reuse old roadway layers than it is to import new materials. If it were not cheaper to recycle a pavement than to build a new one, then recycling would not be used to reconstruct the nation's highway system, regardless of considerations for conserving material and energy resources. However, recycling does conserve resources, both aggregates as well as binder materials. Recycling also reduces the amount of energy consumed in building a section of roadway. Nevertheless, resource and energy savings ordinarily play a secondary role to economics in the decision making process concerning whether or not to recycle a given section of pavement (97).

In-place recycling is not a new concept. Over the years, many state and local highway agencies have employed conventional construction equipment such as bulldozers, graders, and rollers, as well as agricultural machinery, to rip, crush, and blend existing pavement materials in the process of building a reconstructed pavement layer. New binder materials are added to the binder material, often by blending the chosen additive using a disc harrow or motor grader blade. The development of more modern pulverization equipment has made the in-place recycling process much more efficient and cost effective, using milling, planing, and pulvi-mixing machines (97).

Regardless of the equipment combinations employed, the in-place recycling process involves a number of steps or operations. These include pulverization, mixing, spreading, compacting, and curing. The first step in the process is to break up the existing pavement, which can be using a variety of equipment, including dozens with scarifier teeth or rippers, cold planers, milling machines, or rotary mixers. Regardless of what equipment is

used, the purpose of pulverization is to reduce the pavement materials to the proper size. As a rule of thumb, the maximum particle size should not exceed one-half the depth of the recycled, compacted layer.

If no new aggregate is added to adjust the gradation of the pulverized old paving material, the next step is to add new binder material. In the case of fly ash and other chemical reagents (lime, portland cement, or kiln dust), the binder is spread on top of the pulverized material in a powdered form. If new aggregate is required to alter the gradation of the reclaimed pavement, then the new aggregate is added first, blended together with the pulverized material, after which the fly ash and other powdered reagent, if necessary, is added and mixed.

Once the new binder has been adequately mixed with the reclaimed material, the recycled mix must be spread uniformly across the roadway width to be paved. The most common method is to use a grader or bulldozer. Once the recycled material has been properly spread, it must then be compacted. The addition of the proper amount of water is essential to achieve the required degree of compaction in the recycled base. The type of compaction equipment utilized depends on the binder material(s) used and the gradation and strength characteristics of the recycled mixture. Normally, pneumatic tire rollers or steel-wheeled vibratory rollers are employed.

Stabilized recycled base materials must cure sufficiently to gain the desired strength in place prior to being opened for use by traffic. The same basic guidelines for proper curing of new stabilized bases and subbases also apply to recycled stabilized materials. A wearing surface, usually asphalt concrete or a surface treatment of some kind, should be placed on top of the recycled base layer within the first month of construction and before allowing traffic to be placed on the roadways (93).

Current Practice

Demonstration programs concerning various uses for fly ash in highway construction have been sponsored by the Federal Highway Administration (FHWA) and the Electric Power Research Institute (EPRI). Although each of these demonstration programs have included projects in which fly ash was used in embankment construction and as a partial replacement for portland cement in concrete, the principal application for fly ash in each of these programs has been as a component of stabilized bases and subbases. FHWA's Demonstration Program No. 59, Fly Ash in Highway Construction, began in 1981 and comprised a total of seventeen ash utilization demonstration projects, including nine stabilized base projects and three soil stabilization projects (T. Ferragut, Federal Highway Administration. Private Communication). The EPRI high volume fly ash demonstration program included six

highway construction projects using fly ash in six different states during the late 1980's and incorporated the monitoring of engineering performance and environmental characteristics over a three-year time period. The EPRI program included two Class F ash embankments, two Class F ash stabilized base projects, a Class C ash pavement recycling project, and a Class C ash high percentage cement replacement project.

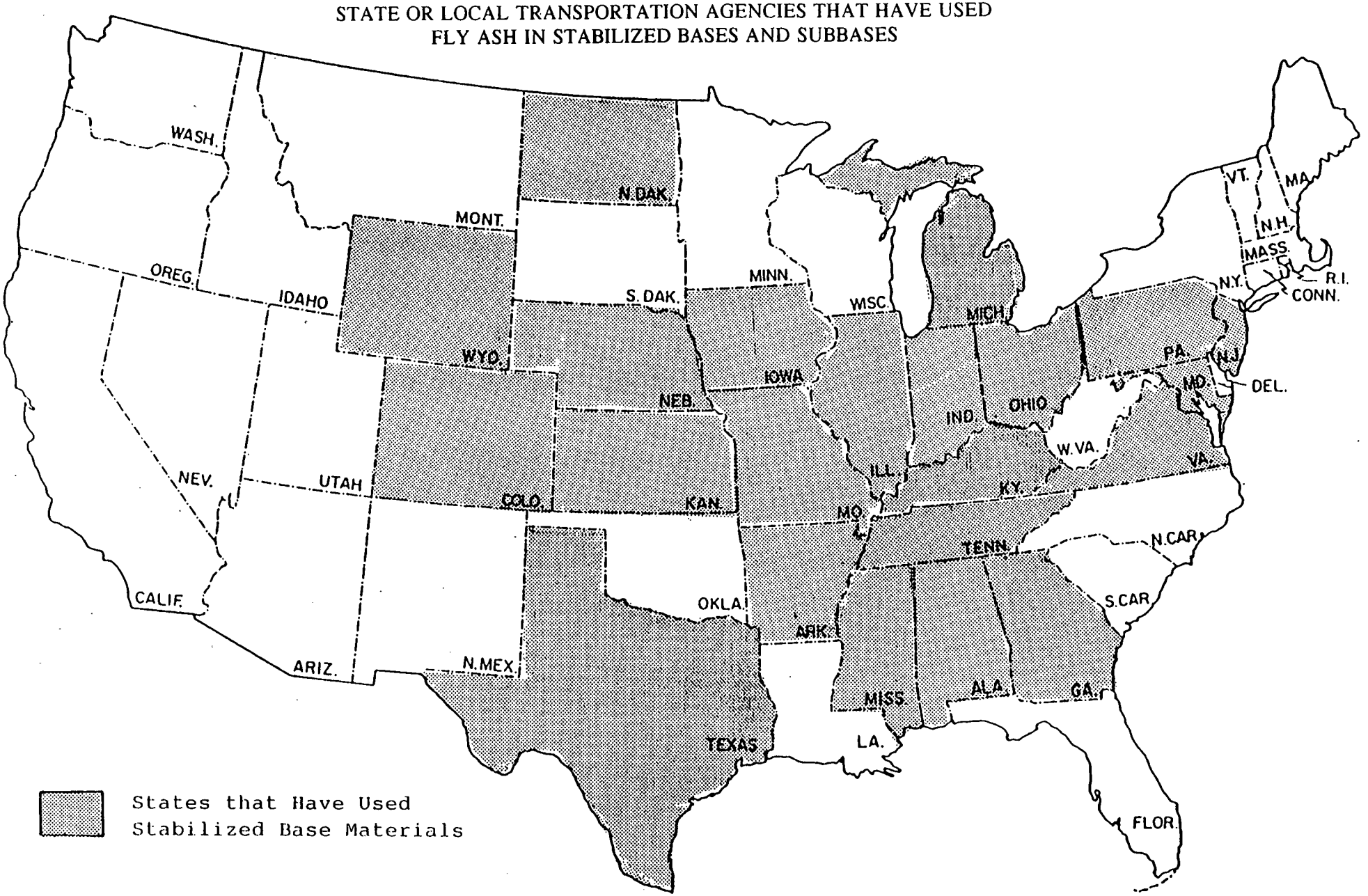
After reviewing extensive technical literature in fly ash utilization, responses to the state highway agency questionnaires, the Purdue University report on the use of waste materials in highway construction (81), and the list of ash demonstration projects undertaken by the Federal Highway Administration (FHWA) and the Electric Power Research Institute (EPRI), there are at least 20 states that have had some experience with the use of fly ash in stabilized bases or subbases. Figure 13 shows the locations of these states. The extent of experience with fly ash stabilized bases varies widely among these states, ranging from states with only one or two demonstration projects to states which have used these base materials extensively for the last 30 to 40 years. Some states, because of their geographical location, have experience only with demonstration projects to states which have used these base materials extensively for the last 30 to 40 years. the use of either Class F or Class C ash as a base stabilizer, while some other states, such as Illinois, have many projects in place using both ash types. Furthermore, there are some states where the use of fly ash in stabilized base course construction has only been done at the local or county level, not on the state highway system. The following paragraphs briefly discuss current practice in each of these 20 states relative to the use of fly ash stabilized bases in their respective states.

Arkansas

In 1982, an 8-inch thick base course was constructed along a 1,400 foot test section of the 38th Street connection road near Pine Bluff. The base course consisted of 100 percent moistened Class C fly ash. This project was constructed as part of FHWA's Demonstration Project No. 59 (110). The Arkansas Department of Transportation has indicated in their questionnaire response that coal ash base course has been investigated and found acceptable. However, fly ash in Arkansas is being used extensively in portland cement concrete.

FIGURE 13

STATE OR LOCAL TRANSPORTATION AGENCIES THAT HAVE USED FLY ASH IN STABILIZED BASES AND SUBBASES



Colorado

In their questionnaire response, Colorado has indicated an investigation or research of Class C fly ash in base stabilization. Based on their investigation, the Colorado Department of Transportation considers this application acceptable. No actual use of Class C ash as a base stabilizer is indicated for state highway construction in Colorado. However, it is believed that Class C fly ash has been used with a retarder to stabilize both gravel and crushed stone bases on municipal streets in Aurora, a suburb of Denver.

Georgia

The Georgia Department of Transportation constructed a ponded ash base course stabilization project in 1985 as part of The Electric Power Research Institute's (EPRI) high volume fly ash demonstration program. Three different test sections were placed, including two cement-fly ash and one lime-fly ash section (111). Fresh dry ash was used instead of pond ash in the lime-fly ash section. The three test sections were designed in the laboratory to each achieve a minimum of 400 psi unconfined compressive strength after 7 days of curing and vacuum saturation testing. The cement-treated pond ash section was the easiest of the three to construct. Georgia's questionnaire response indicates that all fly ash uses, including base stabilizers, have performed successfully.

Illinois

More miles of fly ash stabilized base have been placed in Illinois than in any other state. Most of these projects have been in and around the Chicago metropolitan area and it is estimated that more than 20 million tons of either lime-fly ash or cement-fly ash base materials have been installed over the past 25 to 30 years, involving state, county, and local road construction, representing considerable cost savings (112). The Illinois DOT notes that fly ash as a base course additive is cost effective and has provided acceptable performance.

Iowa

A mixture of lime, Class F fly ash, and soil was successfully used as a base course material on a roadway in Linn County near Cedar Rapids (113). Since the Iowa Department of Transportation does not indicate any use of fly ash for base stabilization, this project was probably constructed for a county or local road agency.

Kansas

Three county gravel roads were recycled in place using Class C fly ash during 1987. At each site, the existing road surface was pulverized, mixed, and redeposited in its original location. Fly ash was spread over the pulverized material by pneumatic tanker at a weight ratio of between 10 to 20 percent by dry weight. Final mixing was performed using the recycling machine. The recycled materials were spread and compacted as the base course for these roadways. A seal coat surface was placed on all three of these roads. This effort was funded as part of the EPRI high volume fly ash demonstration program (114).

Because this demonstration was conducted on county roads, there is no indication of the use of fly ash in road base stabilization by the Kansas Department of Transportation. The questionnaire response from Kansas only refers to the use of fly ash as a stabilization reagent in soil stabilization. However, since the reconstruction of these three locations, over 400 miles of pavement recycling using Class C fly ash has been done in Kansas and Oklahoma (114).

Kentucky

The Kentucky Department of Highways placed a 2-mile long section of kiln dust-fly ash-aggregate base course on Man O'War Boulevard in Lexington during 1984. The kiln dust used for this project was a high calcium lime kiln dust from Maysville, which produced relatively high compressive strengths in the base material (J.P. Nicholson, N-Viro Energy Systems. Private Communication). This project was installed part of FHWA's Demonstration Project No. 59. The Kentucky Highway Department in their highway agency questionnaire response cites fly ash use, as well as kiln dust use, in treated bases as having provided acceptable performance.

Maryland

In the early 1960's, a lime-fly ash-aggregate material was used to construct 22 miles of shoulder base on both sides of Interstate Route 95 north of the Susquehanna River. These shoulders remained in service for nearly ten years and provided excellent performance (115). Maryland Department of Transportation has noted in their questionnaire response that steel slag and fly ash have been used together as a subbase on a research investigation project, but not in highway construction. The results of this use are thus far inconclusive.

Michigan

The Michigan Department of Transportation placed a 4,700 foot long section of cement-fly ash-aggregate base course on Walton Boulevard in Oakland County in 1983. This project was part of FHWA's Demonstration Project No. 59. In 1987, another section of cement-fly ash-aggregate was placed as a shoulder base on a 1,500 foot long section of four lane state primary highway (116), as part of the EPRI high volume fly ash demonstration program. A cement-fly ash mixture containing high carbon Class F ash and 12 percent cement was placed to a compacted depth of 10 inches using a spreader box. Also, a section of cement-fly ash-aggregate base material was placed in 1959 on a roadway in Midland. The performance of fly ash as a stabilization agent has been characterized by the Michigan DOT as good to excellent.

Mississippi

Fly ash was used to construct a 7.5 mile long lime-fly ash-aggregate base course on State Route 63 in Jackson County during 1983 (117). This project was also part of the FHWA Demonstration Project No. 59. The Mississippi Department of Transportation, in their questionnaire response, has indicated that lime-fly ash stabilized courses have performed with excellent success and are being used routinely.

Missouri

During the 1970's and 1980's, at least 750,000 tons of pre-blended lime-fly ash-aggregate base were produced in the Kansas City area, mainly in commercial and municipal projects. The Missouri Highway and Transportation Department evaluated two test sections of lime-fly ash-aggregate base as part of two bridge replacement projects built during the early to mid 1980's and was favorably impressed with the performance (J. Landrum, Missouri State Highway Commission. Private Communication). However, the Missouri questionnaire does not refer to stabilized base as one of the promising ash applications.

Nebraska

The Nebraska Department of Transportation indicated in an earlier questionnaire response to Purdue University that it had previously used fly ash, probably Class C ash, as a subbase additive and reported satisfactory performance. However, the most recent questionnaire response from the Nebraska Department of Transportation mentions that fly ash is used only in portland cement concrete and as a filler in asphalt mixes in Nebraska, although the state does plan to conduct research on the prospective use of fly ash in bases and subbases.

New Jersey

In 1984, the New Jersey Department of Transportation placed 0.4 mile of lime-fly ash-aggregate base course material on Interstate Route 295 near Trenton. This project was included in FHWA's Demonstration Project No. 49, but this particular application is not mentioned at all in the state questionnaire response.

North Dakota

Lignite fly ash has been used with hydrated lime for stabilization of base course aggregates in North Dakota since 1971. During 1983, a one mile stretch of county road south of the Interstate 94 interchange in Morton County was recycled using a mixture of 3.5 percent hydrated lime and 6 percent lignite fly ash (118). In their questionnaire response, the North Dakota Department of Transportation makes no reference to any use of fly ash as a component of stabilized base construction.

Ohio

There have been in excess of one million tons of lime-fly ash-aggregate base placed in municipal and commercial projects in and around the City of Toledo (J.P. Nicholson, N-Viro Energy Systems. Private Communication). During the 1970's, lime-fly ash base was used on eight primary state highway projects in Ohio. There is no mention of such use of fly ash in Ohio's questionnaire response.

Pennsylvania

Aggregate-lime-pozzolan base course materials have been used in hundreds of jobs in southeastern and central Pennsylvania since 1954. Overall, the performance of these materials has been good to very good. However, use of fly ash stabilized base has declined significantly in Pennsylvania during the last 10 to 15 years, due in large part to the need to pave immediately (or as soon as possible) over freshly placed base material, in order to restore traffic volumes with minimal time delay (G. Hoffman, Pennsylvania Department of Transportation. Private Communication). Since there has been virtually no placement of fly ash stabilized base material in the past several years, no mention of these types of applications was made in the Pennsylvania Department of Transportation questionnaire response.

Tennessee

The Tennessee Department of Transportation was also a participant in the FHWA Demonstration Project No. 59 program. In 1982, a 2.3 mile section of State Route 63 was constructed using a lime-fly ash-aggregate base course. There is no mention of stabilized base course as an application for fly ash in Tennessee's response to the state questionnaire. The only fly ash use denoted by Tennessee is as a cement replacement in concrete.

Texas

In 1980, the Texas Department of Highways used mixed in place methods to stabilize the top 6 inches of an 18 inch thick river gravel base on U.S. Route 87 in Wilson County using 1.5 percent lime and 6 percent Class C fly ash. In 1960, an access road in Rockdale, near an Alcoa Company plant, was built with a 6 inch thick lime-fly ash-boiler slag base (B. Bannister, Texas Department of Highways and Public Transportation. Private Communication). In this case, the fly ash used was more than likely a Class F fly ash. The Texas Department of Highways, in their questionnaire response, indicates that fly ash has been used as a soil stabilizer, but does not specifically mention base course use. They do, however, cite base course material as an application for bottom ash, not necessarily in stabilized base, and note that there has been limited use, but no problems.

Virginia

In 1982, the Virginia Department of Transportation constructed a lime-fly ash-aggregate base course on 1.5 miles of the Dulles Airport highway extension in Fairfax County. This project was included in FHWA's Demonstration Project No. 59 program. Fly ash was also used to stabilize several different forms of sulfate waste in a portion of the parking lot at Dulles Airport in 1972, as part of the Transpo 72 exposition. Fly ash is mentioned only for use in pavements, presumably in concrete, in the Virginia response to the state highway agency questionnaire.

Wyoming

The State of Wyoming has used Class C fly ash in cement-fly ash-aggregate base courses because of favorable economics, high in-place strength, and the opportunity to utilize marginal aggregates. Typically, most base mixes use 4.8 to 6.4 percent portland cement and 1.6 to 3.2 percent Class C fly ash, based on dry aggregate weight, with the mixes being produced in a central mixing plant (119). The Wyoming Department of Transportation has indicated in their questionnaire response that fly ash use in cement treated base courses has been very successful and that Class C ash is specified in cement treated bases.

USES FOR RECLAIMED CONCRETE PAVEMENT

General Background

The initial energy crisis in the early 1970's awakened most Americans for the first time to the importance, if not the necessity, of conserving finite material and energy resources to the maximum extent. Members of the technical community suddenly recognized the need to reassess traditionally accepted, but inherently wasteful, design concepts and construction practices, primarily with an eye toward maximizing energy savings.

In November of 1975, the Federal Highway Administration, the Energy Research and Development Administration, and the Federal Energy Administration sponsored a three-day workshop on Optimizing the Use of Materials and Energy in Transportation Construction, which was conducted by the Transportation Research Board. This workshop was attended by 54 representatives of state transportation departments, federal governmental agencies, material suppliers, trade associations, equipment manufacturers, and the academic community. Seven basic topic areas were addressed, including production and construction techniques, and the use of waste materials, by-products, and recycled products. A special report was published by the Transportation Research Board containing the proceedings of this workshop (120).

Although not all materials and/or pavements are suitable for recycling, one of the principal conclusions from the workshops was that recycling of pavement materials is one of the more promising material and energy conserving techniques available to transportation engineers. By reusing old pavement materials removed during reconstruction, the energy required to transport these materials to a disposal site and then haul new materials back to the job site can be saved. Moreover, the materials themselves are a recyclable resource whose reuse significantly reduces the traditional need to supply all new aggregate and binder materials for a reconstruction project.

The earliest experience with recycling old concrete probably occurred in post-World War II Europe, where massive piles of building rubble were recovered and processed into concrete aggregate for reconstruction of war ravaged European cities. However, once the rebuilding programs were over, the recycling of concrete and rubble was generally abandoned. In the United States, pavement recycling was not attempted until the early 1970s. Some of the earliest reported efforts to reuse processed building and paving rubble, starting around 1970, involved using the recycled aggregate material as unbound base material and in asphalt base and binder courses. Within a couple years, recycled concrete aggregate was also being used in asphalt wearing surface mixes.

