199

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 members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration of the U.S. Department of Transportation.

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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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National Research Council
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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 improvements. 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 municipal 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. Reinforcement 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 by-product. 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

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 <u>not</u> 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 conaining 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 mate rials, 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		ACTUAL USE OF FLY ASH		
		ALLOWED	NOT ALLOWED	ROUTINE	EXPERIMENTAL	C or F OR BOTH
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 & 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

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

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