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Workshop Topic 5
WASTE MATERIALS, BY-PRODUCTS, AND RECYCLED PRODUCTS

Expansion, rehabilitation, and maintenance of the transportation system are dependent on a supply of aggregate and binder. Projected aggregate requirements for 1985 are more than double the amounts for 1966, and binder requirements are also expected to increase significantly (1).

The demand for construction aggregates is increasing at a time when sources near urban and other high-use areas are being depleted, and the quality of available materials is either at a low level or becoming unavailable in certain locations because of mining restrictions, environmental protection regulations, and appreciating land values.

A restriction on aggregate and binder availability only recently recognized is that of energy. The primary binders used in paving materials are energy intensive and dependent to a large degree on the availability of natural gas and petroleum. Unfortunately natural gas and petroleum are now in short supply, and the forecast is for this supply to become more critical in the next 10 to 20 years. These critical supplies will almost certainly result in increased costs of primary energy sources, and thus the price of materials, such as binders, that are energy intensive will continue to increase. In addition, binders such as asphalt may eventually become a fuel source, provided the technology is developed to economically remove sulfur from the asphalt.

Although not so energy intensive as binders, aggregates require energy for removal from their source, crushing, sizing, transporting, placing, and compacting. Energy required by increased haul distances resulting from localized aggregate depletion may require that alternative aggregates be investigated.

Shortly before the widespread recognition of the short supply of energy, the concern for the environment became nationally important. A wide variety of environmental legislation was enacted with regard to air, water, and land pollution. One result of this legislation and subsequent regulation is finding suitable places for an abundant supply of waste products from industry, mineral processes, and domestic sources.

The purpose of the discussions conducted under topic 5 was to examine current and innovative practices and research needs concerning the use of wastes and by-products that result from industry, mineral processing, and domestic sources, some of which are now available because of air, water, and land pollution regulations. The reuse or recycling of road-building materials was considered within the scope of this topic. A summary of these discussions follows.

SUMMARY OF DISCUSSION

A recent NCHRP study conducted by Valley Forge Laboratories (2) delineated the types and amounts of waste materials that are potential replacements for highway aggregates. These materials have been classed in terms of industrial wastes, mineral wastes, and domestic wastes. Annually about 3.5 billion tons (3.2 Pg) of these solid wastes are being generated. The materials with the largest available tonnage include fly ash, blast furnace slag, steel slag, foundry wastes, coal refuse, copper tailings, dredge spoil, phosphate slimes, taconite tailings, and iron ore tailings. Another potentially large amount of waste solids may become available in the form of scrubber sludges as power generating facilities begin to use limestone scrubbers for SO_2 removal from stack gases. Many of these materials that exist in relatively large tonnages are located in areas away from urban areas. Thus, the available market is limited.

In addition to their use as aggregates and filler, many waste and by-products have potential use as a binder. Among the more important materials are sulfur and fly ash. Sulfur is expected to increase in supply because of the pollution-abatement programs and the necessity to burn the higher sulfur crudes and coals. Fly ash may be used as a partial replacement for portland cement and as a pozzolan in lime and portland concrete mixtures. Other potential binders may emerge from wood by-products in the form of resins or lignin or from pyrolysis of wood or other materials.

A list of 53 waste materials that have a potential for use as an aggregate, filler, partial binder replacement, or binder is given in Table 1. The probable use of each of the materials in terms of a binder or aggregate is shown together with annual quantity produced (if the information was available), extent of the material, assessment of additional energy required to use the material in the roadway, estimate of cost, potential use, and assessment of research requirements. A further notation indicates whether research has a likely long-term or short-term payoff. The assessment of energy requirements and costs to other materials is on a relative scale. Sufficient information for many of the materials was not available to complete the table.