During the early 1970s, materials research programs were being sponsored by numerous organizations, including the Federal Highway Administration, the Army Corps of Engineers, and several state transportation departments, to determine the suitability for recycling concrete pavement material as aggregate in new concrete mixes. Some of the most significant findings from these research efforts included the following:

1. Coarse aggregate particles produced from crushed reclaimed concrete have good particle shape, high absorption, and lower specific gravity compared to conventional mineral aggregates.

2. Use of crushed concrete as coarse aggregate had no significant effect on the mix proportions or workability of concrete mixtures compared to that of mixtures using conventional aggregates.

3. Use of crushed concrete as fine aggregate resulted in less workable mixtures, requiring more cement due to an increased water demand. Substitution of natural sand for all or a major portion of the fine aggregate was required to produce a workable concrete.

4. Aggregate recycled from low strength concrete is not detrimental to the compressive strength of concrete mixtures that contain this aggregate.

5. The durability of concrete made with aggregate produced from concrete subject to D-cracking can be substantially improved by recycling. Freeze-thaw testing should be done in order to determine whether durable concrete can be produced.

6. The use of water-reducing admixtures is effective in increasing strengths of concrete mixtures containing recycled concrete aggregate. Air-entraining admixtures and fly ash are used to provide durability and improve the workability of concrete made from recycled aggregates (121).

Between 1975 and 1980, a number of concrete pavement recycling projects were successfully completed in locations throughout the United States. States that were early pioneers in the recycling of old concrete pavements into new concrete pavements were Iowa, Illinois, and Minnesota. In 1975, California became the first state to recycle a reclaimed concrete pavement into econocrete (lean concrete base). During this time period, much was learned about different types of equipment and techniques for pavement breaking and separation of reinforcing steel, mesh, or asphalt overlay from the concrete prior to crushing and sizing, as well as cost savings from recycling (121).

In 1980, Minnesota was the first state to undertake the recycling of a D-cracked concrete pavement. Trial mix designs for this project indicated that replacement of 15 percent cement with 20 percent fly ash showed a greatly reduced potential for future D-cracking. Also, crushed reclaimed concrete aggregate finer than the No. 4 sieve was found to be very angular, resulting in an increased water demand. For this reason, natural sand was used with the recycled coarse aggregate. The success of this

project demonstrated that old D-cracked pavements are prime targets for recycling, especially in areas where good quality aggregates are not available (121).

During the 1980s, hundreds of concrete pavement recycling projects were undertaken throughout the country. These projects included airfield as well as highway pavements. Among the leading states in employing recycling techniques to the rehabilitation of old concrete pavements are Michigan, Wisconsin, Iowa, Minnesota, North Dakota, Wyoming, Texas and Oklahoma (121). Recycling projects in these and other states involved reuse of old concrete as coarse aggregate in new concrete pavements, shoulders, and econocrete bases; as aggregate in cement-treated base courses; as aggregate in open graded or unbound bases and subbases; and as riprap and rock base material for embankments. Reclaimed concrete pavement has also been successfully recycled into asphalt paving mixes (122).

Valuable information has been learned and disseminated to the concrete paving industry from more than twenty years of concrete pavement recycling experience. During this time, avoidance of landfilling has become almost as strong an incentive to recycle as cost and energy savings. In addition to improved material preparation and concrete mix design refinements, much has been learned about recycling of distressed concrete pavements from deicing salts or alkali-aggregate reaction. Although much technical data is available on the properties and mix proportions for using recycled concrete aggregate, the final determining factor for selecting recycling as a pavement rehabilitation strategy will almost always be economics. The most effective approach for evaluating the comparative cost effectiveness of different rehabilitation strategies is life cycle cost analysis (122).

Current Practice

A review of technical literature and responses from state highway agency questionnaires indicates that at least 20 states have had experience with the recycling of reclaimed concrete pavement (RCP) into one or more of the above noted applications. A brief discussion of the experiences of each of these selected states is given in the following paragraphs.

Arizona

Reclaimed concrete pavement has been very successfully used in new concrete as well as base materials in Arizona. No further details are available concerning specific projects.

California

Caltrans has reported that broken concrete has been used in aggregate base courses, cement treated bases, and as aggregate in portland cement concrete. Performance is reported as satisfactory. In their questionnaire response, Caltrans also noted that broken concrete is among several waste materials or by-products (including RAP and scrap tires) that have been legislated for reuse by Assembly Bill 1306.

Connecticut

The Connecticut Department of Transportation has successfully used reclaimed concrete pavement (RCP), broken concrete, and demolition rubble as aggregate materials. Reclaimed concrete pavement has been recycled into new concrete and as a subbase material. Broken concrete and demolition debris have been recycled as borrow material, gravel fill, subbase, and processed aggregate base (123). All of these uses are successful. Demolition debris and reclaimed concrete pavement have been mandated for recycling by Connecticut Public Acts 88-231 and 89-386.

Florida

Crushed RCP material is allowed as an aggregate in asphalt concrete paving mixtures. The Florida Department of Transportation has conducted a series of experiments to evaluate the use of aggregates made from crushed portland cement concrete and have concluded that sound concrete can be crushed and recycled into satisfactory aggregate products. No specific information on projects was indicated.

Indiana

The Indiana Department of Transportation has researched reclaimed concrete pavement aggregate for use in new concrete pavement, base and subbase material. To date, the research work has not been completed and results are inconclusive.

Iowa

In their response to the state highway agency questionnaire, the Iowa Department of Transportation has indicated that reclaimed concrete pavement (RCP) material is routinely used in base courses and in concrete pavements. The performance of RCP aggregate in these applications is described as being very similar to virgin materials. Iowa is one of the leading states in the recycling of portland cement concrete pavements.

Kansas

The Kansas Department of Transportation's response to the state highway agency questionnaire indicates the reclaimed concrete pavement (RCP) has been investigated and used as an aggregate in portland cement concrete pavement, cement treated base, and bituminous base for shoulder construction. To date, the results of these RCP aggregate applications have all been inconclusive.

On one of the first Kansas concrete pavement recycling projects, the contractor encountered difficulty separating wire mesh from the old concrete. This resulted in higher crushing costs for the recycled pavement compared to the crushing of virgin aggregate. Use of RCP aggregate in cement treated base and portland cement concrete pavement worked well, but the bituminous shoulder base was more difficult to work with and place because of too much large size aggregate (121).

Louisiana

According to the state highway agency questionnaire responses, Louisiana has utilized recycled portland cement concrete as an aggregate for new portland cement concrete, as well as for base courses. Both of these applications are successful.

Maryland

The Maryland Department of Transportation has used reclaimed concrete as a subbase material. The Department considers this material acceptable and has rated its use as successful.

Michigan

The Michigan Department of Transportation has indicated construction use of recycled concrete both in concrete pavements and in open graded drainage subbase courses. The performance of RCP aggregate in concrete pavements is indicated in the state highway agency questionnaire to be from fair to poor, although no specific problems are noted. The performance of RCP aggregate in open graded drainage courses is still inconclusive, although it is noted that the RCP aggregate used in this application must be asphalt coated.

During the early to mid 1980's, the Michigan Department of Transportation recycled several sections of concrete pavement on Interstate highways, specifically, Interstate 94 and Interstate 75. On these projects, it was discovered that complete coordination is required between the processing of coarse aggregate from crushed concrete and the production rate of the concrete paving machine. The type of crushing equipment and the type of aggre-

gate used in the original pavement are major factors to consider. Tests results show recycled concrete to have high durability, but mixes with a high proportion of crushed concrete in the fines have lower strengths than desired (121).

Minnesota

As noted previously, the Minnesota Department of Transportation was the first state to recycle D cracked concrete pavement. In their response to the DOT questionnaire, only the use of recycled concrete as a base material is mentioned. With respect to performance, there is only a mention about a concern for calcite buildup in the roadway drainage system when using recycled concrete base.

Missouri

The Missouri Highway and Transportation Department, in their response to the state highway agency questionnaire, had indicated that their use of reclaimed concrete pavement (RCP) material has included only fill material and riprap uses to date. The performance of RCP aggregate in these particular uses was indicated as favorable in the questionnaire response.

Montana

In their questionnaire response, the Montana Department of Transportation notes the use of recycled concrete pavement and states that performance has varied widely, with some projects being quite successful and others not. No further details were provided.

Nebraska

The Nebraska Department of Transportation has recycled portland cement concrete into aggregate for use in base courses, as well as in asphaltic concrete. Their usage of RCP aggregate in these applications has met with generally good success and overall performance is considered acceptable for these uses.

New York

The New York State Department of Transportation routinely uses broken concrete as stone fill and for channel protection with very good results. Demolition debris has been used as common borrow, although its use environmentally is questionable. Reclaimed concrete pavement (RCP) material has been routinely used as granular subbase aggregate and in recycled concrete pavement on an experimental basis. Granular subbase has performed excellently. Recycled concrete pavement has provided fair service to date.

North Dakota

Although not noted in their questionnaire response, North Dakota has had previous experience in concrete pavement recycling. The North Dakota Highway Department has completed at least eight recycling projects on Interstate 9 and Interstate 29 through 1988. Tests have shown that crushing potential D-cracking aggregate will reduce the D-cracking once it is recycled. Continuously reinforced concrete can be broken and recycled with nearly all reinforcing steel removed. Crushed concrete fines can be mixed with salvaged bituminous pavement to make a very good base course (121).

Oklahoma

The Oklahoma Department of Transportation has recycled RCP aggregate into new concrete pavements. In their questionnaire response, it is noted that concrete pavement recycling is now being done routinely with acceptable performance results.

Pennsylvania

In Pennsylvania, reclaimed concrete aggregate has been successfully utilized as fill material, subbase material, and as coarse aggregate in concrete pavements. Overall use in these applications is described as limited, with performance characterized as fairly successful.

Texas

In their questionnaire response, the Texas Department of Transportation has indicated research of crushed concrete as a base material being potentially acceptable. No mention is made in the questionnaire response concerning the Department's prior experience in using reclaimed concrete pavement (RCP) aggregate for pavement recycling and other applications.

One of the first concrete pavement recycling projects in the United States took place at Love Field in Dallas during 1964. A new 8800 foot long runway, parallel taxiway and apron, and an extension of an existing 4500 foot long runway were built on a 6 inch cement treated subbase using 72 percent crushed concrete from old pavements and 28 percent natural sand (121).

Wisconsin

The Wisconsin Department of Transportation does not specifically indicate use of reclaimed concrete pavement (RCP) materials in their questionnaire response. However, according to NCHRP's Synthesis of Highway Practice 154, Wisconsin has completed more than a dozen concrete pavement recycling projects during the mid 1980's alone. Tests on concrete specimens made with recycled concrete aggregate indicated that this concrete would be as durable as concrete made with natural aggregates. Many recycled concrete mixtures actually exhibited better durability than concrete with all natural aggregate. So far, no recycled concrete has been rejected as a source of concrete aggregate (121).

Wyoming

The Wyoming Department of Transportation has recycled concrete pavement materials on a fairly routine basis. Concrete pavement recycling is described as successful and is considered an option by the Department for all portland cement concrete pavement rehabilitation projects.

FLY ASH IN CONCRETE AND FLOWABLE FILL

General Background

The use of fly ash as an admixture in portland cement concrete dates back at least 60 years to a time when the U.S. Bureau of Reclamation first began adding fly ash to concrete in large dams in order to reduce the heat of hydration. Many of the biggest concrete dams in the western United States, including Hoover Dam, contain fly ash, much of which during the 1930s through the 1950s had to be shipped by rail from power plants in the Chicago metropolitan area.

As noted in the previous section on base courses, Class F fly ash is technically termed a "pozzolan." This term refers to a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in a finely divided form and in the presence of moisture, react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Calcium hydroxide is liberated during the hydration of portland cement and pozzolans combine with this liberated calcium hydroxide to form stable cementitous compounds which contribute to strength and water tightness in a concrete mix.

In order to be suitable for use as an admixture in concrete, fly ash must meet the physical and chemical requirements of ASTM Specification C618. This specification differentiates between Class F and Class C fly ashes, based on the nature of the coal from which the ash is derived. Class F ash is derived from the burning of subbituminous and lignite coals. Generally, Class F ash is higher in silica and alumina and low in calcium, while Class C ash has somewhat lower silica and alumina with more moderate amounts of calcium compounds. As a result, many Class C ashes are hydraulic or cementitious, in addition to being pozzolanic.

Among the many benefits attributed to the use of fly ash in concrete mixes are:

- Improved sulfate resistance
- Reduction of alkali-aggregate reaction
- Greater ultimate compressive strength
- Improved workability
- Lower heat of hydration
- Easier pumping and placement
- Reduced permeability and steel corrosion (124)

Perhaps the most attractive benefit of using fly ash in concrete is the potential cost savings of replacing cement with fly ash. Depending on logistics and local material costs, savings in the $1.00 to $2.00 per cubic yard range are possible when using fly ash (120).

Despite these benefits, the use of fly ash in concrete also has some possible drawbacks, including the following:

- Fluctuations in entrained air content
- Possible lower early strength development
- Slower initial setting time
- Possible seasonal limitations (124)

There are two concepts of including fly ash in a concrete mix. One concept involves replacement of part of the portland cement in the mix with fly ash. The second concept involves adding the fly ash to the portland cement as an admixture. In the first case, the plain concrete and the concrete with fly ash will probably achieve roughly the same strength after 28 or more days of curing. In the second case, the concrete with the fly ash added will probably remain higher in compressive strength than the plain portland cement concrete. Normal replacement or admixture percentages for fly ash in concrete range from 15 to 25 percent by weight of the portland cement in the mix. The performance of the concrete where 20 percent Type I cement has been replaced by 20 percent fly ash should be about the same as when Type I-P (portland-pozzolan) cement, containing about 20 percent fly ash interground with the cement, is used (125).

When designing a concrete mix incorporating the use of fly ash, the general rule is to replace one pound of portland cement with 1.25 pounds of Class F fly ash, or with 1 pound of Class C fly ash (126). This method of replacement will give workability and strength that is different to obtain without a material having fine siliceous particles. The fine particle sizing and spherical particle shape of fly ash gives mobility to cement particles and the relatively high surface area of the fly ash particles chemically react to form cementitious materials. There are a great many approaches for proportioning concrete, none of which has found total acceptance.

One of the main concerns of users of fly ash in concrete is the potential variability of fly ash due to variations in coal composition, furnace combustion conditions, and ash collection systems. The best indicators of potential variability are the loss on ignition and fineness (127). Most sources that sell fly ash to meet ASTM C618 requirements monitor these two characteristics on a frequent, if not daily, basis. The amount of unburned carbon and the specific surface area are the two characteristics that best correlate with the development of pozzolanic activity in fly ash (127).

Among the more recent developments in using fly ash in concrete are the increased use of Class C fly ash, especially in high strength concrete; the increased use of fly ash with chemical admixtures; and high volume fly ash concrete. The use of a good quality fly ash is essential in the production of high strength concrete, because strength gains achieved with the addition of 20 to 30 percent fly ash cannot be attained with additional cement. Because Class C fly ash has some cementitious properties, as well as pozzolanic properties, high strengths (in excess of 8,000 psi) are possible by adding 250 to 300 pounds per cubic yard of Class C fly ash in concrete having 600 pounds per cubic yard of Type I cement (128). Laboratory trial batches are the most effective way of establishing mixture proportions for fly ash concrete mixes, especially high strength concrete for specific projects.

Recently, researchers have found that superplasticizers can be used with high volume Class F fly ash in concrete that can be proportioned to attain 28 day strengths ranging from 5,000 to 8,700 psi, suitable for structural grade concrete. The addition of low alkali Class F fly ash in concrete increases the durability of concrete to alkali-silica reaction, and also reduces concrete permeability. To optimize these characteristics, laboratory experiments were conducted on concrete mixes incorporating fly ash at various percentages of cement replacement ranging from 40 to 60 percent. A melamine based superplasticizer was used in the trial mixes, with dosages varied to achieve desired workability while maintaining a consistent ratio of water to cementitious material. Concrete containing fly ash up to 60

percent replacement developed 28 day compressive strengths in excess of 4350 psi. Based on these tests, it was concluded that it is possible to proportion superplasticized concrete containing fly ash at cement replacement ratios up to 60 percent to meet the strength and workability requirements for structural grade concretes (129).

A very useful adaptation of fly ash in concrete is the utilization of fly ash in flowable fill or slurry fill mixes. Flowable fill is a fluid or semi-fluid material consisting of a mixture of fly ash, water and portland cement. In some applications, sand and/or bottom ash is also added to the mixture. Flowable fill is essentially a high slump, low density, lean concrete slurry. Flowable fill materials can be placed either by pumping, like a grout, or by pouring, like a wet concrete mix. These materials flow like a liquid, then set up like a solid.

Most flowable fill mixes contain from 3 to 15 percent portland cement by dry weight. In most mixes, the only other solid material used is fly ash, although some fine aggregates (such as bottom ash or sand) are occasionally added to a mix to impart additional strength. Normally, the initial setting characteristics of a flowable fill mix are determined mainly by the percentage of portland cement in the mix. Once the initial set of the material is achieved, the flowable fill will continue to experience steady low to moderate strength gains due to the pozzolanic reaction.

Flowable fill materials are usually placed at a solids content ranging from 60 to 70 percent. Depending on the cement content, the time of initial set may vary from 2 to 6 hours. The unconfined compressive strength of flowable fill after setting is directly related to the cement content. At lower cement contents (3 to 5 percent), the unconfined compressive strength after 28 days is normally in the 75 to 150 psi range. Addition of aggregate (sand, gravel or bottom ash) to a flowable fill mix results in an increased strength development of several hundred psi after 28 days (130).

Flowable fill mixes ordinarily exhibit some additional but limited strength development between 2 and 90 days and very little in the way of strength development beyond 90 days. Materials with an ultimate strength of approximately 150 psi are more than twice as strong as well compacted granular soils, but are still capable of being removed by backhoe. Flowable fill materials are heaviest when wet, but after setting, they have a density that is considerably lighter than most soils, usually in the range of 75 to 100 pounds per cubic foot (130).

Flowable fill is a versatile construction material that has been used in a wide variety of applications including:

- Slurried backfill for walls, culverts and pipe trenches
- Slurried backfill for bridge abutments and retaining walls
- Filling abandoned underground structures or void spaces
- Low density fill material adjacent to existing foundations
- Grouting to fill voids or to reduce seepage

The use of fly ash based flowable fill materials offers a number of advantages compared to the use of conventional earth fill materials that require controlled compaction in layers. These advantages include, but are not necessarily limited to, the following:

- Reduced construction time and labor costs
- Ease of mixing and placement with normal equipment
- Ability to flow into hard to reach places
- Material that is self leveling following placement
- Negligible settlement once the material has hardened
- Set time so that men can work on the surface the same day
- Strength that can be adjusted to suit job requirements
- Weight that is lighter than natural earth materials
- Environmentally acceptable leachate characteristics
- Ability to be placed under adverse weather conditions

Flowable fill materials, although having numerous advantages, also have some limitations that include:

- Frost susceptibility of low strength mixes
- Need for confinement until initial setting
- Mixes with higher than 150 to 200 psi compressive strength cannot be re-excavated
- Consideration for lateral pressure in fluid condition may require backfilling in layers
- Lighter weight pipes must be anchored or tied down

The material characteristics that have the most influence on the behavior of flowable fill mixes are:

- Cement Content
- Moisture Content
- Fluidity
- Time of Set
- Unconfined Compressive Strength

Current Practice

Fly ash is produced at coal-fired utility power plants in 45 different states. The use of fly ash as a partial replacement for portland cement in concrete is specified in 46 states. The only non-ash producing state that does specify fly ash in concrete is California. The four states that do not specify fly ash in concrete are Alaska, Hawaii, Idaho, and Maine.

As a result of a survey of the states that do specify fly ash in concrete, it has been determined that a total of 39 state highway or transportation agencies are actually using fly ash as a partial cement replacement. There are six states that specify fly ash for this application, but for one reason or another have not as yet utilized fly ash in concrete. In several of these states, contractors have either not bid the material or have bid the material, but have not been awarded the job. In one of two states, the available supplies of fly ash have not been fully in compliance with the specification requirements. The six states that specify, but do not use, fly ash in concrete are Connecticut, Delaware, Kansas, Massachusetts, Rhode Island, and Vermont.

