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FINAL REPORT

POTENTIAL FOR UTILIZING INDUSTRIAL WASTES AND BY-PRODUCTS IN CONSTRUCTION OF TRANSPORTATION FACILITIES IN VIRGINIA

by

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Consultant

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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SUMMARY

This report constitutes: (a) a survey to determine the availability in Virginia of waste materials or by-products that may have a potential for use in highway construction, (b) a summary of published literature concerning the use of waste materials in highway construction, and (c) a review of current and previous experimental projects and research in Virginia involving the use of waste materials.

The types of wastes discussed include mining and quarry wastes; metallurgical wastes; industrial wastes, especially fly ash and bottom ash; municipal wastes including incinerator residues, building rubble, asphalt pavement, portland cement concrete pavement, discarded automobile tires, old lubricating oils, and sewage sludge; and agricultural and forestry wastes.

It is concluded that while a number of solid waste products are technologically suitable for use in highway construction, conditions in Virginia are such that the use of such products seldom provides an economical alternative to the use of conventional aggregates. There is a possibility that some wastes can be successfully utilized as a means of avoiding environmentally undesirable accumulations. However, such accumulations do not now appear to be a serious concern within the state.

Because of the continuing development of the technology of using fly ash and other products from coal combustion, the report recommends continuing efforts by Virginia to develop suitable specifications and procedures for utilizing such products — especially fly ash. It is also recommended that increased experimentation with recycling both asphalt and portland cement concrete pavements be undertaken.

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INTRODUCTION

Over the past 10 years considerable attention has been paid to the potential utilization of industrial waste materials and by-products in various segments of the economy. This interest was created by environmental concerns. In particular, the creation of huge stockpiles of solid industrial wastes and the open burning of domestic waste became unacceptable. This led to efforts to find new uses for the solid wastes and also efforts to recover resources from the domestic wastes as well as develop environmentally acceptable disposal procedures for the residues. The developing energy shortage added another dimension to the disposal of domestic wastes since it was realized that the large percentage of combustible material present in such materials represented considerable energy. This energy could be used under proper circumstances as a source of heat and also to provide steam for direct use or for the generation of electricity. Highway and transportation departments are not directly concerned in these efforts, but the growing concerns in many areas about potential shortages of aggregates led to interest in investigating the usefulness of solid wastes in highway construction, particularly those wastes resulting from mining and quarrying operations.

The possibility of using wastes in highway construction principally as a means for solving environmental problems created by the stockpiling or disposal of waste materials has also been considered. With respect to energy conservation it is also reasoned that the use of a waste material in lieu of a new material that must be manufactured or processed from natural resources should be less energy-intensive. However, despite these first impressions that the use of waste materials provides an economical and energy-efficient way to solve such problems, there are a number of factors that make it difficult to routinely use waste products for highway construction in many geographical areas.

PURPOSE AND SCOPE

This study was undertaken to assess the factors in Virginia that affect the use of waste and by-products and to determine, if possible, in what areas of the state use of these materials might be economical or have environmental advantage.

A general survey of the wastes and by-products being generated in Virginia was made and the major needs of the Department of Highways and Transportation were compared with the availability and potential usefulness of such materials. Also included in the survey was a summary of any past use of these materials and an evaluation of their performance and usefulness.

IDENTIFICATION OF USEFUL WASTES AND THEIR AVAILABILITY IN VIRGINIA

To provide the necessary background information on the types of wastes or by-products that have potential application, a literature review was made and some of the more important reports are given in the Appendix as an Annotated Bibliography. Table 1 represents a summary of all the replies received in the state survey. In general, it was found that under present conditions in Virginia opportunities for major savings in either energy, money, or supplies of conventional high quality materials are somewhat limited. However, in some instances developing trends may eventually make waste and by-product utilization a more rewarding activity. The national and international literature identifies those wastes having established uses as well as those having potential for various purposes. Table 2, taken from a report by the Organization for Economic Cooperation and Development (OECD),[1] lists the types of wastes considered to have potential for use in road construction. The OECD report was compiled by 18 researchers from 13 countries including the United States and Canada in North America. The table was distributed by the Transportation Research Board (TRB) as Research Results Digest No. 106, January 1979.