The second major item discussed was that of pavement recycling operations. Two types of construction operations are in general use: in-place recycling and recycling through a central plant. Untreated and treated materials have been recycled by these construction operations. Treated materials are defined here as a chemically bound material. Table 2 gives the various types of pavement recycling operations and the present extent of their use. An estimate of whether the process can be implemented and the process and energy requirements costs are also given and are relative to other items within this table. Heater-planer, heater-scarifier, and heater-scarifier-remix operations have been used in many states and are included. Table 3 gives a list of typical examples of recycling operations in the United States.

CURRENT AND INNOVATIVE PRACTICES

Current regular practices in some portions of the United States are considered to be innovative in other locations. Historically new materials or a construction process is developed in one locale and refined in other localities before being widely accepted. For this reason those waste and by-product materials and the recycling operations that appear promising and are currently practiced in certain localities will be considered innovative, for the use of most of the materials and processes described above is not widespread in the engineering community.

The most promising binder systems from waste and by-product materials appear to be sulfur and fly ash. Relatively large quantities of these materials now exist or will exist in the future. Sulfur may be used as an asphalt extender or perhaps substitute or as a primary cementing agent. Fly ash as a pozzolan in portland cement and lime and cement stabilization appears promising and currently is in fairly widespread use. Promising aggregate substitutes appear to be blast furnace slag, steel slag, bottom ash, and mining wastes.

Recycling operations (Tables 2 and 3) are being used in certain locations. In-place recycling of untreated base courses has become popular on many maintenance and reconstruction projects. The use of heater-planers and heater-scarifiers is also being practiced on an increased scale in certain areas of the country. Recycling of pavement materials by techniques now practiced or that could be developed by short-term research projects must be considered as one of the more promising material and energy-

Table 1. Waste materials.

Material	Probable Use		Annual Quantity[a] ($\times 10^6$ tons)	Extent of Material	Additional Energy Required	Cost	Potential Use	Research Required[b]
	Binder	Aggregate						
Sulfur-asphalt	X	X	NA	National	Low to moderate	Moderate	Probable	Yes, short
Sulfur-primary binder	X		NA	National	Moderate	High	No	Yes, long
Fly ash-lime-cement	X		32	Regional	Moderate	Moderate	Yes	Yes, short
Fly ash, sintered		X	32	Regional	High	High	Yes	Nominal
Fly ash, fill		X	32	Regional	Low	Low	Yes	Nominal
Mine tailings		X	NA	National	Moderate	Moderate	Yes	Nominal
Crusher wastes		X	NA	National	Low	Low	Yes	Nominal
Incinerator residue		X	10	Local	Moderate	Low	Yes	Yes, short
Rubber tires, granulated	X	X	3 to 5	Local	Moderate	Moderate	Yes	Nominal
Rubber tires, vulcanized	X	X	3 to 5	Local	Moderate	Moderate	Yes	Nominal
Waste glass		X	12	Local	Low	High	Yes	None
Blast furnace slag		X	30	Regional	Low	Moderate	Yes	None
Steel slag		X	10 to 15	Regional	Low	Moderate	Yes	None
Dry bottom ash		X	10	Regional	Low	Moderate	Yes	None
Bricks		X	NA	Local	Low	Low	Yes	Nominal
Tile			NA	Local	Low	Low	Yes	Nominal
Stack dust		X	NA	Local	Low to moderate	Low	Yes	Nominal
Stack dust	X		NA	Local	Low	Low	Probable	Yes, short
Resins and lignins	X		NA	Regional	Unknown	Unknown	No	Yes, long
Sulfate and sulfite sludges	X	X	5 to 10	Regional	Low	Low	Yes	Yes, long
Scrubber sludges		X	NA	National	Low	Low	Yes	Yes, short
Slag cements	X		NA	Regional	Moderate	Moderate	Yes	Yes, short
Waste oils	X		NA	National	Low to moderate	Low	Yes	None
Sulfuric acid	X		NA					
Salt water	Low		NA	Local	Low	Low	Yes	Nominal
Oil shale asphalt								
Plastic wastes	X	X	2.5 to 3.0					
Sewage sludge		X	8 to 10					
Wood chips and saw dust			NA					
Pyrolysis	X	X	NA	National	Unknown		Yes	Yes, long
Wet bottom boiler slag		X	5	Regional	Low	Moderate	Yes	None
Foundry wastes		X	20	Local	Low to moderate	Moderate	Yes	Yes, short
Alumina red and brown mud	X	X	5 to 6					
Phospogypsum	X		5					
Phosphate slimes		X	20					
Anthracite coal refuse		X	10					
Bituminous coal refuse		X	100					
Asbestos tailings		X	1					
Copper tailings		X	200					
Dredge spoil		X	300 to 400					
Feldspar tailings		X	0.25 to 0.50					
Gold mining waste		X	5 to 10					
Iron ore tailings		X	20 to 25					
Lead tailings		X	10 to 20					
Nickel tailings		X	NA					
Phosphate slag		X	4					
Slate mining		X	NA					
Waste taconite tailings		X	150 to 200					
Zinc tailings		X	10 to 20					
Smelter waste		X	NA					
Building rubble		X	20					
Ceramic wastes		X	NA					
Rice hulls								
Concrete pipe								