Of the 44 states that produce coal ash, approximately half of these states have sources of both Class C and Class F ash in their state. Not all fly ash is capable of satisfying ASTM C618 specification requirements for use in concrete. However, for the 39 states that do use fly ash in concrete, the reported distribution of the class of fly ash used is as follows:

- 7 states use strictly Class F ash
- 6 states use strictly Class C ash
- 11 states use both types, but primarily Class F
- 7 states use both types, but primarily Class C
- 8 states use both types in approximately equal amounts.

Fly ash is also used with portland cement in grout and flowable fill applications. A total of 30 states have reported using flowable fill mixes, although 5 of these states indicate that they still consider the use of this material in highway construction projects to be experimental. In addition, only 5 of these 30 states have flowable fill mixes in which fly ash is the principal component instead of concrete sand. In most states, sand comprises between 2000 and 3000 pounds per cubic yard of mix, while fly ash generally comprises between 250 and 500 pounds per cubic yard. Flowable fill mixes containing just fly ash and cement with water normally have between 2000 and 2200 pounds of fly ash, with cement contents usually around 5 percent by weight of fly ash, depending on strength requirements (which are generally low). Water is added in sufficient quantity to produce an 8 to 10 inch slump for ease of placement. The five states with flowable fill mixes containing no sand or other fillers include Delaware, Maryland, Michigan, Pennsylvania, and Wyoming.

One page follow-up questionnaires were sent to the 45 states that specify fly ash for use as a partial replacement for portland cement in concrete. The questionnaire asked if each state also permitted the use of fly ash as a raw material in the manufacture of portland cement and as an ingredient in portland pozzolan (Type I-P) cement and what class on classes of fly ash are used in each state. The questionnaire also sought information on what applications are and are not allowed in each state's specifications, and which are either routine or experimental. The following concrete applications were surveyed:

Type of Concrete	Specific Applications
Structural	Foundations Abutments & Piers Retaining Walls Beams & Parapets Bridge Decks
Paving	Roadway Slabs Concrete Shoulders Roller Compacted Slab Grouting
Precast	Medial Barriers Proprietary Walls Noise Walls Box Culverts Concrete Piles Inlets and Manholes
Incidental	Curbs & Sidewalks Divider Islands Channel Linings Headwalls

Table 1 provides a summary of state transportation agency experience in the use of fly ash in concrete, including the use of fly ash in flowable fill. This table indicates which cement replacement applications have been used in each state, which class of fly ash is used in each state, which concrete applications are not allowed in state specifications, which states use flowable fill, and the mix proportions of the flowable fill mix primarily used in each state. Table 1 was developed based on questionnaire responses received from the 45 states which specify fly ash in concrete.

Of the 39 states that are actually using fly ash in concrete, all 39 use fly ash as a partial replacement for portland cement. In addition, 20 states have specifications that permit the use of Type I-P (portland-pozzolan) cement and 7 states also permit the use of fly ash as an allowable raw feed material for the production of portland cement at the plant.

TABLE 1

Summary of State State Highway Agency Experience in the Use of Fly Ash in Concrete

	Fly Ash Applications			Class of Fly Ash Used			Uses of Fly Ash in Concrete That Are Not Allowed in Specifications	Use of Flowable Fill	Flowable Fill Proportions		
	Cement Raw Material	Type I-P Blended Cement	Cement Replace-ment	Class F	Class C	Both			Fly Ash (lbs/c.y.)	Cement (lbs/c.y.)	Sand (lbs/c.y.)
1. Alabama			X			X[1]		X	572	195	2673
2. Alaska											
3. Arizona		X	X	X							
4. Arkansas			X		X		Bridge Decks	X	260	90	varies
5. California		X	X	X							
6. Colorado			X			X		X	300	100	2600
7. Connecticut				None			Box Culverts, Piles				
8. Delaware				None				X*		100	-
9. Florida	X	X	X			X[1]	Curbs & Sidewalks*	X*			
10. Georgia	X		X			X[1]		X*	300	100	2100
11. Hawaii											
12. Idaho											
13. Illinois			X			X[2]		X	300	50	2900
14. Indiana	X	X	X			X		X	330	60	2860
15. Iowa	X		X			X[1]		X	300	100	2600
16. Kansas			X*		None			X	900	600	1200
17. Kentucky		X	X			X[1]	Bridge Decks, Precast*	X	300	50	2750
18. Louisiana		X	X			X[2]					
19. Maine											
20. Maryland		X	X	X			Bridge Decks*	X	1560	82	-
21. Massachusetts				None							
22. Michigan		X	X			X[1]		X	500	50	2850
23. Minnesota		X	X		X			X	250	125	varies
24. Mississippi		X	X			X[2]	Proprietary Walls				
25. Missouri		X	X			X		X	250	100	varies

* Allowed, but considered experimental. [1] Predominantly Class F ash used. [2] Predominantly Class C ash used.

TABLE 1 (cont.)

Summary of State Highway Agency Experience in the Use of Fly Ash in Concrete

	Fly Ash Applications			Class of Fly Ash Used			Uses of Fly Ash in Concrete That Are Not Allowed in Specifications	Use of Flowable Fill	Flowable Fill Proportions		
	Cement Raw Material	Type I-P Blended Cement	Cement Replace-ment	Class F	Class C	Both			Fly Ash (lbs/c.y.)	Cement (lbs/c.y.)	Sand (lbs/c.y.)
26. Montana	X	X	X			X	Structural Concrete	X			
27. Nebraska			X		X			X	200	50	2600
28. Nevada		Natural	X	None							
29. New Hampshire			X								
30. New Jersey		X	X	X			Curbs, Sidewalks, Medians	X			
31. New Mexico		X	X	X							
32. New York			X	X				X	425	200	2500
33. North Carolina			X			X[1]		X*	400	75	
34. North Dakota			X		X		Structural Concrete				
35. Ohio		X	X			X[1]		X	250	100	2850
36. Oklahoma			X		X			X	250	50	2910
37. Oregon			X			X[1]	Piles*				
38. Pennsylvania		X	X			X[1]		X	300	100	2600
39. Rhode Island				None							
40. South Carolina	X	X	X	X				X	400	100	2900
41. South Dakota			X		X			X	300	100	2600
42. Tennessee			X			X[1]					
43. Texas		X	X			X	Beams, Parapets, Piles*				
44. Utah	X		X			X	Class C Ash - Pipe Only	X	350	60	varies
45. Vermont			X*	None							
46. Virginia		X	X	X				X	1000	50	2000
47. Washington			X			X[1]		X*	250	50	2700
48. West Virginia			X	X				X	1200	282	1460
49. Wisconsin		X	X		X						
50. Wyoming			X			X[2]		X	30	100	varies

* Allowed, but considered experimental. [1] Predominantly Class F ash used. [2] Predominantly Class C ash used.

Besides the information presented in Table 1, certain states also provided further remarks or other information on their questionnaires. This further information is briefly discussed in the following paragraphs for states that filled in the remarks column of the questionnaire.

Alabama

Alabama uses both Class F and Class C ash in concrete, but Class F ash is required in salt water environments. Alabama actually has 5 different flowable fill mix designs. The middle mix design (mix 3) proportions are shown in Table 1. Only three of the five flowable fill mix designs contain fly ash.

Arizona

Both Class F and Class C ash are available in Arizona. Class C ash is used only in the private sector, not by Arizona Department of Transportation, which uses only Class F ash.

Arkansas

Although Arkansas has only Class C ash produced in the state, both Class F and Class C are allowed to be used on concrete, but the two ashes must not be mixed. Thus far, Arkansas only has experience with Class C ash. It was noted in the questionnaire response that bridge decks using fly ash concrete are presently disallowed, due to a cracking investigation.

Florida

The Florida Department of Transportation considers fly ash concrete experimental when used for inlets and manholes, curbs and sidewalks, and divider islands. Class F fly ash was used as a partial cement replacement for the construction of the Sunshine Skyway Bridge in Tampa Bay.

Georgia

The Georgia Department of Transportation has used flowable fill as a maintenance item on a limited basis. About 85 percent of all fly ash used in concrete is Class F ash.

Iowa

The Iowa Department of Transportation uses nearly all Class C ash in concrete. Applications in which fly ash is not allowed in the Iowa DOT specifications include beams and parapets and all forms of precast concrete, including medial barriers, proprietary walls, noise walls, box culverts, concrete piles, inlets and manholes.

Kansas

The Kansas Department of Transportation has not as yet used fly ash in concrete or flowable fill on any state jobs, although there has been some use of fly ash in concrete by private industry. Kansas has used bottom ash in flowable fill mixes in lieu of sand. The optimal supplementary physical requirements of ASTM C618, Table 4, are specified for fly ash use in flowable fill mixes. So far, no fly ash has met these requirements.

Kentucky

Among the fly ash concrete applications considered experimental by the Kentucky Department of Transportation are beams and parapets, bridge decks, roller compacted concrete, and all precast concrete uses cited above.

Maryland

The only fly ash concrete application cited as experimental by the Maryland Department of Transportation is its use in bridge decks.

Michigan

About 80 percent of the fly ash used in concrete by the Michigan Department of Transportation is Class F ash. The only concrete applications in which fly ash is routinely used are roadway slabs and shoulders. There are three flowable fill mix designs used in Michigan, as follows:

	Fly Ash	Cement	Sand	Water
Class C	200	--	3300	320
Class F	500	50	2850	320
Class F	2000	100	--	600

Minnesota

All available fly ash used in concrete in Minnesota generally meets specifications for both Class C and Class F, but really is only Class C ash. Both sand and rock are used with cement and fly ash in flowable fill mixes.

Mississippi

The only concrete application in which fly ash is not specified by the Mississippi Department of Transportation is in precast proprietary walls. Roller compacted concrete is not used in Mississippi.

Missouri

In addition to partial replacement of portland cement, fly ash is allowed by the Missouri Department of Transportation as an ingredient of Type I-P interground cement. Although fly ash is permitted to replace up to 15 percent by weight of portland cement, it cannot be used as a replacement for Type III, Type I-P or Type I-P (M) cements. Fly ash concrete is routinely used, but is not allowed in paving concrete from October 15th to April 15th.

Montana

The Montana Department of Transportation does not allow fly ash in concrete in its specifications for structural concrete applications, including foundations, abutments and piers, retaining walls, beams and parapets, and bridge decks. Very little fly ash modified concrete is used in Montana, partly because there are only about 100 miles of concrete pavement and partly because of high transportation costs to ship a low density material over long distances.

New Jersey

Concrete applications in which fly ash is not permitted in New Jersey Department of Transportation specifications are precast medial barriers, curbs and sidewalks and divider islands. It is further noted that white concrete items (curbs, medial barriers) are not permitted to include fly ash.

New Mexico

The New Mexico Department of Transportation routinely uses fly ash in concrete in all applications except beams and parapets and roller compacted concrete. Although both Class C and Class F fly ashes are available, only Class F ash is used in concrete. There is a temporary moratorium on the use of Class C ash in concrete, pending further investigation.

North Dakota

The only concrete applications in North Dakota in which fly ash is permitted by specification are roadway slabs, concrete shoulders, and curbs and sidewalks. Only Class C fly ash is used. During 1988 and 1989, an EPRI demonstration project at the Coal Creek generating station near Falterick involved the placement of nearly 24,000 square yards of 8 inch thick concrete pavement in which Class C fly ash replaced 70 percent of the cement (131).

Ohio

Ohio Department of Transportation has two classes of flowable fill, involving the following proportions:

Fly Ash	Cement	Sand	Water
250	100	2850	500
250	50	2910	500

Nevada

Although the Nevada Department of Transportation allows fly ash in concrete in its specifications, none has been used to date. In roadway slabs and concrete shoulders, quite a bit of I-P cement has been used, but this blended cement contains natural pozzolan and not fly ash.

Oregon

In Oregon, the only experimental use of fly ash in concrete is in concrete piles, which are precast, prestressed members. The Oregon Department of Transportation would allow fly ash to be used in concrete piles if the prestressed concrete fabricators were willing to do so. However, they have not in the past and they still consider such use experimental because of the unknown effect on their release strength.

Pennsylvania

The Pennsylvania Department of Transportation allows the use of bottom ash coarse aggregate (10 percent passing 1/2 inch sieve) or fine aggregate (AASHTO No. 10) to be used in lieu of sand in flowable fill mixes. Three different flowable fill mix proportions are given in the Pennsylvania specifications:

Fly Ash	Cement	Sand or Bottom Ash	Water
300	100	2600	7" + slump
2000	100	--	7" + slump
300	150-200	2600	7" + slump

South Carolina

The only fly ash concrete applications that are not used in South Carolina are beams and parapets and concrete piles.

South Dakota

Only Class C ash is being produced in South Dakota. Fly ash is routinely used in roadway slabs, concrete shoulders, flowable fill, and slab grouting, but seldom used in any other applications. The South Dakota Department of Transportation does not allow Class C fly ash in concrete that is in direct contact with soil. Therefore, fly ash is seldom used in structural concrete in South Dakota.

Texas

Fly ash concrete in Texas is still considered experimental when used in beams and parapets, roller compacted concrete, and concrete piles.

Virginia

A blend of cement kiln dust (CKD) and Type F fly ash is approved by the Virginia Department of Transportation for use in all concrete. Roller compacted concrete is not used in Virginia.

Wisconsin

In Wisconsin, where only Class C ash is available, the use of fly ash in concrete is optional in all applications. Fly ash use in concrete is prohibited after the October 1st cut off date for late season work.

Wyoming

Approximately 90 percent of all fly ash used in concrete in Wyoming is Class C ash. Fly ash is required in roadway slabs, concrete shoulders, cement treated base, and slab grouting. Fly ash is allowed, but not required, in almost all structural concrete. Fly ash is allowed in all concrete in Wyoming, unless there is a reason to delete it. Class F fly ash is required for use in concrete where reactive aggregate is used.

AIR COOLED BLAST FURNACE SLAG IN CONCRETE

General Background

Air cooled slag is the product that results when molten slag is deposited in pits or banks for solidification under atmospheric conditions. The slag may be further cooled by water. Air cooled blast furnace slag, after processing by crushing and selective screening, is an all-purpose construction aggregate. This slag has been used extensively as a coarse aggregate in all types of concrete construction. Slag complies with all the technical requirements of ASTM specification C33 for concrete aggregates (132). Air cooled slag, after crushing, has a cubical, angular particle shape with a minimum of flat or elongated particles. The rough vesicular nature of slag provides increased surface area and imparts good interlocking properties. Slag is relatively light in weight, with a density in the range of 70 to 85 pounds per cubic foot. Slag is durable, abrasion resistant, heat and fire resistant, and non-corrosive due to its alkaline nature (133).

Air cooled blast furnace slag has been used in concrete for buildings, bridges, roadways and airport pavements for more than sixty years. Slag has been used extensively as an aggregate in heavily traveled major highways, including considerable mileage on the Interstate system. Many major bridge structures, highways as well as railroads, have utilized air cooled blast furnace slag in the concrete, dating as far back as 1915. Slag concrete has also provided outstanding performance in retaining walls, parking garages, drainage structures, storm sewer piping, and other transportation related applications (134).

Slag concrete compares favorably in strength, both compressive and flexural strength, with that of concrete made with other types of high quality coarse aggregates. Because of the rough, pitted surface of the slag particles, an excellent bond is developed between the cement mortar and the coarse aggregate. There is also compatibility between the cement mortar and the slag aggregate with respect to the expansion coefficient, regardless of temperature variations. Slag concrete is very durable against cyclic freezing and thawing and is generally not susceptible to alkali-aggregate reactivity. Slag concrete is also superior in terms of fire resistance. Underwriters Laboratories tests on 6 inch slabs containing air-cooled slag aggregate justified a 4-hour fire rating (135).

Current Practice

Reference to technical literature, together with responses from the state DOT questionnaires, indicates that air-cooled blast furnace slag is being, or has been, used as a coarse aggregate in concrete mixes in at least twelve different states. A brief discussion of slag concrete use in each of these states is provided.

Alabama

Although no slag use in concrete is indicated in Alabama's response to the state highway agency questionnaire, reference is made in promotional literature from the National Slag Association to the use of air cooled slag to construct the concrete pavement on Route 31, the principal highway between Montgomery and Birmingham. The highway was built in 1953 as a four lane divided freeway and has provided a high level of service (134).

Delaware

In response to the state highway agency questionnaire, the Delaware Department of Transportation has indicated previous use of blast furnace slag in portland cement concrete. Although no further details were provided, the use of slag in concrete was described as very successful.

Illinois

The use of blast furnace slag in concrete was not indicated in the response to the state questionnaire. However, it is known that slag concrete was used to construct a portion of Interstate Route 270 near Edwardsville (134).

Indiana

Slag use as aggregate in concrete pavement was noted in Indiana's response to the state highway agency questionnaire. Indications from the questionnaire are that slag performance has been generally good and that the material is routinely used. A section of Interstate Route 65 south of Gary was built using slag concrete (134).

Kentucky

Slag concrete is among the uses indicated by the Kentucky Division of Materials in their questionnaire response. Concrete performance was described as acceptable, although no additional details were provided.

Maryland

In response to a previous state questionnaire published by Purdue University, the Maryland Department of Transportation indicated that blast furnace slag had been used in portland cement concrete for highway construction (81).

Michigan

The state highway agency questionnaire response from Michigan cites the use of blast furnace slag as a concrete aggregate, noting that the material is acceptable, but is used with restrictions due to freeze-thaw conditions. Slag concrete has been successfully used on U.S. Route 25 near Detroit and on the Fisher Freeway Bridge carrying Interstate Route 75 over the River Rouge in Detroit (134).

New York

New York Department of Transportation has had some cracking problems with blast furnace slag aggregate in concrete pavements, although slag concrete performance in structures has been acceptable. The problems occurred in western New York State, where transverse cracking in slag aggregate pavements was seven times more frequent than in normal concrete pavements. It was recommended at the time that slag be discontinued as a concrete aggregate in that region (136).

Ohio

Although slag use was only indicated in asphalt pavements in the state questionnaire response, it is known that blast furnace slag has been used in concrete pavements in sections of the Ohio Turnpike and in the Inner Belt interchange in Cleveland, as well as in the Conneaut and Brook Park bridges in Cleveland (134).

Pennsylvania

In the questionnaire response from Pennsylvania, slag is noted as having been utilized for all aggregate uses, which would include concrete. Slag concrete has been used to construct many highways and structures throughout Pennsylvania, including State Route 29 near Palmerton and Route 519 in Washington County, near Pittsburgh, which was originally built in 1922. Among the bridges built with slag concrete are the Commercial Street viaduct on the Penn-Lincoln Parkway in Pittsburgh and the Ravensburgh bridge in Clairton (134).

Texas

The Texas State Department of Highways and Public Transportation's response to the state highway agency questionnaire indicates that blast furnace slag is routinely used as an aggregate in concrete with good results.

West Virginia

The West Virginia Department of Transportation has also indicated in their questionnaire response that blast furnace slag is used as a component of concrete and that performance of the concrete has been acceptable.

GRANULATED BLAST FURNACE SLAG IN CONCRETE

General Background

Granulated blast furnace slag is defined as "the glassy, granular material formed when molten blast furnace slag is rapidly chilled, as by immersion in water" (137). Granulated slag has excellent hydraulic properties so that in the presence of water it will set up similar to cement. When properly compacted, granulated slag can be an excellent base material for pavements, parking lots, and airport runways. At present, granulated slag is used mainly in the manufacturing of cement, either as a raw material in the manufacture of portland cement, as a component of blended cement (portland blast furnace slag cement), or as slag cement.

Although granulated slag has been used for many years as a backfill and base material, its use as a cementitious material in concrete mixes has been more recent, dating back approximately ten years to the construction of a modern slag granulation facility by Bethlehem Steel Company at their Sparrows Point, Maryland plant. There are presently only two other sources of granulated slag in the United States -- International Mill Service at Weirton, West Virginia and Standard Slag Company at Lordstown, Ohio (138). The granulated slag from Sparrows Point is shipped to Blue Circle Atlantic's Ravena, New York cement plant, where it is ground into a slag cement product and marketed under a trade name. Due to the acceptance of this product, the American Society for Testing and Materials (ASTM) developed a specification (C989) for blast furnace slag cement (139).

Although the use of granulated blast furnace slag in concrete had been relatively limited prior to the development of ASTM C989, there was some use of ground granulated slag in blended cement. There has long been a provision in the ASTM C595 specification for the blending of granulated blast furnace slag with portland cement. The specification for Type I-S (portland blast furnace slag) cement calls for intergrinding or blending portland cement with between 25 and 70 percent by weight of finely ground granulated blast furnace slag (140). The C595 specification also calls for a Type I(SM) or slag modified portland cement, in which the slag constituent is less than 25 percent by weight of the blended cement product (140).