All of the five major subdivisions in Table 2 are of some interest in Virginia, although the individual products within each subdivision are considerably more limited than shown in the table and not all major types are actually being generated in Virginia.

Table 1

Types and Sources of Wastes in Virginia Having Potential for Use in Highway Construction

Type of Material	Manufacturer and Location	Previous Use	Possibility of Use	Amount Available (tons)(1)	Present Disposal Method	Considered Environmental Problems	REMARKS
BRISTOL DISTRICT							
Fly Ash	Appalachian Power Co. Clinch River Plant, Cleveland, Virginia, 24225	Yes		25,000/mo			Fly ash partially marketed by Santee Cement Co. Some trucked wet to landfill.
Bottom Ash	Appalachian Power Co. Clinch River Plant, Cleveland, Virginia, 24225	No	Good	5,000/mo			Some used for block. Remainder pumped in slurry to ponds.
Coal Fine Wastes	Westmoreland Co. Storage Division	Not Known	Good	Unlimited	Stockpile	Yes	Mostly shale and sandstone. May be good fill material. (Shale wastes do not have a good record as fill material because of degradation).
Fine Limestone Screenings (- 3/8 in.)(2)	Virginia Lime Co. Ripplemead, Virginia 24150	Yes		> 400,000	Stockpile	Yes	Blended with other material in dense-graded aggregate base - 21A.
Fines and Crude Rock	Sobin Chemical, Inc. Box 38, Piney River, Virginia, 22964	No	Low	?(Small)	Stockpile		Crude rock used in Riprap.
Hardwood Bark	Mead Paper, P.O. 769 Kingsport, Tennessee 37662	Yes	Good	3,000/mo			Could be shredded and used as mulch for slopes in cuts. 1975 study indicated economics are favorable for use, compared to straw
Broken Brick	General Shale Products, Inc. P.O. 3547, CRS-Johnson City, Tennessee 37601	No	Fair	30/mo.			Used in construction of private roads around plant.
Fly Ash	Eastman Chemical Products, Inc., Kingsport, Tennessee 37662		Good	(Large)	Landfill		Some sold.

Table I continued

Type of Material	Manufacturer and Location	Previous Use	Possibility of Use	Amount Available (tons)(1)	Present Disposal Method	Considered Environmental Problems	REMARKS
CULPEPER DISTRICT							
	No wastes reported						
FREDERICKSBURG DISTRICT							
	No wastes reported						
LYNCHBURG DISTRICT							
Fine sand	Kyanite Ming Corp. Dillwyn, Va.	Yes		Unlimited	Stockpile	Yes	Used as filler in aggregate bases.
Stone (Slate)	LeSueur-Richmond Slate Co., Arvonia, Virginia	Yes		Unlimited	Stockpile	Yes	Used in base courses with good results.
Slate	Amlite Corporation Snowden, Va., 24591	No	Good	> 100,000	Stockpile	Yes	Could be used as mineral filler. Has been used in tennis courts and in brick manufacture.
Stone (Slate)	Arvonia-Buckingham Slate Corp., Arvonia, Virginia	Yes		Unlimited	Stockpile	Yes	Used in base courses with good results.
RICHMOND DISTRICT							
Fine Sand Tailings	Feldspar Corporation Montpelier, Virginia	No	Fair	(Large)	Stockpile	Yes	Tests show compliance with specification for fine sand for bituminous concrete.
Fly Ash	VEPO Co., Dutch Gap, Va.	No	Good	(Large)	?	Yes	Some experimental use in concrete.
Clinker (Bottom)	VEPO Co., Dutch Gap, Va.	No	Good	(Large)	?	Yes	May be useful as aggregate in base courses or surfaces.
Old Tires	--------	Yes	Good	(Large)	?	Yes	Used in experimental project (ground rubber from old tires used with aggregate in surface treatment). Rubber and asphalt "cooked" at high temperature to partially dissolve the rubber in the asphalt.