Note: 1 ton = 907 kg.

[a] NA = not applicable.

[b] Short or long indicate whether the research has a short- or long-term payoff.

Table 2. Recycling operations.

Recylcing		Construction Operation	Extent of Use	Implement	Energy Required	Relative Cost
From	To					
Untreated base, subbase, and thin surface	Untreated base	In place	Common	Yes	Low	Low
	Treated base	In place	Common	Yes	Low	Moderate
	Untreated base	Central plant	Rare	Yes	Moderate	High
	Treated base	Central plant	Rare	Yes	High	High
Treated base, subbase, and thin surface	Untreated base	In place	Common	Yes	Moderate	Moderate
	Treated base	In place	Common	Yes	Moderate	Moderate
	Untreated base	Central plant	Rare	Yes	Moderate	High
	Treated base	Central plant	Rare	Yes	High	High
Asphalt-aggregate surface mixture	Untreated base	In place	Common	Yes	Low	Low
	Treated base	In place	Common	Yes	Moderate	Moderate
	Untreated base	Central plant	Limited	Yes	Moderate	High
	Treated base or surface	Central plant	Rare	Yes	High	High
Portland cement concrete surface	Untreated base	In place	Limited	Yes	Low	High
	Treated base	In place	Rare	Probably	High	High
	Untreated base	Central plant	Limited	Yes	Moderate	High
	Treated base or surface	Central plant	Limited	Yes	High	High
Existing base, subbase, and thin surface plus new material	Untreated base	In place	Limited	Yes	Moderate	Low
	Treated base	In place	Limited	Yes	High	Moderate
	Untreated base	Central plant	Rare	Yes	Moderate	High
	Treated base	Central plant	Rare	Yes	High	High
Heater-planer		In place	Common	Yes	High	Moderate
Heater-scarifier		In place	Common	Yes	High	Moderate
Heater-scarifier-remix		In place	Common	Yes	High	Moderate

conserving techniques available to the transportation engineer.

RESEARCH NEEDS

A number of areas in need of research were identified. Table 4 gives a list of recent, ongoing, and proposed research projects in the general area of waste materials and recycling. In general the majority of research effort should be expended on those materials that are in large national supply and are promising aggregate replacements and binder supplements or primary binders. Sulfur research efforts, therefore, appear to be essential and should continue as scheduled. The needed research in the sulfur area should be focused in the following areas:

1. Use of sulfur as an asphalt extender or supplement, mineral filler, and primary binder;
2. Development of equipment to handle sulfur-aggregate systems; and
3. Use of foamed sulfur.

