Use of Waste Materials in Highway Construction: State of the Practice and Evaluation of the Selected Waste Products

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The use of waste materials in highway construction in the United States and applications of selected waste materials, including waste tires, waste glass, reclaimed paving materials, slags and ashes, building rubble, and sewage sludge are discussed. An evaluation based on technical, environmental, and economic factors has indicated that reclaimed paving materials, coal fly ash, blast furnace slag, bottom ash, boiler slag, steel slag, and rubber tires have significant potential to replace conventional materials for various applications in highway construction and should be projected for future construction. Specific applications of the waste products and the potential problems associated with their usage in highway operations, which must be addressed before their extensive use, are included.

Enormous quantities of domestic, industrial, and mining waste are generated annually in the United States. There are three techniques for disposal of these waste materials: (*a*) recycling, (*b*) incineration with or without generation of energy, and (*c*) burial. The published data on current practice indicate that the bulk of domestic refuse is either incinerated or landfilled. Of the total municipal solid waste (MSW) generated in 1988 (i.e., 180 million tons), 13.1 percent was recovered, 14.2 percent was incinerated, and 72.7 percent was landfilled (*1*). Public concern is constantly expressed about the vast quantities of useful materials being discarded or destroyed. Legislation intended to stimulate recycling efforts is in force in a number of states and is being debated in others.

The state of the practice in the use of waste materials in highway construction in the United States and the performance of the selected waste products are discussed. Technical feasibility, environmental consequences, and economic benefits are considered.

STATE OF THE PRACTICE

Questionnaire Survey

To obtain information on current practices in the United States on the use of waste materials in highway construction, a questionnaire was developed and distributed to each state highway agency. The questionnaire requested information on the type of waste materials currently used in highway construction; their applications, annual quantities, and field performance; the materials and applications that appeared favorable and would be projected for future construction; and the materials and uses mandated by state laws. Of the 52 questionnaires distributed, 44 were returned, representing a return ratio of 85 percent (*2*).

Overview of Current Practice

A total of 27 waste products were reported by the 44 state highway agencies responding to the questionnaire. The waste products are currently in use (or being studied experimentally) in a variety of highway applications (see Table 1). Of the 27 waste products, only 11 (reclaimed paving materials, coal fly ash, rubber tires, blast furnace slag, steel slag, coal bottom ash, boiler slag, used motor oil, waste paper, mine tailings, and sewage sludge) are presently used by more than about 7 percent of the respondents. The six waste products currently used (or being studied experimentally) by two of the respondents are building rubble, waste glass, sawdust, ceramic waste, incinerator residue, and highway hardware. The remaining 10 waste products were reported by one of the respondent state highway agencies and are generally available in lesser quantities or their production is restricted to limited geographical locations.

Current practice indicates that reclaimed paving materials, fly ash, and rubber tires are used by a large number of respondents (98, 75, and 68 percent, respectively). The use of blast furnace slag has also been reported by a significant number of respondents (39 percent). The use of steel slag, bottom ash, and boiler slag also seems fairly attractive for highway applications (used by 16 to 20 percent of the respondents). The remaining products are less frequently used by the respondents.

The respondent state highway agencies have generally reported approximate annual quantities of waste materials currently used. The reported quantities indicate that reclaimed paving materials, slags, and ashes are generally used in large quantities. Rubber tires, although used (or studied experimentally) by a large number of states, are generally used in small quantities, with a few exceptions (Arizona, Oregon, and Vermont). This indicates that the use of tires in most of the states is generally in an experimental stage.