Table 1 Continued

Type of Material	Manufacturer and Location	Previous Use	Possibility of Use	Amount Available (tons) (1)	Present Disposal Method	Considered Environmental Problems	REMARKS
SALEM DISTRICT							
Limestone Screenings (passing 3/8 in) (2)	Virginia Lime Co. Ripplemead, Va. 24150	Yes		400,000	Stockpile	Yes	Blended with other aggregate for dense graded base course 21-A. (Source also reported by Bristol District.)
Low Grade Lime	" " "	No	Fair	300,000	Stockpile	No	Combined materials could probably be used as fill materials. Use in stabilization projects would be questionable because of low lime content after stockpiling.
Lime + Fly Ash	" " "	No	Fair		Stockpile	No	
Kiln Scale	" " "	No	Fair		Stockpile	No	
Stack Dust	" " "	No	Fair		Stockpile	No	
Limestone Screenings (passing 3/8 in) (2)	National Gypsum Co. Gold Bond, Va. 24094	Yes		10,000	Stockpile	No	50,000 tons/yr. generated 40,000 tons sold. Blended with other materials for dense-graded aggregate base.
Low Grade	" " "	No	Fair	Total 50,000/yr.		No	Data available on possible uses. Combined materials could probably be used as fill material. Use in stabilization projects would be questionable because of low lime content after stockpiling.
Lime + Fly Ash	" " "	No	Fair				
Kiln Scale	" " "	No	Low				
Stack Dust	" " "	No	Fair				
Fly Ash	Hercules Powder Co. Radford Army Ammunition Plant, Radford, Virginia	No	Good	15,000-35,000/yr.	Landfill	No	Present production buried in landfill
Fly Ash	Appalachian Power Co. Glenlyn, Virginia	Yes	Good	100,000	Stockpile	Yes	Blended into 21-A base, believed to have increased strength.
Slag (Red Dog)	Montgomery County, Va.	Yes		> 40,000	Stockpile	Yes	Material is from abandoned coal mine and is the ash (or slag) remaining after burning of discarded low-grade coal thru spontaneous combustion. Used in aggregate base with good results.
STAUNTON DISTRICT							
Fly Ash	E. I. Dupont de Nemours Co. Dupont Blvd., Waynesboro, Va. 29980	No.	Fair	Not	Not Reported	Yes	May be of adequate quality for cement replacement in portland cement concrete.
Fly Ash	Aufex Fibers, Inc. Front Royal, Virginia	No	Fair	(large)	Not Reported	?	
SUFFOLK DISTRICT							
	No waste materials reported						

(1) 1 ton - 907 kg

(2) 9.5 mm

Table 2

Summary of Established and Potential Uses of Waste Materials and By-Products in Road Construction

Waste Materials and By-products		Binder	Stabilizing Agent	Filler	Aggregate: Portland Cement Concrete	Aggregate: Bituminous Concrete Surface Course	Aggregate: Bituminous Concrete Binder Course	Aggregate: Base and Subbase	Embankment Fill and Improved Subgrades
Mining and Quarry Wastes									
mining and quarrying wastes	a. colliery spoil		P	P	P	P	P	P	E
	b. quarry waste							P	E
	c. mine refuse							P	E
	d. slate waste				P	P	P	P	P
	e. oil shale residue							P	E
	f. china clay sand				E			E	E
	g. potassium salt mine							P	P
tailings	a. iron ore					E	E	E	E
	b. taconite					E	E	E	E
	c. fluorspar							P	P
	d. lead-zinc			P				P	P
	e. copper							P	E
	f. gold							P	P
muds, sludges	a. red mud (alumina)		P						
Metallurgical Wastes									
ferrous slags	a. blast furnace slag								
	- air cooled				E	E	E	E	E
	- granulated	E	E		E			E	
	- pelletized	E	E		E		P	P	
	- expanded				E				
	b. steel slag	P	P			E	E	E	E
nonferrous slags	a. zinc (lead, lead-zinc)		P		E		P	P	P
	b. copper		P					E	E
	c. nickel		P					E	E
	d. phosphate		P		E	E	E	E	E
	waste foundry sand								P
	ceramic and refractory wastes						P	P	P
Industrial Wastes									
ash	a. fly ash	E	E	E	E	P	P	E	E
	b. bottom ash (wet and dry)					E	E	E	E
	c. mixed							P	E
	kiln dust			E					E
	sulphur	E							
	dredge spoil				P	P	P	P	E
	boiler and furnace clinker and slag					E	E	E	E
	waste plastic				P	P	P		P
	pyrite cinders (kiesabbrand)								E
Municipal Wastes									
incinerator residue	a. ash		P	P					E
	b. clinker					E	E	E	E
demolition wastes	a. building rubble					P	P	P	E
	b. asphalt pavement					E	E	E	E
	c. concrete pavement				P	E	E	E	E
	glass and cullet		P				P	P	
	tyres (and rubber)					E	P		
	waste oils								
Agricultural and Forestry Wastes									
wood wastes	a. bark and sawdust								E
	b. lignin		P						
	c. paper mill mud		P						