The use of ground granulated blast furnace slag cement reportedly imparts a number of superior technical properties to concrete in comparison to ordinary portland cement. Extensive research has shown that resistance to alkali-aggregate reaction in concrete can be enhanced by the use of slag cement. Although slag cement may have alkali (sodium and potassium) levels comparable to those of normal portland cement, the slag cement is vitreous or glassy, which results in a strong bonding effect, restricting the movement of sodium ions. Consequently, while 0.60 percent NA_2O equivalent is an appropriate limit for qualify-

ing portland cements, blended cements or slag cements consisting of a minimum of 50 percent granulated slag are able tp safely control alkali-aggregate reaction with up to 1.0 percent NA_2O equivalent (141).

Although early strength development and setting time are slower for slag cement concrete, strengths after 7 days are generally greater for slag cement concrete, compared to normal portland cement concrete. The ultimate strength of slag cement concrete is usually significantly higher than that of normal portland cement concrete. Furthermore, the sulfate resistance of cement can be appreciably improved through the partial replacement of portland cement by ground granulated slag. Air entrained concretes containing ground granulated slag can be expected to have the same quality air void system and freeze-thaw resistance as would be expected of normal portland cement concrete (142).

The abrasion resistance of concrete containing ground granulated slag is generally inferior to that of concrete made with normal portland cement. However, the chloride ion permeability of concrete decreases significantly when granulated slag is used as a partial replacement for portland cement (143). Lower chloride ion permeability diminishes the corrosion rate of reinforcing steel in concrete.

Current Practice

Granulated blast furnace slag has been used as cement or cement replacement in portland cement concrete in at least four states, according to responses from the state questionnaires. These four states are Maryland, New Hampshire, New York and Pennsylvania. The degree of use in each of these states is discussed further in the following paragraphs.

Maryland

Ground granulated blast furnace slag has been used as a pozzolan in concrete on construction projects in Maryland. Its use has been reported as very successful and is considered as an acceptable substitute or supplement for portland cement.

New Hampshire

Blast furnace slag cement has been researched as a cement substitute in structural concrete in New Hampshire and is considered to be potentially acceptable. According to the questionnaire response, slag cement has not as yet been used in highway construction in that state.

New York

Slag cement has been used in New York State on a field experimental basis. Granuated slag was substituted for 50 percent of the portland cement in two bridges over the Chenango River in 1985, involving 454 cubic yards of concrete. Air contents were somewhat lower, although strength gain was higher than normal (144). Although performance to date was reported as fair, New York DOT still considers the potential acceptability of slag cement as inconclusive at this time.

Pennsylvania

Slag cement was used during 1991 in the construction of the recently completed Vine Street Expressway in Philadelphia. This is believed to be the first construction use of granulated blast furnace slag in concrete in Pennsylvania. There has been insufficient time to assess the performance of this material.

HOT MIX ASPHALT PAVEMENT RECYCLING

General Background

Pavement recycling begins with the removal of a predetermined depth of existing pavement for the purpose of rejuvenating and/or rehabilitating said pavement. For asphalt concrete pavements, this can be accomplished by planing, scarifying, or preferably by grinding or milling the pavement. The removed material, in the case of an asphalt concrete pavement, is then generally mixed at allowed percentages with virgin aggregates in-place or at an asphalt concrete producing plant. At that time, it would be common to add designed amounts of asphalt cement and perhaps a pavement recycling material to the blended mix of Reclaimed Asphalt Pavement (RAP) and virgin aggregate. The mix at this time would be ready for placement and compaction.

Hot mix reclaimed asphalt pavement recycling began to become popular during the mid to late 1970's. Although some limited technology existed prior to this time, the mid to late 1970's was the fertile period during which time the process began to be acceptable and somewhat commonplace. The catalysts for the rapid rise in popularity were threefold. The major reason for the concept of reclaiming and recycling asphalt pavements was the Arab oil embargo. As a result of the embargo, crude oil prices rose very sharply which obviously stimulated the concept of RAP. A second important contributor of this period was the development of the pavement milling machine to a point where it became economically and technically competitive to reclaim asphalt concrete pavements. The third and no less significant reason was that drum mixing plants reached significantly high levels of acceptability within the Hot Mix Asphalt (HMA) industry. The

drum mixer was important in rendering practical the HMA pavement recycling processing since the technology for using a batch mixing process was not available during the seventies. Today, using the Minnesota or other processes, batch plants can also produce quality HMA using RAP as a hot mix constituent.

When combining these three situations to act in unison, reclaiming and recycling asphalt pavements come in direct competition with constructing an asphalt pavement made up of all virgin materials. The Federal Highway Administration (FHWA) in 1976 initiated Demonstration Project No. 39, Recycling Asphalt Pavements. The objective of this project was to promote asphalt pavement recycling and to provide state highway agencies with an opportunity to evaluate various asphalt recycling techniques. Approximately 75 different demonstration projects were conducted involving hot, cold, and in-place recycling. This demonstration program was responsible for development of design and construction guidelines now being routinely used. (T.P. Beatty, Federal Highway Administration. Private Communication.)

By the early to mid 1980's, nearly all the states were in the process of writing and adopting specifications for the production of recycled asphalt concrete pavements using RAP as a significant portion of the hot mix. Two authoritative documents of this period which present the state of the art are NCHRP Report 224, Guidelines for Recycling Pavement Materials (145) and Transportation Research Record 780, Proceedings of the National Seminar on Asphalt Pavement Recycling (146).

Surface recycling of an asphalt concrete pavement is generally defined as recycling of the pavement to a depth of one to one and a quarter inches. Surface recycling can be used to correct pavement problems such as shoving, rutting, slipperiness, or surface cracking. It cannot be used to correct the more serious structural problems of deep cracking or base failures. Hot recycling is the process whereby the RAP material or Reclaimed Aggregate Material (RAM) is combined with new asphalt cement and/or recycling agent and/or new aggregate as designed. This is normally accomplished at a central mixing plant. Cold recycling is a process whereby an existing pavement structure is processed in-place or removed and processed at a mixing plant. The reclaimed materials are cold mixed with added liquid asphalt cement and are generally used to produce a higher strength base course.

Surface recycling is a process which involves either the addition of heat or pavement removal without heat. Additional heat processes include the use of heater-planer, heater-scarifier or hot-milling equipment. Cold processes are either cold-planing or cold-milling. The equipment for those processes are manufactured by a number of equipment manufacturers. The most common process currently in use is the cold milling procedure since no

additional heat or extra cost is involved when milling the pavement. The cold milling process also will usually produce a RAP material which does not need to be crushed prior to re-usage.

Deep pavement recycling can involve the same processes as surface recycling but pavement removal can reach depths of five to six inches. This recycling can correct similar pavement disorders as surface recycling, however, to greater depth. Deep pavement recycling should not be used indiscriminantly as a deep pavement removal may completely destroy the structural integrity of the existing pavement structure.

A very good presentation and in-depth explanation of surface recycling (Chapter Three), In-Place Surface and Base Recycling (Chapter Four), and Central Plant Recycling (Chapter Five) are given in the NCHRP Synthesis Report of Highway Practice, Number 54, entitled "Recycling Materials for Highways" (147). There is a definite need for research on the ability to recycle asphalt pavements that contain recycled rubber from scrap tires. This research needs to take into account the process (wet or dry) and amount of rubber in the RAP.

Current Practice

As of 1991, all the states in the union except for Alaska, have operational specifications for the use of RAP in hot mixed asphalt cement concrete pavements. Alaska has only developmental projects under study with no standard specification at this time.

The variation in maximum percentage of RAP used in a hot mix is segregated as to where the recycled material will be used in the pavement structure and from what type of mix plant facility it originated. The following are the present average maximum percentages of RAP allowed based on the two above cited criteria.

* Batch Plant Recycled Hot Mix

  - 42% Asphalt concrete base course
  - 40% Asphalt concrete binder course
  - 25% Asphalt concrete wearing/surface course

The values shown above were determined from information presented in the October, 1991, issue of Roads and Bridges (148). The average values given in this issue reflect approximately seventy-five percent of the states. The remaining twenty-five percent reflected maximum percentages based on conditions of top size and specific conditions of the source of the RAP and where it is to be used in the pavement structure. These types of criteria cannot be quantified for presentation. It is of note that currently eight states (Hawaii, Maine, Mississippi, Montana, New Hampshire, New York, Rhode Island and Tennessee) as well as the District of Columbia, do not allow any RAP whatsoever to be used in wearing or surface courses. One state, Hawaii, does not

permit any RAP to be used in a binder course. This data also shows that virtually no practical differences exist with regard to allowable percentages based on type of plant mix operation. Table 2 indicates which states permit the use of RAP in various pavement layers. Information on RAP performance is given in Table 3.

As follow-up to the state highway agency questionnaires, all 50 states and the District of Columbia were initially polled to substantiate the current usage and acceptability of RAP material, including whether there are any legislative mandates addressing RAP usage. The results of this poll are summarized in Table 3. There is good agreement between the findings of this poll and the Roads and Bridges information concerning the usage of RAP in pavement recycling. The questionnaire responses indicate that at present five states currently have legislation mandating the use of RAP in highway construction projects. The states with legislative mandates are California, Connecticut, Indiana, Texas, and Washington. There were other states that have indicated that legislative mandates may come into being in the near future.

From the initial questionnaire responses, the following are additional areas of information received in the responses from the states that center on the use of RAP in recycled asphalt concrete pavements.

California

The California Department of Transportation (CalTrans) performed a number of experimental projects on pavement recycling under the auspices of the FHWA during the 1980's. As a result of this work, the use of RAP in recycled asphalt concrete pavements became an acceptable standardized procedure. No current studies on the use of RAP were reported by CalTrans at this time.

Colorado

The Colorado Department of Highways first began experimentation with hot mix recycling back in 1978. Ever since then, Colorado has made extensive use of recycled hot mix asphalt concrete pavements. Colorado is still currently experimenting with in-place hot and cold recycling procedures which will become standardized during this decade.

Table 2. Usage of Reclaimed Asphalt Pavement in Various Pavement Layers - 1991*

STATE	Reclaimed Asphalt Pavement		
	Wearing Course	Binder Course	Base Course
Alabama	Yes	Yes	Yes
Alaska	Yes	Yes	Yes
Arizona	Yes	Yes	Yes
Arkansas	Yes	Yes	Yes
California	Yes	Yes	Yes
Colorado	Yes	Yes	Yes
Connecticut	Yes	Yes	Yes
Delaware	Yes	Yes	Yes
Florida	Yes	Yes	Yes
Georgia	Yes	Yes	Yes
Hawaii	No	No	Yes
Idaho	Yes	Yes	Yes
Illinois	Yes	Yes	Yes
Indiana	Yes	Yes	Yes
Iowa	Yes	Yes	Yes
Kansas	Yes	Yes	Yes
Kentucky	Yes	Yes	Yes
Louisiana	Yes	Yes	Yes
Maine	No	Yes	Yes
Maryland	Yes	Yes	Yes
Massachusetts	Yes	Yes	Yes
Michigan	Yes	Yes	Yes
Minnesota	Yes	Yes	Yes
Mississippi	No	Yes	Yes
Missouri	Yes	Yes	Yes
Montana	No	Yes	Yes
Nebraska	Yes	Yes	Yes
Nevada	Yes	Yes	Yes
New Hampshire	No	Yes	Yes
New Jersey	Yes	Yes	Yes

Table 2 (cont.). Usage of Reclaimed Asphalt Pavement in Various Pavement Layers -1991*

New Mexico	Yes	Yes	Yes
New York	No	Yes	Yes
North Carolina	Yes	Yes	Yes
North Dakota	Yes	Yes	Yes
Ohio	Yes	Yes	Yes
Oklahoma	Yes	Yes	Yes
Oregon	Yes	Yes	Yes
Pennsylvania	Yes	Yes	Yes
Rhode Island	No	Yes	Yes
South Carolina	Yes	Yes	Yes
South Dakota	Yes	Yes	Yes
Tennessee	No	Yes	Yes
Texas	Yes	Yes	Yes
Utah	Yes	Yes	Yes
Vermont	Yes	Yes	Yes
Virginia	Yes	Yes	Yes
Washington	Yes	Yes	Yes
West Virginia	Yes	Yes	Yes
Wisconsin	Yes	Yes	Yes
Wyoming	Yes	Yes	Yes
District of Columbia	No	Yes	Yes

* Source - ROADS AND BRIDGES, October 1991, pp. 26 to 29.

Table 3. Reclaimed Asphalt Pavement (RAP) Usage Using Individual Polling of States - 1991

STATE	STATE COMMENTS	LEGISLATIVE MANDATE
Alabama	Excellent	None
Alaska	Acceptable as a subbase	--
Arizona	Very successful in hot mixes and base materials	--
Arkansas	Acceptable as a recycled pavement	--
California	Acceptable in asphalt concrete & cement treated bases w/mixed success	Yes
Colorado	Acceptable in asphalt pavements w/very successful results	--
Connecticut	Acceptable as reclaimed miscellaneous aggregate w/success	Yes
Delaware	None responsive on returned questionnaire	--
Florida	Acceptable in resurfacing projects w/good success	--
Georgia	Acceptable in hot mix & cold mix recycling w/very successful results at a good cost savings	None
Hawaii	Satisfactory success when used in asphalt treated bases	--
Idaho	None responsive on returned questionnaire	None
Illinois	Used in asphalt concrete wearing, base and subbase courses and as a base course and subgrade/embankment course w/good success	--
Indiana	Routinely used in asphalt concrete pavements w/good success	Yes

Table 3 (cont.). Reclaimed Asphalt Pavement (RAP) Usage Using Individual Polling of States -1991

Iowa	Acceptable as asphalt concrete base or surface courses w/acceptable success	None
Kansas	Acceptable in hot & cold recycled asphalt concrete pavements	None
Kentucky	None responsive on returned questionnaire	--
Louisiana	Acceptable as aggregate in asphalt concrete pavements w/success	--
Maine	Acceptable as a base for new asphalt concrete pavement w/success	--
Maryland	Acceptable in recycled hot mix asphalt w/very successful results	--
Massachusetts	Inconclusive as an aggregate substitute in bituminous mixtures	None
Michigan	Acceptable in open and dense graded asphalt pavements w/excellent results	None
Minnesota	Accepted alternate to virgin hot mix asphalt mixes	--
Mississippi	Acceptable in asphalt binder, leveling and base courses w/good success	--
Missouri	Recycled asphalt pavements are used on a regular basis in recycled asphalt mixtures	--
Montana	Unspecified area of use w/varied success from none to quite successful	None
Nebraska	Acceptable in base courses & asphalt concrete mixes w/good success	None

Table 3 (cont.). Reclaimed Asphalt Pavement (RAP) Usage Using Individual Polling of States -1991

Nevada	Acceptable in recycled asphalt pavements w/good performance	--
New Hampshire	Acceptable as RAP & reclaimed stabilized base w/very good success	None
New Jersey	Acceptable in hot mix asphalt w/successful results	--
New Mexico	Used in recycled asphalt pavement w/excellent success	None
New York	Acceptable in hot and cold recycled asphalt pavements and as a stabilized subbase w/excellent success	--
North Carolina	Acceptable in recycled asphalt pavements successfully for the last 10 years	--
North Dakota	None responsive on returned questionnaire	None
Ohio	None responsive on returned questionnaire	None
Oklahoma	Acceptable in recycled asphalt pavements w/routine success	None
Oregon	Acceptable in cold in-place and hot recycled asphalt concrete w/success	--
Pennsylvania	Acceptable in hot mix asphalt pavements w/regular success	--
Rhode Island	Acceptable in cold in-place and hot mix base and binder courses w/success	--
South Carolina	Acceptable in asphalt concretes w/good success	None

Table 3 (cont.). Reclaimed Asphalt Pavement (RAP) Usage Using Individual Polling of States -1991

South Dakota	Used in cold and hot recycled asphalt concrete mixes w/good success	None
Tennessee	Acceptable in asphalt concrete pavement mix w/success	--
Texas	Used routinely in new hot mix asphalt concrete & bridge use w/success	Yes
Utah	Acceptable in recycled asphalt concrete mixes	--
Vermont	Acceptable in stabilized base course/shoulder paving w/success	None
Virginia	None responsive on returned questionnaires	--
Washington	Acceptable in asphalt concrete pavements w/very successful usage	Yes
West Virginia	Acceptable in asphalt concrete base & wearing courses w/success	--
Wisconsin	Acceptable in asphalt concrete base course	--
Wyoming	Acceptable in hot recycled asphalt pavements w/very successful usage	--
District of Columbia	None	None

Connecticut

The Connecticut Department of Transportation has been continuously involved with a series of investigations dealing with the use of waste materials in highway construction. These investigations began in the early 1980's and several reports of their findings are available, the most recent of which is dated March, 1991. This recent report deals with the past and current use of pavement recycling by the Connecticut Department of Transportation.

Florida

Currently, recycling asphalt pavement is standard practice in Florida. The Florida Department of Transportation, by reclaiming and recycling asphalt concrete pavements, has experienced the following benefits or savings from this process:

* Cost - Approximately $18 million per year in paving material alone
* Energy - Approximately 535 billion BTU's per year
* Aggregate - Approximately 865,000 tons per year
* Asphalt Cement - Approximately 13 million gallons per year

Florida also has experienced additional benefits which are incidental to the rehabilitation of an existing asphalt concrete pavement.

Illinois

The Illinois Department of Transportation reports using approximately 570,000 tons of reclaimed asphalt paving material per year.

Kansas

The state of Kansas has experimental field projects in Scott and Gray Counties which have been monitored and reported upon by the Kansas Department of Transportation. The reports contain data on both hot and cold mix recycling.

Kentucky

At present, the University of Kentucky is researching the use of all roadway materials and new products used in roadway pavement construction, including the usage of RAP.

Maine

Over the last two years, the Maine Department of Transportation has utilized approximately 166,700 tons of hot recycled asphalt pavement. Of this total, approximately sixty percent was virgin material and forty percent was reclaimed asphalt pavement. This material was utilized in three different projects constructed in 1989. No indication was given of the present status of these roadways. In addition, a study dealing with utilizing recyclable materials in construction was initiated in January, 1991.

Missouri

The Missouri Highway and Transportation Department reports using up to 40,000 tons per year of reclaimed asphalt paving as an additive to their wearing courses. They also report that RAP pavements are cost effective, give good performance and are environmentally acceptable.

New Jersey

The New Jersey Department of Transportation is planning to research the use of reclaimed asphalt pavements as aggregate base courses in roadway construction.

New York

Although nothing is currently underway in regard to the use of RAP materials, the New York Department of Transportation did complete research in this area during the 1980's, resulting in the publication of at least two research reports on this subject.

North Dakota

The North Dakota Department of Transportation is planning further research into the of recycling of asphalt pavement materials. No specifics were identified in their proposed research work.

Oregon

Oregon State University is presently conducting research in the area of cold in-place and hot recycled asphalt concretes. No details of this work were provided. The Oregon Department of Transportation has been quite active in researching and studying nearly all the phases of reclaiming and recycling existing asphalt concrete pavements. There have been no less than seven completed studies and ensuing reports dating from 1977 to 1991 on this subject. It is anticipated that the Oregon State study will add to this existing volume of information.

Rhode Island

The Rhode Island Department of Transportation reports that they consume approximately 14,000 tons of RAP per year (consisting of thirty to forty percent recycled hot mix material). Cold in-place recycling is also used whereby the old asphalt concrete pavement is sometimes processed with a gravel subbase. Cold in-place recycling involves approximately 10,000 tons of asphalt pavement per year.

South Carolina

Clemson University is presently conducting experimentation and research in the area of recycled asphalt pavements. No further information on this research program was provided.

Vermont

The Vermont Agency of Transportation is planning future research into the expanded usage of recycled or reclaimed asphalt pavements. No specifics of the research program were given.

Wisconsin

Marquette University is presently engaged in research dealing with recycled asphalt pavements. Also, the Wisconsin Department of Transportation is planning future research in the area using recycled asphalt pavements in wearing courses. No further information was available concerning either research program.