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TABLE 1 CURRENT USES OF WASTE MATERIALS IN THE UNITED STATES HIGHWAY INDUSTRY

Waste Material	States Using the Material[a]	Material is Used as Additive to[b]:/ Material is Used as[b]:				Other Uses[c]
		Wearing Course	Base	Subbase	Subgrade/ Embankment	
Reclaimed Paving Materials	43	23/8	26/16	14/8	6/5	3 (sh)
Coal Fly Ash	33	22/1	6/2	7/0	5/2	9 (cc)
Scrap Tires	30	22/0	6/1	1/0	3/3	11 (cs)
Blast Furnace Slag	17	5/4	3/5	0/3	1/2	4 (cc)
Steel Slag	9	4/1	2/2	1/0	0/2	1 (ic)
Coal Bottom Ash	7	2/0	2/1	1/1	1/1	3 (ic)
Boiler Slag	7	4/0	1/1	0/1	0/1	3 (ic)
Used Motor Oil	7	-	-	-	1/0	3 (recycle) 3 (apf)
Waste Paper	7	-	-	-	-	5 (ls) 2 (recycle)
Mine Tailings	5	-	-	-	0/5	-
Sewage Sludge	3	1/0	-	-	-	3 (ls)
Building Rubble	2	-	1/0	1/0	0/1	-
Waste Glass	2	1/0	2/0	-	-	-
Sawdust	2	-	-	-	0/2	-
Ceramic Waste	2	1/0	1/0	1/1	0/1	1 (pb)
Incinerator Residue	2	2/0	1/0	-	-	-
Highway Hardware	2	-	-	-	-	2 (recycle)

[a]Of the 44 states who responded to the questionnaire.
[b]The figures under each column indicate the total number of states that currently use the material.
[c]Abbreviations used: sh-shoulders, cc-cement concrete, cs-crack sealant, ic-ice control, apf-asphalt plant fuel, ls-landscaping, and pb-pipe bedding.
[d]A (-) indicate data not applicable.

The evaluation of waste materials with respect to economic, technical, and environmental factors is generally reported as at least competitive with conventional materials, satisfactory, and acceptable, respectively, with some exceptions. The most varied experience is reported in the case of rubber tires. Of the 30 state highway agencies that reported the use of waste tires in highway construction, 64 percent described their experience in the use of this product in asphalt pavements. In summary, 50 percent of those who reported their experience consider its use as uneconomical, 30 percent experienced poor performance, and 9 percent are doubtful about its environmental acceptability. The use of glass is reported as uneconomical by the only state highway agency that offered comments. One state highway agency identified potential problems with steel slag related to its expansive nature when used as an aggregate in portland cement concrete (PCC) and also expressed doubts about its environmental acceptability. Some of the agencies also expressed doubts about the environmental acceptability of reclaimed paving materials, fly ash, blast furnace slag, and sewage sludge. The only state highway agency that reported experience in the use of incinerator residue considers it environmentally unacceptable.

The survey indicates that the use of waste materials, in the majority of the respondent states, is not required by state laws. However, a number of state legislatures are considering required use of some waste products in highways to reduce waste disposal problems. This has stimulated research and investigations to determine the suitability of a number of waste products. Ten waste products were selected and have been evaluated in some detail in later sections.

RUBBER TIRES

Background

An estimated 240 million waste tires are discarded annually in the United States. Generation was higher in the 1970s and early 1980s, but the trend to smaller and longer-wearing tires has reduced the quantities (*1*). Projected estimates indicate a modest growth in tonnage and nearly a flat percentage of total generation (2.0 million to 2.2 million tons from 1995 to 2010). Small amounts of rubber are recovered for recycling (5.6 percent was recovered in 1988).

Tires occupy a large landfill space. Disposal of large quantities of tires accordingly has many economic and environmental implications. Scrap tire piles, which are growing each year, pose two significant threats to the public: fire hazard (once set ablaze, they are almost impossible to extinguish) and health hazard (the water held by the tires provides an ideal breeding ground for mosquitoes) (*3*).

Use of Scrap Tires in Asphalt Pavements

Crumb rubber additive (CRA) is the generic term for the product from scrap tires used in asphalt products. Addition of CRA to asphalt paving products can be divided into two basic processes. The wet process blends CRA with hot asphalt cement and allows the rubber and asphalt to fully react in mixing tanks to produce an asphalt-rubber binder. The dry process mixes CRA with the hot aggregate at the hot mix asphalt (HMA) facility before adding the asphalt cement to produce a rubber-modified HMA mixture. The four general categories of asphalt paving products that use CRA include crack/joint sealants, surface/interlayer treatments, HMA mixtures with asphalt-rubber binder, and rubber-modified HMA mixtures.