Fly ash is another promising binder. Substantial research has previously been conducted in this area. Implementation and resolution of certain problems unique to particular fly-ash supplies are needed. The use of lignins and sulfites as binders needs long-term research efforts.

Promising research associated with aggregate replacements is in the areas of fly ash, bottom ash, blast furnace slag, steel slag, and mining wastes. Although these materials are now being used, optimization of their use in terms of material and energy conservation has not been intensively explored. Since conventional aggregate supplies are ample at the present time in many areas, the use of wastes and by-products must be justified for each case on both an economic and an energy basis.

Quarry by-products including fines offer potential for use in the pavement provided existing specifications are reviewed and altered to permit their use if performance is not sacrificed. As much as possible of the products produced from a given aggregate source should be used in an acceptable manner so that both materials and energy can be conserved.

Recycling operations are in need of research programs to improve both in-place and central plant recycling equipment. The biggest need for in-place equipment is to develop a pulverization system that does not need constant repair. This is particularly critical when surfacing materials are pulverized. Air pollution problems associated with hot, central plant recycling of asphalt concrete pavements must be solved and one hopes this can be done by minor changes to existing equipment. Energy requirements and costs associated with various recycling operations must be determined to provide the necessary input to the engineering community.

Another potential research program considered to be of importance is that of determining when a rejuvenating agent is to be added to the recycled asphalt mixture, what type, and how much. Private industry should develop materials; however, testing and evaluation techniques should be developed by public agencies.

Suggested research projects of a more general nature include

1. Pavement design concepts that consider rehabilitation,
2. Energy requirements and costs of various rehabilitation alternatives,
3. Identification of materials suitable for recycling,
4. Energy and material-efficient pavements, and
5. Alternative binders from renewable resources.

Pavements should be designed such that rehabilitation techniques are energy efficient and inexpensive as possible. The pavement may have to be designed such that the surface is the weak link in the structure since repair can be effected most easily at the surface. For example, ways to design and construct the surface material for easy recycling should be investigated. The energy requirements and costs for various re-

Table 3. Recycling projects.

Type of Material Recycled	Location of Project	Use of Aggregate	Remarks	Reference
Unstabilized base course	Florida	Unstabilized base		4
	Michigan	Stabilized base		5
Stabilized base course	Wisconsin	Unstabilized base	No. 8 wire mesh also processed to meet specifications	6
	Texas	Asphalt stabilized base		19
Portland-cement concrete	Michigan		Predict improved skid resistance and stronger pavement	7
	District of Columbia	Aggregates in general		8
	California	Stabilized base, untreated base	Compaction tests showed crushed rubble is superior to many plant-run aggregates	9
	Wisconsin	Untreated	Crushed old paving brick	6
	California	Lean mix cement base	Excess air in mix required use of de-air-entraining agent	10
	Texas	Asphalt stabilized base		—[a]
	Texas	Asphalt stabilized base, asphalt concrete	Some air pollution problems experienced	3
	Texas	Asphalt stabilized base, asphalt concrete seal coat	Old airfield pavement used	—[a]
	Texas	Asphalt concrete seal coat	Aggregate was produced at a cost less than conventional aggregate	11
	Louisiana		Old pavement was broken, seated, and overlaid	12
Asphalt concrete	California	Stabilized base	Metradon pulverizer used	14
	Indiana	Asphalt stabilized base	Some air pollution problems experienced	—[a]
	Iowa	Asphalt stabilized base		6
	Utah	Asphalt concrete surface course	Some air pollution problems experienced	—[a]
	Massachusetts	Base material for runway	15 percent cost savings over conventional methods	13
	Nevada	Asphalt concrete surface course	New plant used that eliminates air pollution	15
			Substantial fuel and materials savings, reduced oxidation of asphalt	16
			No environmental problems	17
			Little difference in recycled and new asphalt concrete	18
	Texas	Asphalt concrete surface course	Drum mixer used	—[a]
	Texas	Asphalt stabilized base and asphalt concrete	Air pollution problems encountered with both conventional and drum mixer plants	25
	Texas		Cold process	—[a]

[a] Information obtained from private communication or unpublished documents.