District of Columbia

The District of Columbia is planning research in the area of using reclaimed asphalt pavement material as subbase for roadways. No other details of the research are known.

Current Usage of RAP by State Highway Agencies

In addition to the general information on reclaimed asphalt pavement (RAP) provided in Tables 2 and 3, specific information on RAP quantities and percentages currently being used was requested from state highway agencies. A follow-up questionnaire on RAP usage was sent to all 50 states, each of which responded. The questionnaire asked about annual quantities of RAP produced and used, the percentage used in various pavement layers, the amount of cold recycling (if any), and whether or not RAP stockpiles are accumulating.

The results of the state highway agency questionnaire on the current use of RAP are summarized in Table 4. The responses were quite interesting and varied. The following comments are based on the average response to each question contained in the questionnaire.

Forty percent of the states are not aware of the approximate tonnage of RAP produced within their states. Surprisingly, twenty-five percent are not aware of the tonnage of RAP that finds its way into state paving projects. Of the states that did report tonnage values, on the average eighty percent of the RAP produced within the state was recycled into state hot mix asphalt concrete (HMAC) paving projects.

Currently, the states allow an average of twenty to twenty-five maximum percent RAP in wearing or surface course mixes. The estimated actual current usage in wearing or surface courses is about twenty percent. State specifications currently allow an average maximum of forty percent RAP in binder courses. Presently, the estimated average RAP in binder courses is twenty-five percent. The average maximum amount of RAP in base courses is noted to be forty to forty-five percent. The estimated average usage in base courses is twenty-five percent.

Approximately two-thirds of the states allow the use of RAP in cold recycling projects. Additionally, two-thirds of the states report that the RAP stockpiles in their respective states are not growing larger.

A very current pavement recycling process named the Cyclean Method of HMAC pavement recycling is currently being studied by a number of states such as Pennsylvania, Texas, California, Michigan and perhaps others. This method employs the use of microwave energy in the process and by so doing, the method is able, in some instances, to recycle one hundred percent RAP into an HMAC mix. No additional asphalt cement is required but an aromatic oil rejuvenator is added to the RAP mix during mixing. Since the Cyclean Method is relatively recent, no prior data or experience is available concerning the longevity of the resulting pavement. Test pavements in the cited states have been placed and will be carefully monitored in future years.

TABLE 4: CURRENT STATUS OF RAP USE IN ASPHALT PAVING

State	Total Tons of RAP Per Year		Maximum Amount RAP in HMAC Pavement Layers						Do You Use RAP In Cold Recycling?	RAP Stockpile Growth
	Produced	Used in HMAC	Wearing Course	Specs Used	Binder Course	Specs Used	Base Course	Specs Used		
Alabama	Unknown	Unknown	12	10/12	50	20/30	50	20/30	Yes	No
Alaska	10,000	Zero	30/50	30	30/50	30	50/100	50	Yes	No
Arizona	500,000	70,000	0	0	40	30	40	30	Yes	Yes
Arkansas	100,000	Zero	70	20/30	70	20/30	70	20/30	Yes	Yes
California	535,000	Unknown	50	35	50	35	50	35	Yes	Yes
Colorado	250,000	192,000	30	11	30	11	30	11	Yes	No
Connecticut	50,000	22,500	40	15	40	15	40	15	No	No
Delaware	Unknown	30,000	30	10	50	10	50	10	No	No
Florida	800,000	750,000	0	0	50	35/40	60	40/45	No	No
Georgia	Unknown	245,000	25 or 40	20/25	25 or 40	20/25	25 or 40	20/25	No	No
Hawaii	Unknown	30,000	0	0	0	0	30 or 40	30	No	Yes
Idaho	100,000	45,000	40/50	40/50	--	--	--	--	Yes	No
Illinois	Unknown	500,000	15	10	25	25	25	25	No	Yes
Indiana	Unknown	100,000	20 or 50	0	20 or 50	20	20 or 50	20	No	No
Iowa	100,000	100,000	30	20	35	25	35	25	Yes	No
Kansas	1,150,000	855,000	50	50	50	50	50	50	Yes	Unknown
Kentucky	100,000	Zero	30	15/20	30	15/20	30	15/20	No	No
Louisiana	150,000	110,000	0	10	30	20	30	20	No	No
Maine	100,000	40,000	0	0	40	20	40	20	Yes	Yes
Maryland	404,000	400,000	30	20	50	20	50	--	No	No
Massachusetts	600,000	132,000	10	10	20 or 40	20/25	20 or 40	20/25	Yes	Yes
Michigan	500,000	285,000	50	20	50	35	50	35	Yes	No
Minnesota	Unknown	1,100,000	30	15	50	30	50	30	Yes	Yes
Mississippi	Unknown	Unknown	0	0	30	20	30	25	Yes	No
Missouri	100,000	3,000	50	35	50	--	50	--	Yes	Yes

TABLE 4. CURRENT STATUS OF RAP USE IN ASPHALT PAVING (Con't.)

State	Total Tons of RAP Per Year		Maximum Amount RAP in HMAC Pavement Layers						Do You Use RAP In Cold Recycling?	RAP Stockpile Growth
	Produced	Used in HMAC	Wearing Course	Specs Used	Binder Course	Specs Used	Base Course	Specs Used		
Montana	Unknown	Unknown	None	N/A	None	30/40	None	30/40	Yes	Yes
Nebraska	250,000	230,000	50	20/50	50	20/50	50	20/50	No	No
Nevada	Unknown	Unknown	0	0	15	0	--	--	Yes	Yes
New Hampshire	40,000	25,000	0	0	50	20	50	20	Yes	Yes
New Jersey	140,000	68,000	10	10	20	20	20	20	No	Yes
New Mexico	200,000	80,000	20/50	35	20/50	35	--	--	Yes	No
New York	Unknown	45,000	0	0	50 or 70	20/30	50 or 70	20/30	Yes	No
North Carolina	400,000	400,000	60	20	60	20	60	20	Yes	Yes
North Dakota	380,000	180,000	50	30/50	50	30/50	50	30/50	Yes	No
Ohio	Unknown	Unknown	30	18	50	20	50	25	Yes	No
Oklahoma	Unknown	Unknown	0	0	25	--	25	--	--	No
Oregon	Unknown	73,000	20	10/15	20	10/15	30	30	Yes	Unknown
Pennsylvania	Unknown	Unknown	15	10	No Limit	15	No Limit	15	Yes	Unknown
Rhode Island	100,000	16,000	0	0	50 or 70	900	50 or 70	9/30	Yes	Yes
South Carolina	Unknown	Unknown	10	10	15	15	20	15	No	Yes
South Dakota	Unknown	50,000	50	40	50	40	50	40	Yes	No
Tennessee	Unknown	Unknown	0	0	35	25	35	--	Yes	Yes
Texas	425,000	100,000	No Limit	20/35	No Limit	20/35	No Limit	20/35	Yes	No
Utah	Unknown	Unknown	15/60	50	15/60	50	15/60	50	No	Yes
Vermont	25,000	25,000	100	15	100	15	100	15	Yes	No
Virginia	500,000	500,000	25	10/15	25	10/15	25	10/15	No	No
Washington	40,000	40,000		20/40		20/40		20/40	No	No
West Virginia	50,000	5,000	No Limit	10	No Limit	20	No Limit	20	No	No
Wisconsin	800,000	280,000	35	30	45	35	--	--	Yes	No
Wyoming	Unknown	Unknown	50	40	50	40	50	40	No	No

SCRAP TIRE RUBBER IN HOT MIX ASPHALT PAVEMENTS

General Background

Rubber in various forms has been used for many years in hot mix asphalt (HMA) pavements. The literature indicates that a serious effort has been made to use rubber in HMA mixtures from the late 1960's into the early 1980's. The addition of rubber will generally change the characteristics of an HMA mixture by increasing the stiffness or compacted stability, improving the aggregate-cement bond, and adding a higher degree of flexibility to the finished HMA pavement, especially at lower ambient temperatures. Although the cited properties of an HMA-rubber mixture are enhanced, the detrimental feature is the increased temperature required for mixing, placement and compaction of the material.

Rubber may be added to an HMA mixture preblended with asphalt cement (wet) or as a crumb rubber (dry). The wet process of adding rubber involves the process of grinding the scrap rubber from discarded tires and then blending the ground rubber with hot asphalt cement. The ground rubber and hot asphalt cement react to form a homogeneous cementing agent. During the processing, mixing, and reacting, solvent agents such as kerosene (McDonald Process) or extender oils (Arizona Refinery Process) are added to reduce the mixture's viscosity so that mixing, placement and compaction are more easily realized. The reported advantages of this asphalt cement-rubber blending process are the following:

- added flexibility
- tougher (higher cement blend viscosity and higher compacted stability) HMA mixtures with an elastic responsive pavement matrix
- improved aging properties
- recycling of a waste material, namely, scrap tires.

The crumb rubber or dry process also involves grinding the scrap rubber into granules of coarse to fine sizing. The ground scrap rubber, however, is blended with a pre-heated aggregate and for all practical purposes replaces a portion of the aggregate. It is during the hot mixing of the HMA mixture that the hot asphalt cement and a portion of ground rubber particles may react to form the composite hot binder. This process was originally developed in Sweden during the 1960's and was distributed under the patent name "Rubit." In the 1970's the process was brought to the United States and promoted under the U.S. patent name PlusRide™. Some of the possible benefits of Plus Ride™, as indicated in the product literature, are the following:

- Pavement thermal and reflective cracking are reduced
- Increased pavement toughness particularly in regard to the rate of pavement wear under the influence of studded tires
- de-icing properties due to the elastic response of of the pavement matrix
- lower pavement tire noise
- recycling of a waste material, namely, scrap rubber.

The four main areas where the asphalt cement-rubber or HMA-rubber mixtures are currently used with an acceptable level of success are:

- crack/joint sealer -- no aggregate matrix
- surface/interlayer treatments such as a Stress Absorbing Membrane (SAM) or a Stress Absorbing Membrane Interlayer (SAMI). The basic difference between a SAM and a SAMI is that the SAM is basically a surface layer of material using an asphalt-rubber binder material with an aggregate application whereas the SAMI is basically the same as a SAM but is a stress absorbing layer within a pavement structure. A SAMI would have an HMA overlay covering it. SAM's or SAMI's can be hot plant mixed as well as direct field applied.
- an HMA mixture using a latex asphalt-rubber binder
- a rubber modified HMA mixture, that is, the crumb rubber aggregate replacement process.

It should be noted that the environmental and health and safety impact of using scrap tire rubber or other forms of scrap rubber in asphalt concrete pavements are not well known. This is particularly the case when an existing pavement containing scrap tire rubber may possibly be a candidate for reclaiming at a later date.

FHWA Demonstration Programs

The Federal Highway Administration initiated demonstration project No. 37, Use of Discarded Tires in Highway Construction, in 1976. This project remained active for nearly ten years. The purpose of this project was to encourage state highway agencies to use scrap rubber from discarded tires, primarily as an asphalt modifier in stress absorbing membranes (SAM) and stress absorbing membrane inter-layers (SAMI). A total of 40 demonstration projects were constructed and evaluated in 13 states during this time period, involving 18 stress absorbing membranes and 22 interlayers.

Performance evaluations have shown that in many states asphalt-rubber chip seals and interlayers are more effective than conventional chip seals and interlayers in preventing or controlling reflection cracking in asphalt pavements (T.P. Beatty, Federal Highway of Administration. Private Communication).

A more recent evaluation of asphalt-rubber systems was conducted under a Federal Highway Administration (FHWA) pooled fund study. Over 200 experimental rubber-modified pavements were evaluated relative to their performance in asphalt-rubber seal coats and innerlayers and in rubber-filled asphalt concrete.

Experimental sections of asphalt-rubber performed the same or worse in approximately 80 percent of the test sections, while experimental sections of rubber-filled asphalt concrete performed the same or better in approximately 95 percent of the sections. Although the pooled fund study was conducted on a nationwide basis, the generally favorable performance of asphalt-rubber systems in these and previous tests in Arizona is in contrast to the overall results of the pooled fund study. This suggests that climatic conditions may be an important factor in the performance of asphalt rubber systems (149).

Current Practice

During the latter half of 1991, each of the states and the District of Columbia were initially polled by the authors to substantiate current usage and policies of using either an asphalt cement-binder product or an HMA-rubber mixture for each governmental agency. The results are summarized in Table 5. In general, the following summative observations can be made:

- Approximately 20 percent of the states, as well as the District of Columbia, are using various forms of scrap rubber in asphalt as a result of legislative mandates.
- Approximately 20 percent of the states do not currently use any form of scrap tire rubber in asphalt products.
- Over 30 percent of the states and the District of Columbia report inconclusive acceptability of using any form of scrap tire rubber in asphalt products.
- Two states experienced unacceptable results using scrap tire rubber and currently are not allowing scrap tire rubber to be used in asphalt products.

TABLE 5

Reclaimed Scrap Tire Usage
Based on State Highway Agency Questionnaire Responses

States	States Comments	Legislative Mandate
Alabama	No reported use or prospective use of the waste material in asphalt	none
Alaska	Inconclusive results using scrap tires in pavements	—
Arizona	Acceptable use of scrap tires in asphalt-rubber binders at a very successful level	—
Arkansas	Acceptable use of scrap tires in HMA mixtures; however, the success of usage is presently under review	—
California	Acceptable use of scrap tires in asphalt concrete and chip seals with mixed level of success	yes
Colorado	Inconclusive acceptability of scrap tires as scrap rubber interlayers	—
Connecticut	Acceptable use of scrap tires in asphalt pavements at a sucessful level	—
Delaware	No reported use or prospective use of the waste material in asphalt	—
Florida	Acceptable use of scrap tires in asphalt cements and asphalt pavements with relatively good success	yes
Georgia	Acceptable use of scrap tires in hot poured joint and crack sealer at a successful level	none
Hawaii	No reported use or prospective use of the waste material in asphalt	—
Idaho	No reported use or prospective use of the waste material in asphalt	none
Illinois	Acceptable use as an additive to crack sealers with good success	yes
Indiana	Inconclusive results using scrap tires in asphalt mixtures--relatively successful use after one years' experience	—
Iowa	Inconclusive results using scrap tires in asphalt concrete-the relative success of material is unknown at present	none

TABLE 5 (continued)

Reclaimed Scrap Tire Usage
Based on State Highway Agency Questionnaire Responses

States	States Comments	Legislative Mandate
Kansas	Inconclusive results using scrap tires in asphalt concrete pavements with inconclusive levels of success	none
Kentucky	No reported use or prospective use of the waste material in asphalt	—
Louisiana	No current use of the waste material in asphalt concrete pavements--legislation exists to recycle rubber tires	yes
Maine	Inconclusive results using ground scrap tires as an asphalt binder additive with no reported level of success	yes
Maryland	Inconclusive results using scrap tires in a hot mixed asphalt mixture with no reported level of success	—
Massachussetts	Acceptable use of scrap tires in asphalt binder but unacceptable use of rubber tires as aggregate substitute--relatively successful in SAMI's	none
Michigan	Inconclusive acceptability using scrap tires in asphalt pavements with poor levels of success and early pavement failures	none
Minnesota	Inconclusive acceptability of scrap tires in asphalt mixes with no reported levels of success	—
Mississippi	Inconclusive acceptability using scrap tires in asphaltic pavements with no reported levels of success	yes
Missouri	Experimental use of scrap tires in asphaltic wearing and base courses with reported good level of success after 1 year	yes
Montana	Scrap tires used in asphaltic concrete (PLUS RIDE) and in chip seals with very successful results	none
Nebraska	Inconclusive acceptability using scrap tires in asphaltic concrete mixtures with no reported level of success	none
Nevada	Acceptable use of ground tire rubber in chip seal binders with relatively good performance and success	—

TABLE 5 (continued)

Reclaimed Scrap Tire Usage
Based on State Highway Agency Questionnaire Responses

States	States Comments	Legislative Mandate
New Hampshire	Acceptable use of ground scrap tires as SAMI's with no reported levels of success	none
New Jersey	Inconclusive acceptability using scrap tires in hot mix asphalt concrete with successful usage reported	none
New Mexico	Scrap tires used in SAMI's with reported fair levels of success	none
New York	Inconclusive acceptability using scrap tires as aggregate in asphaltic pavements with fair levels of success. Acceptable as a joint filler material with good success levels	yes
North Carolina	Inconclusive acceptability using scrap tires as aggregate in an asphaltic mix with no reported level of success	yes
North Dakota	Unacceptable use of scrap tires in roadway construction with poor levels of success reported	none
Ohio	Acceptable use of ground scrap tires in roadway construction at unreported levels of success--no great benefits to be realized	none
Oklahoma	Inconclusive acceptability using scrap tires as an asphalt modifier with no reported level of success	none
Oregon	Acceptable use of scrap tires in SAMI's, pavements and chip seals with mixed levels of success--none of the identified uses permitted for various cited reasons	yes
Pennsylvania	Acceptable use of scrap tires in asphalt pavements with fair levels of success	—
Rhode Island	Satisfactory performance using granulated scrap tires in asphalt mixtures, but further use is unlikely due to added cost	—
South Carolina	Acceptable use of scrap tires in rubber based asphalt chip seals with good levels of success reported	none
South Dakota	No reported use or prospective use of the waste material in asphalt	none

TABLE 5 (continued)

Reclaimed Scrap Tire Usage
Based on State Highway Agency Questionnaire Responses

States	States Comments	Legislative Mandate
Tennessee	Acceptable use of ground scrap tires as an asphalt joint sealing material with successful results reported	—
Texas	Acceptable use of ground tire rubber as hot rubber asphalt seal coat with good success levels reported	—
Utah	No reported use or prospective use of the waste material in asphalt	—
Vermont	No reported use or prospective use of the waste material in asphalt	—
Virginia	Use of scrap tires reported in highway construction with good levels of success reported	—
Washington	Acceptable use of crumb rubber in asphalt concrete pavements with moderate success levels; however, will not be used routinely because it is not cost effective	yes
West Virginia	No reported use or prospective use of the waste material in asphalt	—
Wisconsin	Unacceptable use of crumb tire rubber in asphalt concrete because it results in brittle pavements	yes
Wyoming	Inconclusive acceptability using scrap tires in asphalt concrete friction courses with no reported level of success--pavements are cost prohibitive	—
District of Columbia	Inconclusive acceptability using scrap tires in asphalt binders with no reported levels of success	none

The following states do not intend to use scrap tires either because of poor results or because costs are too high:

- Iowa (cost)
- Maine (poor performance)
- Michigan (poor performance)
- North Dakota (poor performance)
- Rhode Island (cost)
- Wisconsin (poor performance)
- Wyoming (cost)

The following are additional specific areas of information provided in the initial questionnaire responses from the states and the District of Columbia regarding the use of scrap tire rubber in asphalt products and asphalt concrete pavements. States not specifically mentioned in the following paragraphs offered no response to the use of scrap tires in asphalt.

Alaska

Alaska has performed in-house research concerning the use of scrap tires in pavements which indicated inconclusive results. No further research is anticipated at this time.

Arizona

Arizona has performed in-house research concerning the use of scrap tires in asphalt rubber binder which indicated potentially acceptable results. The state has used scrap tires in highway construction with very successful results.

Arkansas

Arkansas has performed in-house research concerning the use of scrap tires in hot asphaltic mixes which indicated potentially acceptable results. Currently, the use of scrap tires in highway construction is under review.

California

California has performed in-house research concerning the use of scrap tires in asphalt concrete and in chip seals which indicated potentially acceptable results. Scrap tires have been used in highway construction with a mixed level of success. At least two technical reports are available from CALTRANS on the use of scrap tire products, "CALTRANS Experience with Rubberized Asphalt Concrete" (150) and "Rubberized Asphalt for Chip Seals" (151).

Colorado

Colorado has performed in-house research concerning the use of scrap tires in scrap rubber interlayers which indicated inconclusive results as to potential acceptability. No additional research or planned use of this scrap material in hot mix asphalt was indicated by this state.

Connecticut

Connecticut has performed in-house research concerning the use of scrap tires in highway pavements which indicated potentially acceptable results. They have successfully used scrap tires in highway construction although they did not indicate where the scrap material was being utilized. At least one technical report is available from the state which is titled "Recycled Rubber in Roads" (152).