Crack/Joint Sealant

Crack/joint sealant is an asphalt-rubber product blending 15 to 30 percent CRA with the asphalt cement. It is covered in the American Society for Testing and Materials' specifications (ASTM D3406). The results of the survey reported here (Table 1) indicate that 11 state highway agencies currently use asphalt-rubber as a crack/joint sealant. The performance of asphalt-rubber as a crack/joint sealant is reported to be satisfactory. Stephens (*4*), based on a 9-year evaluation of field performance of asphalt-rubber as joint sealant, reported that site-mixed materials performed better than premixed materials.

Surface/Interlayer Treatments

Surface/interlayer treatments may use an asphalt-rubber binder with 15 to 30 percent CRA. This application of CRA began in the late 1960s and was patented under the trade name SAM (stress absorbing membrane) and SAMI (stress absorbing membrane interlayer).

SAM is a chip seal with an asphalt-rubber sealant. The purpose of this layer is to seal the underlying cracks, thereby preventing the entry of surface water into the pavement structure. It is also intended to absorb the stresses that would lead the underlying cracks reflecting up to the surface. It is formed by applying asphalt-rubber on the road, covering it with aggregate, and seating the aggregate with a roller. The thickness of the application usually varies from ⅜ to ⅝ in. (*5*), and 0.5 to 0.65 gal/yd^2 of binder is applied to the surface. Another approach to the construction of a SAM is to proportion and mix the asphalt-rubber material and chips in a conventional asphalt hot mix plant and to place the resulting mixture on a grade with a conventional asphaltic concrete spreading machine. However, the cast-in-place SAMs have performed better (*6*).

SAMI is a layer, with an asphalt-rubber binder, sandwiched between the road base and an overlay. The only difference between SAM and SAMI is that SAM does not have an overlay, whereas SAMI does. The purpose of SAMI is to reduce reflection cracking by cushioning or dissipating the stresses from the underlying pavement before they are transferred to the overlay. The procedure in placing the SAMI is similar to that used in placing the SAM, with a few differences in design aspects.

Asphalt-Rubber Mixtures

Since the late 1960s, the use of asphalt-rubber binder in HMA mixtures has been researched. Two such processes have been reported.

In the McDonald process, initiated in 1968, hot asphalt cement is mixed with 25 percent ground tire rubber to establish a reaction and then is diluted with kerosene for easy application (*7*). The Arm-R-Shield or Arizona refinery process, initiated in 1975, was patented by the Union Oil Company. It is currently marketed by Arizona Refinery Company (ARCO). The ARCO product incorporates extender oils and 18 to 20 percent recycled rubber from scrap tires directly in the hot liquid asphalt (*7*). The reported benefits of using Arm-R-Shield modified hot mix surfacing include flexibility down to −26°C (−15°F), higher viscosity than conventional asphalt at 60°C (140°F), a tougher and more elastic surface, greater resistance to aging, and recycling of used tires (*8,9*).

Rubber Modified Asphalt Mixtures

The concept of introducing coarse rubber particles into asphaltic pavements (using the dry process) was developed in the late 1960s in Sweden. It was originally marketed by Swedish companies under the patented name Rubit. This technology was introduced in the United States in the 1970s as the patented product PlusRide and is marketed by All Seasons Surfacing Corporation of Bellevue, Washington (*10,11*). The PlusRide process typically uses 3 percent by weight granulated coarse and fine rubber particles to replace some of the mix aggregates. The reported advantages of PlusRide in HMA applications are as follows: reflective and thermal pavement cracking are greatly reduced, resistance to studded tire wear is increased, skid resistance is increased, ice removal is easier, pavement tire noise is suppressed, and tires are recycled (*9,12*).