Table 4. Summary of research in the area of waste materials, by-products, and recycled products.

Agency	Status or Year Started	Title
FHWA	Completed	Highway Litter in Highway Construction and Maintenance
FHWA	Completed	Sulfate-Fly Ash-Lime-Aggregate Mixtures at Dulles Airport
FHWA	Completed	Production of Synthetic Aggregate From Municipal Incinerator Residue
FHWA	Completed	Rubber-Asphalt Binder for Seal Coat Construction
FHWA	Under way	Incinerator Residue in Bituminous Base Construction
FHWA	Under way	Lime Treatment of Incinerator Residue for Base
FHWA	Under way	Technology for Use of Waste Sulfates as Aggregates and Binder
FHWA	Under way	Technology for Use of Incinerator Residue as Highway Material
FHWA	Under way	Use of Waste Sulfate for Remedial Treatment of Soils
FHWA	Under way	Power Plant Bottom Ash in Black Base and Bituminous Surfacing
FHWA	Under way	Availability of Mining Wastes and Their Potential for Use as Highway Material
FHWA	Under way	Production of Synthetic Aggregate by Fusion of Incinerator Residue
FHWA	1975	Advanced Technology Materials Applied to Guideways, Highways, and Airport Runways
FHWA	1975	Extension and Replacement of Asphalt Cement With Sulphur
FHWA	1975	Demonstration Project on Recycling of Asphalt Pavements
FHWA	1976	Evaluation of Wood Resins and Lignins as Substitutes for Asphalt
NCHRP	1976	The Reuse of Materials in Pavement Rehabilitation
NCHRP	1976	Upgrading Poor Performance Aggregates for Use in High Type of Pavements
FHWA	1977	Materials and Techniques for Improving Engineering Properties of Sulphur
FHWA	1978	Rapid Removal Methods for Portland Cement Concrete Pavement
FHWA	1978	Equipment for Economical Recycling of Highway Materials for Maintenance
FHWA	1978	Development of Pilot Manufacturing Process for New and Improved Aggregate
FHWA	1978	Development and Design of Flexible Sulphur-Concrete Paving Mixtures
FHWA	1978	Development and Design of Rigid Sulphur-Concrete Paving Mixtures
California	Under way	Fill Stabilization With Nonbiodegradable Wastes
Arkansas	Completed	Production of Binders and Fillers From Cellulosic and Man-made Polymeric Wastes Generated in Arkansas
North Dakota	Completed	Laboratory Evaluation of Lignite Fly Ash in Portland Cement Concrete
Arizona	Under way	Utilization of Waste Boiler Ash in Highway Construction in Arizona
Arkansas	Completed	Use of Fly Ash as Fill and Base Material in Arkansas Highways
Arizona	Under way	Investigation of Chemical and Physical Properties of Rubber-Asphalt Mixtures
Texas	Under way	Engineering, Economy, and Energy Considerations in Design, Construction, and Materials

habilitation alternatives, including the use of recycling, waste materials, overlays, and heater-planing, must be determined to allow the practicing engineer the opportunity to optimize design and rehabilitation alternatives. Not all materials and pavements are suitable for recycling. The recycling technique must match the rehabilitation need. For example, a bituminous-stabilized base that has water susceptibility problems should not be recycled without some type of acceptable treatment. Heater-planer and heater-scarifier operations are limited in their application, and these limitations should be defined. Projects 4 and 5 above were considered by other groups, and details are not presented here.

CLOSING REMARKS

Waste materials, by-products, and recycling operations offer energy, material, and cost-saving alternatives that can be immediately implemented. Additional research is required to optimize certain uses and to develop others as outlined above. Perhaps the single biggest need is to implement what is currently practiced.

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