Florida

Florida has performed in-house research concerning the use of scrap tires in rubber-asphalt pavements which indicated potentially acceptable results. The University of Florida has assisted in this research. Florida has used ground tire rubber in asphalt with relatively good success. Several research reports are available from the State Materials office in Gainesville which document the demonstration projects and summarize the research findings. Demonstration projects have proven that ground tire rubber could be used successfully to modify the asphalt binder in surface mixes and in impermeable membrane interlayers.

Georgia

Georgia has performed in-house research concerning the use of scrap tires in hot poured crack and joint sealer which indicated potentially acceptable results. It has successfully used scrap tires in the hot poured sealer material in highway construction.

Illinois

Illinois has used scrap tires as an additive to crack sealers in highway construction. There are plans to do research concerning the use of scrap tires as an asphalt cement modifier in seal coats and in hot mix asphalt mixtures. The state is of the opinion that scrap tires are cost effective and perform in a way comparable with virgin materials.

Indiana

Indiana has performed in-house research concerning the use of scrap tires in asphalt mixtures using both the wet and dry process. The potential acceptability of using this scrap material is inconclusive since their research is incomplete. The state has used asphalt-rubber materials (wet process) successfully based on good performance after one year of service. They have indicated that the asphalt-rubber material is expensive.

Iowa

Iowa has performed in-house research concerning the use of scrap tires as an additive to asphalt concrete. The results of this research were inconclusive as to its potential acceptability. The state has used scrap tires in highway construction but is concerned with the increased construction cost and unknown benefits associated with the use of this scrap material.

Kansas

Kansas has performed in-house research concerning the use of scrap rubber tires in asphalt concrete pavements. Research results were also inconclusive regarding potential acceptability. Kansas is planning further research dealing with scrap tires as used in asphalt concrete pavements prepared by the hot recycled, dry process method. Scrap tires have been used by the state in highway construction.

Maine

Maine has performed in-house research concerning the use of scrap tires as an additive to asphalt binders in pavements. The results were inconclusive as far as its potential acceptability is concerned. The use of ground rubber slurry seal as a crack reducing interlayer was deemed not acceptable because it did not reduce cracking and because it trapped water at the underside of the pavement. At least one technical report is available from the state titled "The Use of Tire Rubber in Pavements" (153).

Maryland

Maryland has performed in-house research concerning the use of scrap tires in hot mixed asphalt mixtures. The results were inconclusive in terms of its potential acceptability. The University of Maryland has performed research of this material which deals with the state of the art synthesis report on the use ground rubber in hot mixed asphalt.

Massachusetts

Massachusetts has performed in-house research concerning the use of scrap tires as an aggregate substitute in bituminous mixtures. This research indicated a potentially acceptable use of scrap tires in asphalt but a potentially unacceptable use of scrap tires in asphalt as used in SAMI's. The research also found that scrap tires used as an aggregate were not acceptable due to repeated poor results.

Michigan

Michigan has performed in house research concerning the use of scrap tires in bituminous pavements. The use of scrap tires in highway construction is not considered acceptable by the state because of early failures, poor results to date and other problems.

Minnesota

Minnesota has performed in-house research concerning the use of scrap tires in asphalt mixes. Results to date are inconclusive with respect to potential acceptability. The University of Minnesota has performed research in the area of the use of polymerized crumb rubber. The state has used scrap tires in asphalt but success of some is tempered by the question of cost effectiveness. State conducted research has included the use of asphalt rubber in interlayers, seal coats, crack sealing and asphalt concrete systems, as well as the use of patented rubber modified asphalt concrete. Present state research include efforts to construct a non-patented rubber modified asphalt concrete overlay and a special rubber modified asphalt mixture using higher percentages of rubber for use in biking or jogging paths.

Mississippi

Mississippi has performed in-house research concerning the use of scrap tires as an additive in asphalt pavements. To date, research results are inconclusive regarding potential acceptability.

Missouri

Missouri has performed in-house research concerning the use of scrap tires in bituminous pavements with no reported levels of potential acceptability. The state has used ground rubber incorporated in asphaltic concrete experimentally. After one year, the pavement appears to be in good condition. The state has also used scrap tires in patented asphalt mixtures in highway construction. The

state is planning additional research in the use of rubber from scrap tires in bituminous mixtures.

Montana

Montana has used scrap tires (as granular pellets) in a Plus Ride™ test section of paving with very successful results. The state is also increasing the use of rubber asphalt materials in chip seals.

Nebraska

Nebraska has performed in-house research concerning the use of scrap tires in asphalt concrete mixtures which indicated inconclusive results as to its potential acceptability.

Nevada

Nevada has performed in-house research concerning the use of ground tire rubber in chip seal binders which indicated a potential acceptability of the scrap material. The state has used ground tire rubber in highway construction and reports good performance of the material.

New Hampshire

New Hampshire has performed in-house research concerning the use of ground scrap tires as SAMI's, which indicated potentially acceptable results. The state is planning additional research using ground scrap tires in bituminous pavements. The state has used ground scrap tires in highway construction but question the cost effectiveness of using this material.

New Jersey

New Jersey has performed in-house research concerning the use of scrap tires in hot mix asphalt, the results of which are inconclusive with respect to its potential acceptability. The state is planning additional research using scrap tires in hot mix asphalt. The state has used scrap tires successfully in highway construction.

New Mexico

New Mexico has used scrap tires in SAMI's with a fair degree of success.

New York

New York has performed in-house research on use of scrap tires as an aggregate in asphalt pavements which indicated inconclusive results as to its potential acceptability. This use has been experimentally field tested and has shown a fair performance. The state has also researched scrap tires as pavement joint fillers which indicated potentially acceptable results. Use of rubber in joint fillers is currently a field standard which has shown good performance at this time. At least three technical reports are available from NY DOT on the use of this scrap product, namely, "Use of Scrap Tire Rubber in Asphalt Pavements," "Evaluation of Use of Rubber-Modified Asphalt Mixtures for Asphalt Pavements in New York State," and "Experimental Construction of Rubber-Modified Asphalt Mixtures for Asphalt Pavements in New York State" (154, 155 and 156).

North Carolina

North Carolina has performed in-house research concerning the use of scrap tires in asphalt mixes. Thus far, the results of this research have been inconclusive. North Carolina State University has also researched the use of rubber from tires in bituminous paving mixtures.

North Dakota

North Dakota has used scrap tires in highway construction with poor results. Due to the poor performance, the state has determined that scrap tires are not considered acceptable for highway construction purposes.

Ohio

Ohio has performed in-house research into the use of rubber as an additive in asphalt concrete. The University of Akron has also researched the use of liquid latex rubber as an additive to asphalt concrete. The results of both of these research programs have proven inconclusive to date. The state has used ground scrap tires in highway construction with acceptable success but no apparent great benefit.

Oklahoma

Oklahoma has performed in-house research concerning the use of scrap tires as an asphalt modifier which indicated inconclusive results as to its potential acceptability. The state is planning additional research using scrap tires as an asphalt modifier.

Oregon

Oregon has performed in-house research concerning the use of granulated scrap tires in rubber-filled asphalt concrete and ground rubber as used in asphalt-rubber concrete, asphalt-rubber chip seal binder, and in SAMI's. The research indicated inconclusive results as to the potential acceptability of using granulated tires in rubber filled asphalt concrete. However, ground rubber in the named uses was found potentially acceptable. Oregon is planning additional research using granulated scrap tires in rubber filled asphalt concrete and ground scrap tires in asphalt rubber concrete. The state has experienced successful results using the ground rubber from scrap tires, but mixed results using granulated rubber from scrap tires. The state does not consider the granulated rubber acceptable for highway construction because of inconsistent performance. The ground rubber in asphalt-rubber concrete and asphalt rubber chip seals is not considered acceptable because these uses are not cost effective. Oregon State University has also researched rubber modified asphalt concretes. At least six technical reports were made available from the Oregon DOT on the use of scrap tires, as follows:

- "Appendix A: Investigation of Ravelling on PLUS RIDE"
- "Evaluation of Asphalt Additives"
- "Five Year Performance of Asphalt Additive Test Sections"
- "Stress Absorbing Membrane Interlayer Adopted as 'Permitted Alternative' for Oregon Highways"
- "Stress Absorbing Membrane Interlayer"
- "Evaluation of Rubber Asphalt Chip Seals in Oregon"

Pennsylvania

Pennsylvania has performed in-house research concerning the use of scrap tires in bituminous concrete which indicated potentially acceptable results. The state has used scrap tires in highway construction experimentally with fairly successful results.

Rhode Island

Rhode Island has used granulated scrap tires in the dry process. This pavement was placed approximately four years ago and its performance to date has been satisfactory. No further use of Plus Ride™ is anticipated due to its cost.

South Carolina

South Carolina has performed in-house research concerning the use of scrap tires in a rubber based asphalt chip seal which indicated potentially acceptable results. The state is planning additional research using scrap tires in hot mix asphalt. The state has used scrap tires in highway construction with good success.

Tennessee

Tennessee has performed in-house research concerning the use of ground scrap tires in asphalt joint sealant which indicated potentially acceptable results. The state has successfully used ground rubber crack sealants in highway construction.

Texas

Texas has performed in-house research concerning the use of ground tire rubber in seal coats, crack sealant and hot mixed asphalt concrete which indicated potentially acceptable results. The state is planning additional research using ground tire rubber in hot mixed asphalt concrete. Texas A&M University has also researched the use of ground tire rubber in hot rubber asphalt seal coats. The state has routinely used ground tire rubber in hot rubber seal coats with good results. The state encourages the use of ground tire rubber by allowing for fifteen percent higher bids than conventional asphalt, on a life cycle cost-benefit basis.

Virginia

Virginia has performed in-house research concerning the use of rubber in hot mixed asphalt pavements with no reported potential acceptability. The state has used rubber in highway construction with good success in limited quantities.

Washington

Washington has performed in-house research concerning the use of crumb rubber in asphalt concrete pavements and indicated potentially acceptable results. The state has had moderate success using crumb rubber as an asphalt additive in highway construction. The state presently considers Plus Ride™ as not acceptable in highway construction because it is not cost effective (157).

Wisconsin

Wisconsin has performed in-house research concerning the use of scrap tires as an asphalt concrete additive with no reported potential acceptability. The University of Wisconsin-Madison has also researched scrap tires with no specific use reported. The state has deemed the use of crumb rubber in asphalt concretes as not acceptable in highway construction because of brittle pavements.

Wyoming

Wyoming has performed in-house research concerning the use of scrap tires as a crumb rubber additive in asphalt for open graded friction causes. This testing was indicated inconclusive results as to its potential acceptability. The state has used rubber tires in friction courses in highway construction but reports that this use is cost prohibitive.

District of Columbia

The District of Columbia has performed in-house research concerning the use of scrap tires in an asphalt binder which indicated inconclusive results in terms of potential acceptability. The District originally began experiments with rubber in a bituminous pavement as far back as 1951. Although a preliminary evaluation (results not reported) of this experimental pavement was made two years after placement, no final evaluation was made. In the summer of 1991, a new asphalt-rubber pavement test section was to have been constructed in the District, the confirmation of which is not reported.

Current Use of Crumb rubber Modifier (CRM) by State Highway Agencies

In addition to the general information on scrap tire use in asphalt paving that was provided in Table 5 more specific information on usage of crumb rubber modifier (CRM) in various asphalt related applications was requested from state highway agencies. A questionnaire on CRM usage was sent to 40 states which had previously indicated their use of scrap tires in asphalt. Each of these 40 states was asked about the type of crumb rubber process used (wet or dry), how many crumb rubber projects were placed, what type of projects, their degree of success, and their cost effectiveness. The questionnaire also asked state highway agencies certain questions related to Federal mandates for recycling of scrap tires into asphalt pavements.

The results of the state highway agency questionnaire on the current use of CRM are summarized in Table 6. The 10 states that were not sent a questionnaire are designated in Table 6 as having made no response. As was true in analyzing the results of the

TABLE 6. CURRENT STATUS OF CRUMB RUBBER MODIFIER (CRM) USE IN ASPHALT PAVING

State	Estimated CRM Generated No. of Tires	Current Use of CRM In HMAC Pavement or Seal Coats			Type of Process Used			CRM Use Rating			Use if Not ISTEA
		Yes	No	Exp.	Wet	Dry	Both	Successful	Economical	Inconclusive	
Alabama	No Response										
Alaska	250,000	--	X	--	--	X	--	Yes	--	--	Yes
Arizona	Unknown	X	--	--	X	--	--	Yes/No	Yes/No	--	Yes
Arkansas	2,000,000	--	--	X	X	--	--	--	--	Inc.	Exp.
California	30,000,000	X	--	--	--	--	X	Yes/No	Yes/No	--	Yes
Colorado	3,200,00	--	X	--	--	--	--	Yes/No	Yes/No	--	Exp
Connecticut	3,500,000	--	--	X	--	--	X	Yes	No	--	No
Delaware	No response										
Florida	9,750,000	--	--	X	X	--	--	Yes	Yes	--	Yes
Georgia	6,500,000	--	--	X	X	--	--	No	No	Inc.	Exp
Hawaii	No response										
Idaho	No response										
Illinois	No response										
Indiana	5,200,000	--	--	X	--	--	X	No	No	Inc.	Exp
Iowa	3,000,000	--	--	X	--	--	X	No	No	Inc.	No
Kansas	Unknown	--	--	X	--	--	X	No	No	Inc.	Exp
Kentucky	No response										
Louisiana	No response										
Maine	1,200,000	--	--	X	X	--	--	--	No	Inc.	No
Maryland	4,500,000	--	--	X	X	--	--	Yes	No	--	Exp
Massachusetts	6,500,000	--	--	X	--	--	X	Yes/No	No	--	Exp
Michigan	9,000,000	--	--	X	--	--	X	No	No	Inc.	No
Minnesota	4,000,000	--	--	X	--	--	X	Yes/No	No	--	Exp
Mississippi	Unknown	--	--	X	X	--	--	--	No	Inc.	Exp
Missouri	4,500,000	--	--	X	X	--	--	Yes	No	Inc.	Exp

TABLE 6. CURRENT STATUS OF CRUMB RUBBER MODIFIER (CRM) USE IN ASPHALT PAVEMENTS (Con't)

State	Estimated CRM Generated No. of Tires	Current Use of CRM In HMAC Pavement or Seal Coats			Type of Process Used			CRM Use Rating			Use if Not ISTEA
		Yes	No	Exp.	Wet	Dry	Both	Successful	Economical	Inconclusive	
Montana	Unknown	--	--	X	--	--	X	Yes	No	Inc.	Exp
Nebraska	1,500,000	--	--	X	X	--	--	--	--	Inc.	Exp
Nevada	Unknown	X	--	--	X	--	--	--	--	Inc.	Exp
New Hampshire	Unknown	--	--	X	X	--	--	Yes	No	Inc.	Exp
New Jersey	750,000	--	--	X	--	--	X	--	No	Inc.	Exp
New Mexico	1,500,00	--	X	--	--	--	X	No	No	Inc.	Exp
New York	12,000,000	--	--	X	--	X	--	No	No	--	Exp
North Carolina	Unknown	--	--	X	--	X	--	--	--	Inc.	Exp
North Dakota	Unknown	--	--	X	X	--	--	No	No	--	No
Ohio	14,000,000	--	--	X	X	--	--	No	Yes	--	Exp
Oklahoma	Unknown	--	--	X	--	--	X	Yes/No	No	--	Exp
Oregon	2,200,000	--	--	X	--	--	X	Yes/No	--	Inc.	Exp
Pennsylvania	12,000,000	--	--	X	--	--	X	--	--	Inc.	Yes
Rhode Island	Unknown	--	X	--	--	X	--	--	--	Inc.	No
South Carolina	Unknown	--	--	X	--	X	--	No	No	Inc.	Exp
South Dakota	No response										
Tennessee	Unknown	--	X	--	--	--	--	--	--	--	Exp
Texas	18,000,000	Yes	--	--	X	--	--	Yes	Yes	Inc.	Exp
Utah	No response										
Vermont	500,000	--	--	X	X	--	--	Yes/No	No	--	No
Virginia	Unknown	--	--	X	X	--	--	No	No	Inc.	Exp
Washington	Unknown	--	--	X	X	--	--	Yes/No	Yes/No	--	Exp
West Virginia	No response										
Wisconsin	4,500,000	--	--	X	X	--	--	No	No	--	Exp
Wyoming	Unknown	--	--	X	X	--	--	Yes/No	No	--	No

RAP questionnaire, the results of the CRM questionnaire represent the average conditions noted in responses from the states on their use of crumb rubber modifiers.

Only one-half of the states had an approximate count of the number of scrap tires generated within their state. Although a large number of states are using CRM in HMAC, three-fourths still consider the use of CRM in HMAC as experimental. The majority of the states are using either the wet process, or both the wet and dry processes, in incorporating CRM into hot mixes. The states are equally divided as to the success of pavements which have CRM in them. There was no indication as to the definition of success. Three-fourths of the states indicated very clearly that the incorporation of CRM into HMAC was not economical. The economics, or lack thereof, of using CRM in HMAC pavements will have a significant negative effect on the outcome of Life Cycle Cost Analyses as far as HMAC pavement's competitive position with Portland Cement Concrete (PCC) pavements is concerned. A number of states have thus far experienced inconclusive results using CRM in HMAC pavements.

A most interesting response in the questionnaire was to the question which addressed the use of CRM as described in Section 1138 of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. If ISTEA did not mandate the use of CRM in HMAC pavements, two-thirds of the states indicated that they would only consider the use of CRM in HMAC pavements as experimental at the present time. One can only speculate as to specific reasons the states may have as for such a response, but their response clearly indicates that the majority of states are currently not ready to adopt CRM as a standard material in their specifications with respect to the manufacturing and/or use of CRM in highway pavement construction.

The Maryland Department of Natural Resources (MD DNR) independently sent their own questionnaire to all 50 state highway agencies and the District of Columbia (D.C.) during mid-1992 to assess the reuse of scrap tires in asphalt paving. The MD DNR survey contained 13 questions, several of which had three or more sub-parts. This survey sought information on crumb rubber use, as follows:

- Asphalt-rubber processes used
- Miles paved and degree of success
- Cost of asphalt-rubber compared to asphalt
- Other uses for scrap tires in highways

By December, 1992, 46 of 50 states had responded to this questionnaires. States not responding include Idaho, Kentucky, Montana, and Ohio. Out of 46 responses, 39 states have used crumb rubber in some type of asphalt pavement application. The wet process is being used in 33 states, the dry process in 22

states, with 27 states having used crumb rubber in stress-absorbing membrane interlayers (SAMI's). Although 23 states now consider their asphalt-rubber projects successful, 28 states do not consider such projects to be economical.

The MD DNR survey indicates that there are crumb rubber suppliers located in 15 different states. At least 30 states have contractors with experience in placing asphalt-rubber pavements. Of the 46 states that have responded, 27 still consider the use of crumb rubber in asphalt paving to be experimental. States that no longer consider asphalt-rubber experimental are Arizona, California, Connecticut, Missouri, Nevada, Texas, and West Virginia. California considers the dry process as experimental, but not the wet process.

SLAGS AND ASHES IN HOT MIX ASPHALT PAVEMENTS

General Background

Slags are the by-products from iron blast furnaces, steel mills, and metal smelters. Slag materials are labeled as iron blast furnace slag, steel slag, and non-ferrous slags (copper, lead, zinc, molybdenum, and phosphate. Ash refers to the particulate and granular by-products from coal burning power plants. Various forms of coal ash are dry bottom ash, wet bottom ash or boiler slag, and fly ash. All of these materials have been produced for many years and have won gradual acceptance as aggregates in pavement construction over the past forty to fifty years. Blast furnace slags, steel slags, and some non-ferrous slags have been successful replacements for both coarse and fine aggregates.

Although slag materials of themselves possess admirable qualities such as hardness, angular shape, good skid resistance, and availability, they also exhibit characteristics which are undesirable in asphalt pavements or which cause difficulties in replacing conventional aggregates in asphalt concrete mixtures. The most restrictive characteristic of the slag materials is their generally high absorptive quality. This high absorption (in some cases, above two percent by weight) requires the use of additional asphalt cement binder, which in turn raises the unit cost of producing the asphalt concrete mixture. Most slags, due to their high absorption, attract and retain moisture more readily than conventional aggregates and, therefore, require additional energy to render them sufficiently dry for use in as asphalt paving mixture.