Discussion of Scrap Tires in Asphalt Pavements

Various laboratory and analytical studies (*6,13–16*) and industry publications (*8,12*) indicate that adding CRA to asphalt paving products (as a binder or as an aggregate) improves the engineering characteristics of the pavements, including service life. However, a careful analysis of information obtained as a result of the questionnaire survey and scrutiny of the published literature indicates that these claims are not always substantiated by the field performance of asphalt paving products containing CRA. Experience in the use of CRA in asphalt paving products showed both successes and failures.

The experience of a number of states in the use of CRA in asphalt paving products was studied to establish the causes of observed failures (*2*). However, it appeared that with a few exceptions, the failures and successes had been random, and no definite reasons could be offered with confidence for this unusual behavior (same percentage of CRA used in similar products under similar climatic environments demonstrated different behavior—one failed within a short period of construction, whereas the other performed much better than the control sections). Various reasons have been offered for the inadequate performance of the products (*17*). The writers believe that more research (analytical, laboratory, and field studies) is required to completely understand this technology.

Our study (*2*) indicated that asphalt paving products with CRA have also demonstrated consistently better performance in some states [e.g., Alaska (rubber-modified asphalt) and Arizona (asphalt-rubber)]. Similarly, some of the asphalt paving products, including two products that use asphalt-rubber binder (i.e., joint/crack sealant and SAMs) have displayed better performance in most of the cases and suffered fewer failures.

Various studies on the economics of using CRA in asphalt paving products (*14,17,18*) indicate that the products are not cost-effective, since the performance of the products is generally not commensurate with the enormous increase in cost (the cost is generally 50 to more than 100 percent above conventional materials). However, the additional cost of asphalt-rubber binder as a joint/crack sealant is justified in view of better performance. Similarly, additional costs of materials used in SAMs has also been acceptable on the basis of life cycle cost in most of the cases, due to its somewhat better performance and generally longer service life.

The asphalt paving products containing CRA are generally acceptable from an environmental viewpoint. However, some concerns have been expressed over increased air pollution as a result of adding rubber to the mix and the requirement of elevated temperatures during mixing.

The recycling of conventional asphalt pavements has gained wide popularity because of obvious economic and environmental benefits. Research studies have generally not addressed this issue (limited studies have been performed, but conclusions cannot be generalized (*19*)) in the cases of asphalt-rubber or rubber modified asphalt. If these pavements cannot be recycled on completion of their service lives, the disposal of these pavements will create another major waste disposal problem.

Use of Tires in Subgrade/Embankment

Two techniques to incorporate waste tires in subgrade/embankment are to use shredded tires as a lightweight fill material and to use whole tires or their sidewalls for soil reinforcement in embankment construction. Both techniques are practical and have been researched by some of the state highway agencies. The concept of using tires in embankment is also extended to enhance the stability of steep slopes along the highways (*20*), for temporary protection of slopes (*21*), for retaining of forest roads (*22*), and for protection of coastal roads from erosion (*23*).

Use of Tires as Lightweight Aggregates

Construction of roads across soft soil presents stability problems. To reduce the weight of the highway structure at such locations, wood chips or sawdust have traditionally been used as a replacement for conventional materials. Wood is biodegradable and thus lacks durability. Rubber tires are non-biodegradable and thus more durable.

The Oregon DOT used 400,000 shredded tires as a lightweight fill on Highway 42 (Coos Bay–Roseburg) 3 mi east of Camas Valley in a slide area and described the experience as a success (*24*). The Mn/DOT has experimented with the use of scrap tires in roadway fill across a swamp that was underlain with peat and muck. About 52,000 shredded tires were used as lightweight fill material in a 250-ft section of roadway. The section is reportedly performing satisfactorily (*25*). The University of Wisconsin-Madison has constructed a test embankment consisting of 10 sections using locally available soil and shredded tires in a number of different ways, including pure tire chips, tire chips mixed with soil, and tire chips layered with soil (*26*). Their preliminary monitoring and evaluation of the test embankment indicates satisfactory performance.