Bottom ash, boiler slag, and fly ash have also been used successfully in asphalt concrete mixes as fine aggregates and mineral filler, respectively. These by-products are virtually available nationwide for use in pavement construction, although

neither has been used extensively in hot-mix asphalt mixes. Bottom ash and boiler slag have been used sporadically as aggregates in asphalt paving. Bottom ash is well graded, but can be absorptive. Some bottom ash sources may degrade slightly upon compaction. Also, pyrites must be separated from the bottom ash or pop-outs may occur. Boiler slag is black, glassy, and more uniform in gradation, with initially no asphalt absorption.

In the case of fly ash, substitution of the filler constituent of an asphalt concrete mixture is nearly nonexistent today because of the strict environmental requirements imposed on the asphalt concrete industry. Recyclable baghouse fines, collected at the asphalt concrete plant, are quite abundant. These recovered fines, in quantities as required, are recycled directly at the plant to satisfy mix filler requirements. Consequently, the use of coal fly ash as a mineral filler in asphalt paving is not a high volume market.

Current Practice

From the responses received from the state DOT questionnaires, the following general statements can be made.

- Approximately 14 percent of states have indicated an acceptance of the use of air cooled blast furnace slag as an aggregate in asphalt concrete pavements.
- Approximately 12 percent of the states have researched the use of steel slag in asphalt concrete mixtures. All but one of these states indicated its potential acceptability for use. That one state indicated that research results on this material have been inconclusive.
- Only four states have indicated any research work on the use of dry or wet bottom ash in asphalt paving. One of these states indicated no potential acceptability while the other three indicated a positive acceptability.
- Sixteen percent of the states have researched the use of fly ash in asphaltic concrete mixtures. Virtually all states found fly ash acceptable, although one state considered it unacceptable, and two other states had inconclusive results.

The following are specific areas of information regarding the research and use of slag and ash by-products in asphalt concrete mixtures.

California

California has performed in-house research on the use of slags. The slags that were researched were not described, but are believed to include both blast furnace and steel slags. California's research has yielded inconclusive results regarding potential acceptability, probably due in part to some slag stockpiles being commingled, that is, containing both blast furnace and steel slags together.

Illinois

Although Illinois did not indicate any specific research, the state did indicate that they have used blast furnace and steel slags in asphalt concrete mixtures. Also, there has been no research of fly ash, although some previous use has been made of fly ash as a mineral filler.

Indiana

Indiana indicated it has performed in-house research on the use of slags as an aggregate in pavement construction. The slags were identified as blast furnace slag and boiler slag. The research indicated potential acceptability of these waste materials. No additional research was indicated in-house. It was also noted in the questionnaire that Purdue University will be performing their own research studies on selected by-product materials, especially bottom ash.

Iowa

It was reported that the University of Iowa has or will be researching the use of fly ash in highway construction with no specific mention as to how the ash would be used.

Kansas

Kansas has performed in-house research into the use of slags and coal ash in asphaltic concrete pavements and as an additive in bituminous cold recycling operations. Research on the use of blast furnace slag and steel slag was considered inconclusive as far as their potential acceptability is concerned. Bottom ash and boiler slags are considered acceptable as aggregates for cold recycling and fly ash is acceptable as a mineral filler.

Kentucky

Kentucky has performed in-house research into the use of slags in asphalt concrete mixtures. Both blast furnace and steel slags are considered acceptable in asphalt concrete mixes. No further research is anticipated at this time.

Louisiana

Louisiana has performed in-house research into the use of blast furnace slag and steel slag as aggregate replacements in asphalt concrete mixtures. Some research has also involved the use of fly ash as a filler material. All three materials were reported as potentially acceptable in terms of their use in asphalt concrete mixtures. No additional research is anticipated.

Michigan

Michigan has performed research on the use of fly ash and blast furnace slag in asphalt concrete mixtures. Michigan found the use of fly ash to be potentially acceptable in asphalt concretes. The state also found blast furnace slag potentially acceptable with restrictions, although these restrictions were not defined. No additional research is planned.

Minnesota

Minnesota has evaluated the use of boiler slag in asphalt concrete mixes. The potential acceptability of boiler slag as an asphalt aggregate is considered inconclusive at this time. No additional research was anticipated in this area.

Missouri

Missouri has researched the potential use of various sources of slag and coal ash, specifically, wet bottom boiler slag, blast furnace slag and steel slag. Missouri has used all of these materials successfully in asphalt concrete mixtures. Additional research is anticipated on the use of dry bottom ash in asphalt concrete mixtures.

Nebraska

Nebraska has investigated the use of Class C fly ash as filler in asphalt concrete mixes. The state indicates a potential acceptability for Class C ash in asphalt mixes. No additional research was indicated in-house, however, it was reported that the University of Nebraska has or will be researching high volume utilization of coal ash in Nebraska.

New Jersey

New Jersey has performed in-house research in the use of fly ash as a mineral filler in hot mix asphalt concrete mixtures. Their research indicated a potential acceptability for fly ash. No additional research is currently planned.

New York

The State of New York has researched the use of fly ash as a mineral filler in asphalt concrete mixes. The results are thus far inconclusive, although no additional research was indicated by the state.

Pennsylvania

Pennsylvania has investigated the use of both blast furnace slag and steel slag as aggregate replacements in asphalt concrete mixtures. Their research indicates a potential acceptability of each type of slag. Both types of slag have been used as asphalt aggregate for many years.

South Carolina

South Carolina has performed research in the use of steel slags in asphalt concretes. Their research indicates a potential acceptability for the intended use of the steel slag, although no additional research is planned.

Tennessee

Although Tennessee did not perform any formal research on the use of phosphate slags in asphalt concrete surface mixes, they indicate the successful use of this material in asphalt pavement construction over many years.

Texas

Texas has performed in-house research on the use of bottom ash and blast furnace slag in hot-mix asphalt concrete mixes and in chip seals. In both cases, the materials were found potentially acceptable for use. No additional research is planned.

Virginia

Although Virginia indicated in-house research of fly ash and slags in pavements, no specifics were indicated as to type of pavement. No indication of potential acceptability or additional research was made.

West Virginia

West Virginia has performed research on the use of fly ash as a mineral filler and blast furnace slag as an aggregate replacement in asphalt concrete mixtures. The research has indicated the potential acceptability of both of these materials. In addition, consideration is being given to the use of steel slags in a hot mix asphalt concrete wearing

course on several projects. No formal research has been performed on steel slag at this time and no additional research is planned.

Wyoming

Wyoming has performed research on the use of bottom ash as an aggregate replacement in asphaltic concrete pavements. The research indicates no potential acceptability for this use of bottom ash. No additional research is planned.

FIELD EXPERIENCE OF WASTE MATERIALS IN ASPHALT CONCRETE PAVEMENTS.

Many waste materials or by-products used in asphalt concrete mixtures have been laboratory researched by state highway or transportation departments, universities and other agencies. As a result of such research, many states carried their investigations to the point of incorporating selected waste materials or by-products in experimental asphaltic pavements. In some cases, the materials proved to be acceptable aggregate replacements or binder extenders, whereas others were deemed unacceptable for use in asphalt pavement construction. This section of Volume 2 presents the experiences of states that have constructed such experimental pavements or are routinely using waste materials or by-products in asphalt paving mixtures.

Alabama

- Coal refuse waste (Red Dog) was used in an asphalt concrete pavement and was found satisfactory. The two reported problems with this material were observed non-uniform density and a variable hardness.
- Blast furnace slag was used in an asphalt pavement and was found to be excellent. The pavement has outstanding abrasive characteristics and a skid resistant quality.
- Steel mill slag was also used in an asphaltic pavement and was also excellent, having outstanding abrasion resistance characteristics and skid quality.
- RAP was used in a pavement with excellent results.
- Reclaimed concrete pavement (RCP) was used in a pavement with satisfactory results. However, the RCP material did produce a paving mix with excessive fines.

Alaska

- No field experiments were reported.

Arizona

- The use of scrap tires has been very successful when blended directly with asphalt cements to produce an asphalt-rubber binder product.
- The inclusion of RAP in hot mixes and ensuing pavement placement has been very successful.
- The use of kiln dust is not considered acceptable in asphalt mixtures because it has no value as mineral filler.

Arkansas

- Scrap tires have been incorporated in asphalt pavements but results are inconclusive and are still under review.
- RAP has been used in asphalt pavements. These pavements are currently being evaluated with no results reported.

California

- RAP has been used in asphalt pavements but the success of such use is mixed. No reasons were given for this evaluation.
- Scrap tires have been used in hot-mix asphalt and chip seals but the relative success of each is mixed. No further explanation was given for this evaluation.
- Assembly Bill No. 1306 legislatively mandates the investigation of RAP and scrap tires.

Colorado

- RAP has been used in asphalt pavements very successfully. The use of RAP in asphalt concrete pavements is not considered a standard product at the present time.
- Crushed concrete pavement is not considered acceptable in asphalt paving because it produces a harsh mix, has high absorption and is associated with severe cracking problems.

Connecticut

- Scrap tires have been successfully used in AC pavements.
- RAP has been successfully used in asphalt pavements.
- Waste glass has been investigated in the laboratory as an aggregate substitute in asphalt mixtures, in response to the Connecticut Legislature's Environment Committee.
- The use of RAP was required by the legislative mandate of Connecticut Public Acts 88-231 and 89-386.

Delaware

- No field experiments were reported.

Florida

- Scrap tires have been used in asphalt pavements with good success.
- RAP has been used in asphalt pavements with good success.
- Waste glass can be used in asphalt pavements but reduces quality because of stripping. Consider use only on low traffic roadways.
- The use of scrap tires in asphalt mixtures was investigated in response to a state legislative mandate.

Georgia

- RAP has been used in AC pavements very successfully and with favorable cost savings.
- Scrap tires have been used in hot pour joint and crack sealers and the results were successful.
- Used motor oil has been successfully used as a fuel for asphalt plants.

Hawaii

- RAP has been used in asphalt concrete base courses and was determined to be satisfactory for this purpose.

Idaho

- No field experiments were reported.

Illinois

- Foundry sand as a substitute for fine aggregate was found to be unacceptable because the material had too fine a gradation and was contaminated with oil.
- Scrap tires were used as an additive in crack sealers and were found acceptable as well as cost effective in comparison to virgin materials.
- RAP was used in asphalt pavements with no apparent or reported problems. The use of RAP was cost effective.
- Coal fly ash was used in asphalt pavements with acceptable performance within limits. Fly ash mineral filler was cost effective and environmentally acceptable.
- Blast furnace slag was used in asphalt pavements and performed excellently when the physical characteristics were controlled. An environmental concern was expressed with regard to potential effluent problems.
- Coal bottom ash or boiler slag was used in seal coating and its performance was excellent, displaying a high friction resistance potential. It was deemed cost effective and no environmental problems were noted.
- Steel slag was used in asphalt pavements and performed excellently where used. Although its cost effectiveness is rated good, it does have an expansion potential and possible environmental effluent problems.

Indiana

- Asphalt rubber (wet process) was used in an asphalt pavement and has shown good performance after one year of service. It is considered expensive compared to asphalt cement.
- Slags and ashes are routinely used in asphalt pavements and performance has been generally good.
- RAP has been routinely used in asphalt pavements with good performance.
- The investigation of RAP, scrap tires and foundry sand was legislatively mandated in 1991.

Iowa

- RAP has been used in asphalt pavements and performs in a very similar manner to virgin materials.
- Adding scrap tire rubber to asphalt concrete mixtures and/or pavements has increased construction costs and provides no known long term benefits.

Kansas

- The relative success of using coal fly ash, coal bottom ash, boiler slag, mine tailings and RAP in asphalt pavements appears to be good, although not directly reported.
- The relative success of using scrap tires, blast furnace slag and steel mill slag is reported to be inconclusive at this time.

Kentucky

- Blast furnace slag and steel slag were used in asphalt pavements, with the use of both materials considered successful.

Louisiana

- The use of fly ash as a filler material in asphalt pavements was reportedly successful.
- The use of RAP as an aggregate for asphaltic concrete was also reported to be successful.
- The use of fly ash was investigated as a result of federal legislation.
- The use of scrap tires in asphalt was covered in a legislative mandate.

Maine

- The use of RAP in asphalt pavements was reported successful.
- The use of ground rubber slurry seal as a crack-reducing layer is not considered acceptable because it did not reduce cracking and trapped water at the pavement underside.
- Granulated tire rubber in asphalt was investigated because of a legislative mandate known as Public Law 1989, Chapter 585.

Maryland

- The use of RAP in hot-mix asphalt was reported as very successful.

Massachusetts

- The use of incinerator ash as a fine aggregate in asphalt pavements has produced good results. It is reported that an experimental asphalt pavement with incinerator ash has been in service for approximately ten years.
- The use of scrap tires in asphalt SAMI layers has been relatively successful.
- The use of scrap tires as an aggregate in asphalt pavements (dry process) has produced poor results as of this time. This application is not considered acceptable for usage.

Michigan

- The use of RAP in asphalt pavements has produced excellent results.
- The use of fly ash as a mineral filler in asphalt pavements has produced good to excellent levels of performance.
- Slags have been used in asphalt pavements with moderate to good success. When used in concrete, their use is restricted by consideration of freeze-thaw cycle exposure.
- The use of scrap tires in asphalt pavements have reportedly produced poor results to date. This material is considered unacceptable for usage due to early failures and other problems.

Minnesota

- The use of RAP in asphalt pavements is considered an acceptable alternate to conventional mixtures.
- Scrap rubber tires in asphalt product systems were investigated. There is some concern as to the cost effectiveness of using scrap tires in hot-mix asphalt.
- The relative success of using sewage sludge incinerator ash as a mineral filler in asphalt pavements was unreported. However, concerns about future long-term liability were noted. To date, performance appears to be acceptable.

Mississippi

- RAP is routinely used in hot-mix asphalt pavements and the reported relative success was good.
- The use of scrap tire rubber was investigated in response to a legislative mandate.

Missouri

- The use of ground rubber in asphalt pavements has been reported to be relatively successful. At least one reported asphalt-rubber pavement appears to be in good condition after approximately one year of service.
- Mine tailings (Joplin chat), steel slag, boiler slag and RAP have all been used on a regular basis in hot-mix asphalt pavements.
- Ground rubber from scrap tires was investigated in accordance with a legislative mandate, House Bill 530 (1990).

Montana

- RAP has been used in asphalt pavements with a reported wide range of relative success.
- Scrap tires (granular pellets) used in a dry process test section of pavement were reported to be very successful. In addition, scrap tire rubber is also being used in increasing amounts in chip seal applications.

Nebraska

- RAP has been used in asphalt pavements and is reported to be generally successful.
- The use of fly ash in asphalt pavements raises some question as to material compatibility with asphalt in regard to its relative success.

Nevada

- The use of RAP in asphalt pavements has provided successful performance.
- The use of ground tire rubber as a chip seal binder has resulted in successful performance.
- The use of waste sulfate as an asphalt cement extender in hot mix pavements has indicated a successful performance. However, it is reported that using this waste material is considered uneconomical at this time.
- The use of mine tailings in asphalt pavements has provided good performance.
- The use of recycled LDPE plastic as a binder modifier for asphalt mixtures has thus far given inconclusive results. Research on this material is still in progress.

New Hampshire

- The relative success of using ground scrap tires as a SAMI was unresolved. However, a concern was raised as to the cost effectiveness of the use of this material as described.
- The use of RAP in asphalt pavements is reported to have provided very good success.

New Jersey

- The use of fly ash has been used successfully as a mineral filler in asphalt pavements. Also, waste glass, RAP and scrap tires have all been utilized successfully as aggregate supplements in hot mix paving.

New Mexico

- The use of RAP in asphalt pavements has been reported to be highly successful.
- The use of scrap tires in a SAMI application is reported to be only fairly successful for this use.

New York

- The use of fly ash as a mineral filler in asphalt paving mixtures is reported to have produced poor performance.
- The use of waste glass in hot-mix asphalt mixtures is considered to have given satisfactory performance.
- The use of kiln dust as a mineral filler in asphalt mixes and pavements is reported to have provided an excellent performance for the use described.
- The use of mining wastes or mine tailings in asphalt pavements has provided excellent performance in the pavement where these materials have been used.
- The use of recycled plastics as an additive to asphalt cement is considered to have provided good performance for the use described.
- The use of RAP in asphalt pavements is a New York State standard and has given excellent performance in place.
- The use of scrap tires as an aggregate in asphalt pavements is in the field experimental stage and to date has shown only a fair performance record.
- The use of scrap tires as a pavement joint filler is presently a New York State standard and has shown good performance in the field.
- Sulfate waste has been used as an asphalt cement extender and is presently in the field experimental stage. The results to date indicate a good performance record.

North Carolina

- RAP has been used successfully in asphalt pavements for the past ten years.
- The North Carolina DOT has experimentally placed a quarter mile of crumb rubber asphalt pavement on its State Project 8.1500605. This experimental roadway was described in its final report dated February, 1991. No results of field performance were reported at this time.
- The use of waste glass from Christmas ornaments and waste ceramic tile in asphalt pavements is not considered acceptable because using these materials is not cost effective. There are also concerns as to hazardous lead content levels and a lack of adhesion of asphalt to the ceramic particles.
- The use of scrap tires was investigated in response to a legislative mandate, although it was not identified.

North Dakota

- Scrap rubber tires have been used in asphalt pavements with reportedly poor performance. Scrap tires in asphalt pavements are not considered acceptable in highway pavement construction because of its poor performance to date.
- The use of sulfate waste in highway construction is reported to be only fairly successful. No specific area of sulfate waste usage was identified.

Ohio

- The state of Ohio has used ground scrap tires in asphalt pavement and reports acceptable performance,. However, the state does not see any great benefits in using scrap tires in asphalt-rubber.

- Blast furnace slag has been used in highway construction but no specific use was reported. Use of slag provides good skid resistance, but may be expansive when subjected to moisture.

Oklahoma

- RAP has been successfully used in asphalt pavements and is presently being used on a routine basis.
- Mine tailings have been successfully used in skid resistant seal coats and are now being used routinely.

Oregon

- RAP, both cold-in-place and hot recycled asphalt, has been successfully used in pavement construction.
- The use of scrap tires as asphalt-rubber binder has given mixed results relative to performance and is considered an experimental use at present.
- Asphalt-rubber SAMI has been successful to date but is still considered an experimental use.
- Scrap tires as asphalt rubber chip seals have been successful, but, at present, are not used in highway construction.
- Oregon has ruled as unacceptable the use of scrap tires (rubber filled asphalt concrete) because of inconsistent pavement performance.
- The use of asphalt-rubber adds to the benefits of the product, but also involves additional costs for the production of a ton of this material. For this reason, the product is not considered acceptable for use in highway construction.
- Although scrap tire use in asphalt rubber chip seals is quite successful, it is not acceptable for use in highway construction because it is not as cost effective as using emulsified asphalt cements for chip seal applications.
- The use of granulated scrap tires in asphalt is at present pending state legislation to this effect.
- Coal fly ash was used as a mineral filler in asphalt mixtures but was eliminated for further consideration because of a lack of technological benefit and because it was not cost effective.

Pennsylvania

- Scrap tires, although experimental in nature, have been used in constructing hot mix asphalt pavements. The reported results have been fairly successful.
- RAP has been used very successfully for a number of years and at present is used on a routine basis.
- The use of steel slag as an aggregate in asphalt pavements has been used very successfully for many years and is used widely on a routine basis.
- Blast furnace slag as an aggregate in asphalt pavements has also been used very successfully for many years and is also used widely on a routine basis.
- The use of waste glass has been legislatively mandated under ACT 101, The PA State Recycling Law. This law does not cite any specific usage of the waste glass material.

Rhode Island

- The use of scrap tires as Plus Ride™ was incorporated in a short section of experimental pavement approximately four years ago. At this time, pavement performance had been satisfactory. However, it was reported that inclusion of scrap tires is not cost effective.
- RAP has been included for a number of years in asphalt pavements with no reported assessment of performance. It is assumed that the RAP material is at this time acceptable.

South Carolina

- RAP has been incorporated into asphalt pavements with successful performance.
- Scrap tires have been incorporated into asphalt pavements with good success being reported.
- Blast furnace slags have been incorporated into asphalt pavements with reportedly good success.
- Steel slags have been incorporated into asphalt pavements, but the degree of success has been questionable. No further elaboration was provided.

South Dakota

- RAP has been used in asphalt pavements with reportedly good performance.