The Minnesota Pollution Control Agency sponsored a study on the feasibility of using waste tires in subgrade roadbeds (*27*). Twin City Testing Corporation of St. Paul, Minnesota, performed the laboratory study to evaluate the compounds produced by the exposure of tires to different leachate environments. They found that the recommended allowable limits set by the Minnesota Department of Health for drinking water were exceeded under "worst case" conditions for certain parameters.

The use of shredded tires in embankments as lightweight fill offers some economic and technical advantages under certain conditions. However, further research is required to address the various issues affecting long-term performance, including environmental concerns.

Use of Tires for Soil Reinforcement

Various agencies have practiced and evaluated the use of tires for soil reinforcement. Forsyth and Egan (*28*) described a method for use of waste tires in embankments and considered it promising. The method involves the use of tire sidewalls as mats or strips in an embankment to increase its stability. Their study indicated that the systematic inclusion of tire sidewalls benefits a fill and thus permits steeper side slopes and increases resistance to earthquake loading. Encouraged by the results of their study, Caltrans designed a tire-anchored wall system, in which tire sidewalls are used to anchor timber-retaining structures (*29*). The use of tires in retaining structures has also been practiced primarily for maintenance and rehabilitation of road embankments (*22*). Whole tires anchored in the backfill are used in various configurations for wall heights up to 10 ft. This application is economical, results in moderate face settlement, and may have aesthetic and environmental implications.

WASTE GLASS

Background

The generation of waste glass constituted 6.7 million tons in 1960. It continued to grow over the next two decades, but then glass containers were widely replaced by other materials, principally aluminum and plastics. Thus, the fraction of glass in the MSW declined in the 1980s, from 15 million tons in 1980 to 12.5 million tons in 1988. The projected estimates demonstrate a continuous declining trend in the generation of waste glass. An increase in the recovery of waste glass for recycling is predicted, from 1.5 million tons in 1988 to 2.1 to 3.1 million tons in 1995 (*1*).

The most obvious use for waste glass (commonly called cullet) is to recycle it to make new glass. However, the entire waste glass generated cannot be reused by glass manufacturers since only color-sorted and contamination-free cullet is considered feasible for reuse in the glass industry. Therefore, significant quantities of glass may be available for secondary applications. The feasibility of using waste glass in highway construction has been examined in the past. Various studies evaluated the use of waste glass as aggregate replacement in PCC structures and pavements (*30–32*). Asphalt pavements have also been studied (*33,34*). Glass has also been used as unbound aggregate in base layers and as fill material in embankments (*35*).

Use of Glass in Asphalt Pavements

Two states, Connecticut and Virginia, have recently conducted feasibility studies on the use of glass in asphalt pavements (*36,37*). The ConnDOT study, based on a review of literature, reports that glasphalt (glass-asphalt mixes in which glass replaces the conventional aggregates) was successfully mixed and placed in at least 45 locations in the United States and Canada between 1969 and 1988, mostly on city streets, driveways, and parking lots. It identifies potential problems with glasphalt, including loss of adhesion between asphalt and glass, maintenance of an adequate level of skid resistance, and breakage of glass and subsequent raveling under studded tires. The report recommends that glasphalt be used only as a base course (if laboratory mixes prove acceptable) to minimize potential skid resistance and surface raveling problems. Their economic analysis indicates that the use of glasphalt would be uneconomical (estimated at 15 percent more than conventional HMA in Connecticut under ideal conditions).

The limited laboratory study conducted by the Virginia DOT (*37*) indicates that the use of glass in asphalt mixes is technically feasible (with some reservations about the ability of glass to resist moisture damage) if several restrictions are observed. The restrictions include limitation of glass content to 15 percent or less; determination of the optimum asphalt content with the target percent of glass to be used; gradation controls of 100 percent passing the ⅜-in. sieve and a maximum of 6 percent passing the No. 200 sieve; and a tensile strength ratio (TSR) of the mix of 0.9 or higher. On economic feasibility, Hughes (*37*) concludes that "there is little monetary incentive to use recycled glass at the present time" in glasphalt in Virginia.

Use of Waste Glass in Portland Cement Concrete

The feasibility study conducted by ConnDOT (*36*) concluded that glass is not suitable for placement in PCC pavement or structures in ConnDOT facilities. The conclusion is based mainly on the study reported by Johnston (*31*), which indicated that glass is highly susceptible to alkali-aggregate reaction. The reaction between glass and cement causes expansion of glass and reduction in concrete strength. The elongated particles typical of glass cullet also present a problem with the workability of the concrete mix.

Use of Glass in Base Layers/Embankment Construction

The use of glass in unbound aggregate base layers is technically feasible (*37*). However, the use of glass as an aggregate will require it to be crushed to the appropriate gradation and pretreated if the level of contamination is not within acceptable limits. The economics of using glass in embankments depend on the local conditions.

RECLAIMED PAVING MATERIALS

The results of our questionnaire survey indicate that reclaimed paving materials are the most widely used waste products by the United States highway industry. Of the 44 state highway agencies responding to the questionnaire, 43 are engaged in testing, evaluation, and use of these materials in a variety of applications (see Table 1). The experiences of state highway agencies indicate that the use of these materials is economically feasible (cost competitive with the virgin materials), technically feasible (performance very good to satisfactory), and generally acceptable from an environmental viewpoint (good to satisfactory). A few state highway agencies have expressed their concerns over air pollution from effluents during heating of reclaimed asphalt pavements (RAP).

Recycling of Asphalt Pavements

Recycling of asphalt pavements is not a new concept. The first mention of recycling is in Warren Brothers portable asphalt plant sales brochure of 1915 (*38*). However, it was not until the oil crisis of the early 1970s, which rapidly increased asphalt prices and energy costs, that recycling became a feasible method of lowering highway construction costs. There have been numerous laboratory, field, and synthesis studies on the various aspects of hot mix and cold mix recycling (*39–41*). The experience of a number of states in recycling asphalt pavements has also been documented in NCHRP (*39*).

Recycling of asphalt pavements is a proven fact and many viable processes exist. It is generally cost-effective, and recycling of pavements has a positive impact on the environment. The potential problem of air pollution from asphalt plant operation can be reduced by installing emission control devices to make it environmentally safe. However, there is a need to standardize the design, construction, testing, and evaluation procedures.

Recycling of Concrete Pavements

The recycling of PCC pavements has been researched and practiced for a number of years in the United States (*42,43*). Experiences of a few state highway agencies and research findings were analyzed to determine the feasibility of recycling PCC pavements (*2*). Our analysis concluded that recycling of PCC pavements is technically and economically feasible. In addition, recycling of pavements will reduce waste disposal problems. However, further research is needed to address the potential problems (e.g., cracking of recycled concrete pavement) and to refine the mix design procedures and construction techniques. The economics of recycling PCC pavements vary with local conditions.

SLAGS AND ASHES

Slags and ashes, derived from the iron, steel, and electrical power industries, are perhaps the waste materials of greatest interest to the highway industry, given their wide availability and scope of uses. The by-products of the iron and steel industry, which have been historically used in the highway industry, are iron blast furnace slag and steel slag. The by-products of coal-burning plants, which have been widely tested in service and are useful for a wide range of engineering applications, are coal dry bottom ash, wet bottom ash, and fly ash.

Iron Blast Furnace Slag

Iron ore, coke, and limestone are heated in the blast furnace to produce pig iron. Produced simultaneously in the blast furnace is a material known as blast furnace slag. It is defined as "the non-metallic by-product consisting essentially of silicates and aluminosilicate of lime and other bases," and it leaves the blast furnace resembling molten lava (*35*).