Tennessee

- The use of RAP in asphalt pavements has proven to be highly successful.
- The use of phosphate slag as coarse aggregate in asphalt concrete surface mixes has proven to be very successful.
- The use of ground scrap tires as a crack sealant has proven to be a very successful application of this scrap material.
- The use of used motor oil as a fuel source at an asphalt plant has proven to be a very successful use of this waste material.

Texas

- RAP has been used routinely in hot mix asphalt pavements and as bridge overlay material with much success.
- Ground tire rubber has been routinely used in hot rubber-asphalt seal coats with acceptable performance.
- Bottom ash has been used in limited amounts in asphalt pavements and to date has not caused any problems.
- Crushed clay pipe has been used in only one asphalt pavement and at this time has performed satisfactorily.

- Blast furnace slag has been used routinely as aggregate in asphaltic concrete as well as aggregate in seal coats. Good performance results were reported for both the slag in each of these respective uses.
- The use of RAP has been legislatively mandated in asphalt experimental projects.
- Although not mandated, the use of ground scrap tires is encouraged by allowing the acceptance of a 15 percent higher bid than conventional asphalt concrete in the life cycle cost-benefit analysis.

Utah

- RAP has been used in hot mix asphalt pavements with no reported assessment of performance to date.

Vermont

- RAP has been used in asphalt pavements with reportedly successful performance for these pavements.
- Waste glass is not considered acceptable in asphalt pavements, due principally to the variability of the waste glass material.

Virginia

- The performance of scrap tires in hot-mix asphalt pavement construction has reported as good in limited quantities.

Washington

- Crumb rubber has been used as an asphalt additive in hot-mix asphalt pavements with moderate success.
- RAP has been used in asphalt pavements and has shown very successful results.
- The use of sulfate waste as an asphalt cement binder substitute is not considered acceptable in pavement construction because it is not cost effective.
- The use of crumb rubber aggregate from scrap tires is not considered acceptable in asphalt pavement construction because it is not cost effective.
- All recyclable materials for highway construction are investigated under legislative mandate, Senate Bill 5143. This bill is a mandate for Washington DOT to do a 'State of the Art' assessment by January 1, 1992.

West Virginia

- Fly ash as a mineral filler in asphalt mixtures was considered potentially acceptable.
- Blast furnace slag used in asphalt mixtures was found to be potentially acceptable.

- The use of steel slag in an asphalt wearing course was found to be inconclusive in terms of its potential acceptability for use as a coarse aggregate.
- RAP used in asphalt paving mixtures was found to be potentially acceptable for its intended use.

Wisconsin

- The use of crumb rubber in asphalt pavements is not considered acceptable because the waste material produces brittle pavements. The use of crumb rubber from scrap tires was investigated under a legislative mandate.

Wyoming

- RAP is commonly used in asphalt pavements and is reported to be very successful.
- Scrap tires have been used in asphalt pavement friction courses with an unreported level of success. Scrap tires are not considered acceptable in highway construction because they are not cost effective.
- The use of bottom ash in plant mixed asphaltic pavements is not considered acceptable because of low durability and the highly absorptive nature of the material.

District of Columbia

- No field experiments were reported.

CHAPTER THREE

SHORTAGES OF AGGREGATES AND/OR BORROW MATERIALS

Because of the need to supply large quantities of raw materials (earth, stone, sand and gravel) to the construction industry, supplies of these natural resources are gradually being depleted in many parts of this country. Some areas are not blessed with deposits of high quality rock or granular materials, while in other areas some sources of these materials may not be readily accessible because of land development or zoning restrictions against mineral extraction. Shortages of high quality aggregates and/or granular borrow materials can be attributed as much or more to lack of availability in a certain area than to an absence of such materials.

Although technical acceptability and economic competitiveness are necessary for the recycling and reuse of waste materials and by-products in highway construction, the availability of a waste material or by-product in an area that is experiencing shortages of naturally occurring construction materials is another factor which could stimulate the use of non-conventional materials.

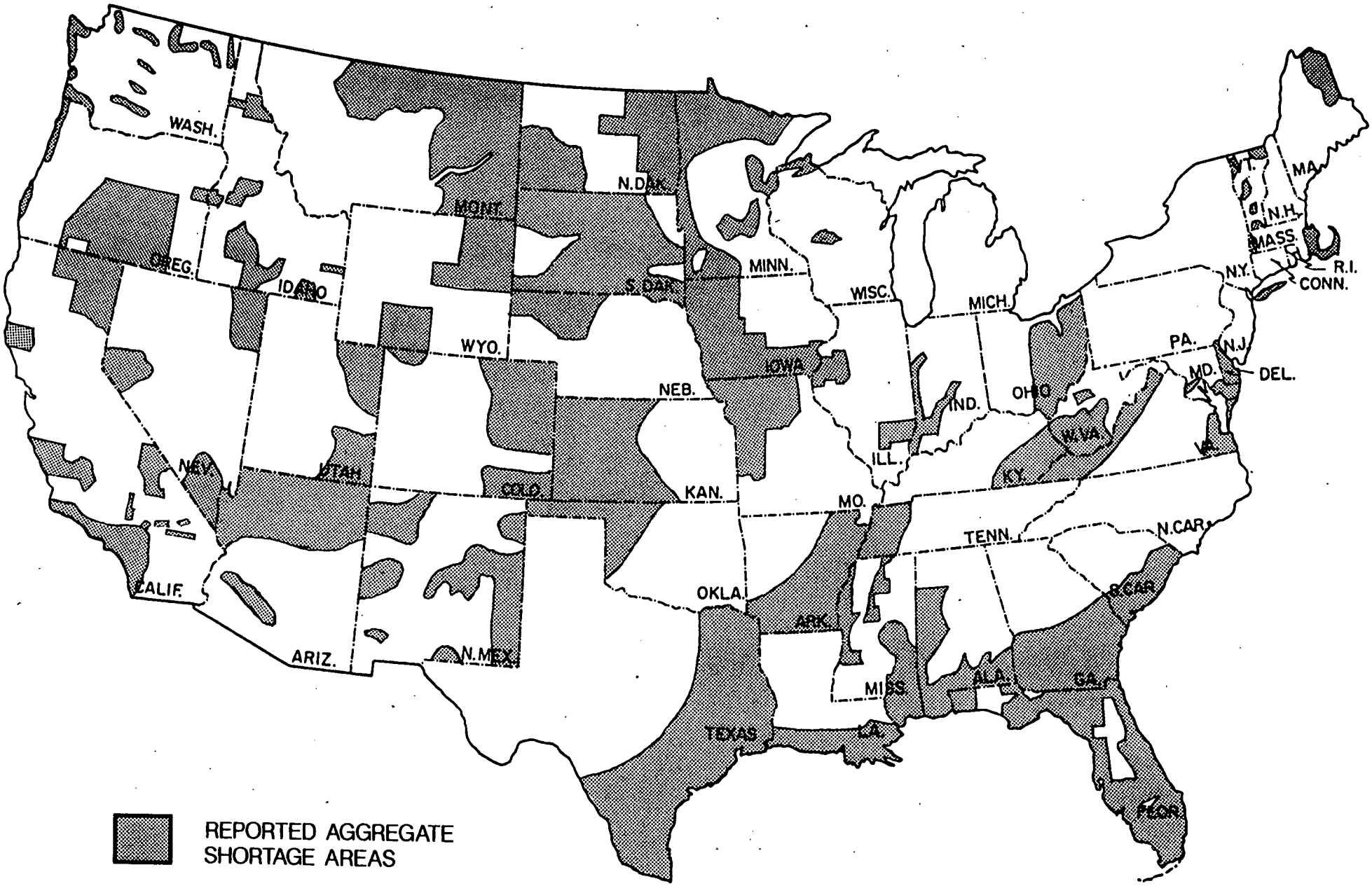
A survey was conducted to gain a more complete understanding of the possible existence of shortages of aggregates and/or borrow materials in the continental United States. The survey consisted of a written request to the chief materials engineer in each state transportation agency, asking for locations within each state where high quality aggregates and/or granular borrow material were in short supply, or not available within a 50-mile hauling distance. Each letter was accompanied by a map of that state, with symbols to indicate the locations of the shortage areas.

Responses were received from 40 of the 48 states in the continental United States concerning locations of shortage areas for natural aggregates and/or granular borrow materials within these states. Alaska and Hawaii were not contacted relative to locations of such shortages. The responses received usually included a transmittal letter and/or a state map marked with shortage area locations, if there were any in that particular state.

From this information, together with a previously published investigation of conventional aggregate shortages by Witzcak et. al. (158), a map showing the locations of reported aggregate shortage areas has been prepared. Figure 14 shows these areas of the continental United States where aggregate shortages have been indicated, either recently by state highway agency personnel or from earlier studies.

FIGURE 14

LOCATIONS OF REPORTED AGGREGATE SHORTAGES



In many cases, additional information beyond that concerning natural aggregate shortages was provided by state highway agency respondents. Some respondents provided a brief discussion of the causes for high quality aggregate shortages within their state, sometimes including the geologic description of prevalent rock type involved. In other cases, locations of granular borrow material shortages (which are not shown in Figure 14) were also indicated on individual state maps. A discussion of individual state responses providing additional information over and above that shown on Figure 14 is included in this chapter.

Alabama

Some shortages of granular borrow material in Alabama have been indicated in the eastern part of the state, east of the Coosa River and in north central Alabama in the vicinity of Huntsville, on the north and south sides of the Tennessee River. Granular borrow material is also in somewhat short supply in Sumter County along the western border, west of the Tombigbee River.

Arkansas

According to the Arkansas State Highway and Transportation Department, the aggregate shortage area shown in Figure 14 also represents an area that is generally deficient in granular borrow materials. Although there are isolated sources of sand and gravel within this area, most granular borrow deposits have been depleted and only marginal quality materials remain (Jim Gee, Engineer of Materials and Research. Private Communication).

Arizona

Correspondence from the Arizona Department of Transportation indicates that there are generally shortages of high quality aggregates in many parts of Arizona, but not in the Phoenix and Tucson metropolitan areas. There are, however, no shortages of granular borrow material in the state (Douglas A. Forstie, Assistant State Engineer. Private Communication).

California

The state map of California, which showed the locations of aggregate shortage areas, also showed the locations of granular borrow material shortage areas. The locations of both shortage areas were identical.

Colorado

The locations of granular borrow material shortages were indicated on the map of aggregate shortage areas as being in essentially the same locations as those of aggregate shortages. The only exception in Colorado was in the northeast corner of the state, where there is no granular borrow shortage indicated along the Platte River.

Connecticut

The state map of Connecticut was marked to indicate locations of trap rock quarries and gravel pits. There are twelve quarries and eight gravel pits scattered throughout the state. Locations of several other quarries and/or gravel pits in nearby New York and Massachusetts were also indicated. Since there are no areas in Connecticut that are more than approximately 15 to 20 miles away from a source of aggregate or granular borrow material, there are no shortage areas within the state.

Florida

The Florida Department of Transportation returned two state maps, one showing shortage areas for limerock base aggregate and the other showing shortage areas for silica sand. Generally, shortages of either or both types of aggregate are being experienced in most areas of the state, except for some counties in the north central part of Florida.

Georgia

In addition to a shortage of high quality aggregates in the southern half of Georgia, there is also a shortage of granular borrow material in nearly all of the counties in the northern part of the state.

Idaho

No granular borrow material shortages were indicated on the state map of Idaho.

Illinois

The state map of Illinois showed two areas where there has been a reported shortage of high quality aggregates for concrete and bituminous construction. In addition, portions of about 17 counties south and east of the area in western Illinois have experienced some shortages of concrete aggregates. It has also been reported that no general areas in Illinois have a shortage of granular borrow materials (James G. Gehler, Engineer of Materials and Physical Research. Private Communication).

Indiana

In general, nearly every section of Indiana has a number of producers of high quality aggregate materials. The only exceptions to this are in the southwestern portions of the state where deleterious constituents plague deposits along the Wabash River and the West Fork of the White River. Sand and gravel producers are quite numerous throughout Indiana, so there are no shortages of granular borrow materials (Robert J. Rees, Field Support Geologist, and Kenneth R. Hoover, Chief, Division of Materials and Tests. Private Communication).

Louisiana

The state map of Louisiana shows a shortage of both high quality aggregate and granular borrow material along the Gulf Coast, encompassing New Orleans and extending as far north as Lafayette. The predominant aggregate in the remainder of the state consists of river gravel, with a diminishing supply of shell. There are also at least 50 approved out of state suppliers of aggregate (mostly limestone and sandstone) that are used throughout Louisiana (Jarvis J. Poche, Materials Engineer Administrator. Private Communication).

Maine

There is a note on the state map of Maine that nearly all the glacially deposited sands and gravels in the northeast part of the state have moderate to poor hardness and wear qualities. There are, however, some local sources of bedrock in the area from which high quality aggregate could be manufactured. Shortages of granular borrow material may also exist in that area due to the lack of local glacial deposits.

Maryland

In addition to aggregate shortage areas in the southern half of the Eastern Shore and between Baltimore and Washington, D.C., the state map of Maryland also indicates two granular borrow shortage areas. These areas are in the southern half of the Eastern Shore and the western portion of the state, roughly from Frederick to Cumberland.

Massachusetts

The state of Massachusetts, in addition to indicating two areas of aggregate shortages (the eastern and western sides of the state), also shows shortages of granular borrow materials in the Boston metropolitan area and along the entire Cape Cod peninsula. Shortages of high quality aggregate and granular borrow materials are also shown for Martha's Vineyard and Nantucket islands.

Minnesota

Areas of aggregate shortages in Minnesota include the seven-county Minneapolis-St. Paul metropolitan area, where supplies are becoming depleted; the border lakes region along the Canadian border, with thin to non-existent glacial deposits; the Red River Valley area, with intermittent and inadequate gravel deposits; and the southwest region along the Iowa border, where a scarcity of gravel is compounded by a high percentage of undesirable shale particles. No granular borrow shortage areas were identified by the Minnesota Department of Transportation.

Mississippi

Several high quality aggregate shortage areas were indicated on the state map of Mississippi. Besides these areas, three granular borrow shortage areas were also shown on the map. One includes Jackson and an area to the north into Madison County. The second, in the eastern part of the state, extends north from Starkville nearly as far as Tupelo and south to Dekalb. The third includes the three counties along the Gulf Coast.

Missouri

Missouri has shortages of high quality aggregate in the northern and western counties of the state, including the Kansas City area. Missouri has granular material as stream deposits, but, as such, does not have what could be classified as borrow sites because of size.

Montana

The state map for Montana shows that shortages of high quality aggregates are prevalent throughout nearly all of the eastern part of the state and much of the northern portion. According to the state map, there are also interspersed shortages of granular borrow material within the same general area that was shown to have aggregate shortages.

Nebraska

According to the state map for Nebraska, there is a shortage of high quality aggregate materials in the northwest corner of the state. There is no shortage of granular borrow material in Nebraska (Laird E. Weishahn, Flexible Pavement Engineer. Private Communication).

New Jersey

Although no aggregate shortages were indicated on the New Jersey state map, there was one area in the state where a shortage of granular borrow material was indicated. This was in the northeast part of the state (Bergen, Essex, and Union Counties), across the Hudson River from New York City.

New Mexico

The state map for New Mexico shows at least four or five different areas of high quality aggregate shortages within the state, the largest of which lies along the eastern border. Although this area is shown as having a shortage, it has a wealth of caprock caliche, but it is not necessarily a high quality source of aggregate. There is no shortage of granular borrow material in New Mexico (James Yarbrough, Materials and Testing Engineer. Private Communication).

New York

Fine aggregates are in short supply in New York State only in the New York City-Long Island area, where land development and zoning have largely restricted the development of new material sources. Throughout the rest of the state, there are aggregate sources everywhere, although the quality is uneven. Granular borrow material is not in short supply anywhere in New York State (Wayne J. Brule, Director, Materials Bureau. Private Communication).

North Dakota

According to the state map of North Dakota, there are two sizeable areas of high quality aggregate shortages within the state. One is along the entire eastern border, including 17 counties. The other is to the south and west of the Missouri River in the southwest corner of the state, involving at least 14 counties. The map also indicates that there is a shortage of granular borrow materials in the southwest corner of North Dakota.

Oklahoma

As indicated in the state map of Oklahoma, there are high quality aggregate shortages in the western panhandle area of the state. There are no generalized shortages of granular borrow material, only isolated local problems.

Oregon

The state map of Oregon shows one large shortage area in the south central part of the state. Both high quality aggregates and granular borrow materials are in short supply. Most of the area along the west coast is also deficient of aggregate and borrow material, as well as a small area along the Snake River on the eastern border between Oregon and Idaho. Oregon's Highway Division considers a shortage to be beyond a 30 to 40 mile haul distance, with a high quality aggregate being one that can consistently meet the state specifications for portland cement concrete aggregate and asphalt cement specifications (William J. Quinn, Engineer of Materials and Research. Private Communication).

Rhode Island

Although no shortages of high quality aggregate or granular borrow material have been indicated for Rhode Island, there is an increasingly limited availability of these materials in the state because many quarries and pits which are sources of high quality materials are becoming depleted. A proposed revision of coarse aggregate specifications would relax the Los Angeles Abrasion loss requirement, but invoke a more stringent fractured faces requirement for crushed natural gravel (Colin A. Franco, Chief Civil Engineer, Materials Section. Private Communication).

South Carolina

A shortage of high quality aggregates is indicated along the coastline of South Carolina, extending about 40 to 50 miles inland, according to the state map. Also indicated on this map is an area where granular borrow material is in short supply in the northwest portion of the state, encompassing about 17 or 18 counties along or near either the North Carolina or Georgia border.

South Dakota

A state map of South Dakota indicates that shortages of high quality aggregate exist throughout much of the state. There are, however, no shortages of granular borrow material.

Texas

There is a sizeable area within the eastern one-third of the state of Texas, to the east and south of the Balcones Fault, which does not have an adequate supply of high quality aggregates. To the north and west of this fault, limestone is found in abundant supply. Generally, granular borrow material is also not readily available within this shortage area except in those counties bordering the Rio Grande River (Donald O'Connor, Materials and Tests Engineer. Private Communication).

Vermont

Generally speaking, Vermont's river valleys contain glacial lake deposits, while upland areas are covered by poor quality glacial tills. Areas with a poor supply of gravel usually also have a poor supply of granular borrow. The only exception to this is in the Champlain Valley in the northwestern portion of the state, which does not have good gravel but does have lake sand deposits and rock quarries (Alan J.McBean, Chief Geologist. Private Communication).

Virginia

There is a shortage of high quality aggregates in the eastern part of Virginia. In the western part of the state, carbonate rocks are predominant and they are plentiful. However, specifications for aggregates used in concrete pavements and bridge deck approach slabs require non-polishing siliceous aggregates. Therefore, this requirement results in a shortage of aggregates for these applications along the western border of Virginia. There is no general shortage of granular borrow materials (Celik Ozyildirim, Senior Research Scientist. Private Communication).

Washington

The state map of Washington indicates a number of areas throughout the state in which there are reported shortages of high quality natural aggregates. Each of these areas is also experiencing a shortage of granular borrow material (Keith W. Anderson, Project Manager. Private Communication).

West Virginia

West Virginia has a generous supply of high quality aggregates available in most areas, either locally or within easy access from neighboring states. If an area of shortage or limited local supply does exist, it is in some of the southern counties or in an area just above Kanawha County, as indicated on the state map. These areas consist mainly of sandstone, shale, and coal. Although there are pockets of high quality sandstone available, for the most part these areas can be considered as having localized shortages, not only because of a limited supply, but also because of the difficulty of access. No shortages of granular borrow materials were indicated (Gary L. Robson, Director, Materials Control, Soil and Testing Division. Private Communication).

Wisconsin

Wisconsin considers the lack of high quality aggregates within a 20 mile haul distance as a localized shortage. Using this criteria, a small area in the central part of the state was designated on the state map as an aggregate shortage area. No shortage of granular borrow material was indicated (Clyde N. Laughter, Chief Geotechnical Engineer. Private Communication).

Wyoming

The state map of Wyoming indicated two relatively large portions of the state as having shortages of high quality aggregates. One is in the northeast quadrant, including all or parts of at least 8 counties. The other is in the south central portion of the state, east of the Flaming Gorge Reservoir, including parts of two counties. There do not appear to be any shortages of granular borrow materials in Wyoming.

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