Selective cooling of the liquid slag results in four distinct types of blast furnace slag: (*a*) air-cooled (solidification under ambient conditions), which finds extensive use in conventional aggregate applications; (*b*) expanded or foamed (solidified with controlled quantities of water, sometimes with air or steam), which is mainly used as lightweight aggregate; (*c*) granulated (solidified by quick water quenching to a vitrified state), which is mainly used in slag cement manufacture; and (*d*) pelletized (solidified by water and air-quenching in conjunction with a spinning drum), which is used both as a lightweight aggregate and in slag cement manufacture. The bulk of iron blast furnace slag produced in the United States is of the air-cooled variety (*44*).

Miller and Collins (*35*) rank iron blast furnace slag as having the highest potential among the waste materials for use in highways. Emery (*44*) identified the features of air-cooled blast furnace slag that make it attractive for highway applications: low compacted bulk density (typically 1200 to 1450 kg/m^3), high stability (California bearing ratio $>$ 100) and friction angle (approximately 45 degrees), high durability and resistance to weathering and erosion; free draining and not frost susceptible; and noncorrosive to steel and concrete.

The engineering properties of air-cooled iron blast furnace slag and the current practice indicate that its use in various highway applications is economical and technically feasible. However, some doubts are expressed about its environmental acceptability that need to be further investigated.

Steel Slag

Steel slag is a by-product of the steel industry. It is formed as the lime flux reacts with molten iron ore, scrap metal, or other ingredients charged into the steel furnace at melting temperatures around 2800°F. During this process, part of the liquid metal becomes entrapped in the slag. The molten slag flows from the furnace into the pit area where it solidifies, after which it is transferred to cooling ponds. Metallics are removed by magnetic separation (*35*).

Steel slags are highly variable, even for the same plant and furnace. Steel slags have high bulk density and a potential expansive nature (volume change of up to 10 percent attributed to the hydration of calcium and magnesium oxides). In view of their expansive nature, steel slags are not feasible for use in PCC.

Steel slags have been used in the highway industry in asphalt mixes, pavement bases and shoulders, fills, and for ice control grit. Their most promising application is in asphalt mixes, since asphalt coating eliminates the expansion-related problems (*44*). However, the leachates from this material may be undesirable from an environmental viewpoint.

Coal Bottom Ash

The materials collected from the burning of coal at electric utility plants are referred to as power plant ash. They are produced in two forms: bottom ash and fly ash. Bottom ash is the slag that builds up on the heat-absorbing surfaces of the furnace and subsequently falls through the furnace bottom to the ash hopper below. Depending on the boiler type, the ash under the furnace bottom is categorized as dry bottom ash (the ash in a solid state at the furnace bottom) or wet bottom ash (the ash in a molten state when it falls in water). It is more often called boiler slag. Of the 17.5 million tons of bottom ash produced in 1986 in the United States, 13.4 million tons was dry bottom ash (*45*).

Recently, comprehensive laboratory studies have been conducted on the feasibility of using bottom ash in highway construction at Purdue University (*45–47*). The results of the studies (*45,46*) suggested that bottom ashes have a nonhazardous nature, minimal effects on groundwater quality, low radioactivity, and low erosion potential, but that they may be potentially corrosive.

Coal Fly Ash

Fly ash is the finely divided residue that results from the combustion of ground or powdered coal and is transported from the combustion chamber by exhaust gases. It is a siliceous material that, in the presence of water, combines with lime to produce a cementitious material with excellent structural properties. However, the properties depend on the type of coal-burning boiler. There are three types: (*a*) stoker-fired furnaces, usually not good for highway purposes; (*b*) cyclone furnaces, generally not good for use in PCC and not widely available; and (*c*) pulverized coal furnaces, usually the best quality and produced in large quantities (*48*).

Fly ash represents nearly 75 percent of all ash wastes generated in the United States (*35*). Our questionnaire survey shows that fly ash is the second most widely used waste product in practice. However, there is still much opportunity to expand the use of this product, since the reported data indidicate that 80 percent of the fly ash produced in 1984 in the United States was wasted in disposal areas (*48*).

Use of Fly Ash in Cement Concrete Mixes

The technology for use of fly ash in PCC and stabilized road bases is fairly well developed and has been practiced for many years. There is an abundance of published literature including synthesis study and technology transfer guidelines (*48,49*) on the various aspects of the use of fly ash in PCC. It was known that PCC can benefit from the addition of fly ash as early as 1914. Subsequent research has identified many benefits of the addition of fly ash in concrete mixes, including improved workability, reduced heat of hydration, increased ultimate strength, increased resistance to alkali aggregates, resistance to sulfate attack, reduced permeability, and economy (*48*). The benefits realized will depend on the type of cement, fly ash, mix design, and construction procedures. A study evaluating fly ash as an admixture in PCC (*50*) did not recommend its use for bridge decks, heavily loaded PCC pavements, or prestressed concrete structures.

Use of Fly Ash in Embankments

Faber and DiGioia (*51*) described case histories of embankment projects in which fly ash was used as a fill material, and the experience is reported as successful and economical. Lewis (*52*) has described the construction of a fly ash highway test embankment in Illinois. The performance of this embankment has been reported as satisfactory. However, this application is presently not much practiced. Although large quantities of fly ash can be consumed in embankments, the implications of this application are less known, especially its impact on groundwater quality.

BUILDING RUBBLE

Building rubble discussed in this subsection includes any suitable construction material resulting from the destruction/ demolition and removal from any existing structures and buildings. Building rubble is generally a heterogeneous mixture of concrete, plaster, steel, wood, brick, piping, asphalt cement, glass, and so forth. Paulsen et al. (*53*) estimated that roofing waste contains about 36 percent asphalt cement, 22 percent hard rock granules, 8 percent filler, and smaller amounts of coarse aggregate and miscellaneous materials. Substantial variability in the composition of building rubbles is also expected. However, it is important to consider the feasibility of its use in highway construction, since large quantities of this material may be generated as a result of some catastrophic activity, like earthquakes. Five million tons of concrete debris was generated in the 1971 San Fernando earthquake (*54*).

The research and experience (*53,55*) in the use of building rubble indicate that it has a potential for use as subbase and subgrade/embankment material. However, its technical and environmental suitability must be determined before use. The economics of using building rubble depends on many factors, which vary with local conditions.

SEWAGE SLUDGE

Sewage sludge is created as solids are removed from wastewater during treatment. Most of the sludge is harmless organics. Nutrients like nitrogen and phosphorus are also present and can make for an effective fertilizer. But sludge also contains contaminants taken from wastewater, such as heavy metals, organic carcinogens, and pathogens. Currently, more than 7 million dry tons of sludge is produced each year in the United States. Disposal is as follows: municipal landfills, 41.0 percent; incineration, 21.4 percent; land application, 21.4 percent; distributing and marketing, 9.1 percent; and others, 12.9 percent (*56*).

The review of available information on the use of sewage sludge indicates that its by-products (i.e., compost and incinerated ash) have potential for use as a fertilizer and as an aggregate in landscaping and highway construction, respectively (*57–59*). The use of compost is beneficial but has potential safety and environmental risks, whereas use of sewage ash as an aggregate has technical, economic, and environmental implications. The risks must be investigated before their use in highways.

CONCLUSIONS AND RECOMMENDATIONS

An evaluation based on technical, environmental, and economic factors indicated that reclaimed paving materials, coal fly ash, blast furnace slag, bottom ash, boiler slag, steel slag, and rubber tires have significant potential to replace conventional materials for various applications in highway construction and should be projected for future construction. Technical, economic, and environmental problems associated with various applications of waste materials, identified under each waste material and briefly discussed, must be addressed before extensive use of these waste products in highway construction.

ACKNOWLEDGMENTS

The authors would like to thank the Indiana Department of Transportation and the Federal Highway Administration for support of this work. Thanks are also expressed to all the United States highway agency officials who responded to the survey questionnaire of this study.

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Publication of this paper sponsored by Committee on Soil and Rock Properties.