E Established Use (accepted practice in road construction)

P Potential Use (research and development have indicated technical feasibility)

Source: Reference 1.

The wastes and by-products to be discussed in more detail in this report are as follows:

1. Mining and quarry wastes of various types.

2. Metallurgical slags, including blast furnace slag, steel slag, and nonferrous slags.

3. Lime wastes including sludges from stack scrubbers.

4. Agricultural and forestry waste, including bark, sawdust and lignin.

5. Residues from the burning of coal, including fly ash, bottom ash and boiler slag with emphasis on fly ash.

6. Municipal wastes, including incinerator residues, old concrete pavements, asphalt pavements, discarded automobile tires, used lubricating oils, and sewage sludge.

Mining and Quarry Wastes

The Federal Highway Administration (FHWA) conducted a nationwide survey of mining and metallurgical wastes to determine the availability of such materials and to assess their potential for use in various aspects of highway construction. The results of this study, conducted by Valley Forge Laboratories, Inc. for the FHWA, is reported in four reports, summarized in the appended Annotated Bibliography (see references 1-8, 1-9, 1-10, and 1-12). In Volume II of the FHWA report[2] it is noted that Virginia has five major sources of mineral wastes. These are rock and tailings from an open-pit feldspar mine in Nelson County (Lynchburg District); waste rock and tailings from an underground gypsum mine in Washington County (Bristol District); waste rock and tailings from an iron mine in Pulaski County (Salem District); waste rocks from a slate mine (quarry) in Buckingham County (Lynchburg District); and waste rock and tailings, principally dolomite, from a zinc mine in Wythe County (Bristol District). In addition, this report cites the availability of a large amount of coal-refuse piles in the southwestern part of the state, including Buchanan, Tazewell, Dickenson, Wise, Russell, Lee and Scott Counties. In discussing the trends and future generation of mining and metallurgical wastes, this report states the situation for Virginia to be: "There is one large zinc mine in Virginia and a number of coal mines in the southwest portion of the state. Mining trends in Virginia are oriented toward the coal industry, since it is a growing industry in this state."

The report cites plans for two new coal mines. One in Buchanan County and the other in Esserville.

The responses to the questionnaire sent to each District Engineer in Virginia generally confirm the findings in the FHWA report. However, except for the use of crushed slate for base courses in the Lynchburg District, there is very little potential for use of any of these identified products in highway construction. The by-product from the zinc mine in Wythe County is mostly in the form of a fine slurry and is marketed as an agricultural lime. Similarly, the by-products of the gypsum mine are essentially completely utilized. The unburned waste materials from coal mines are chiefly shales that are unstable as a highway material and, under present circumstances, cannot be economically used in fills or embankments.

Slags, or "Red Dog", the product obtained when coal mine refuse piles are completely burned out, can be used under some circumstances and some limited use of them has been made in Virginia. A study in 1975 by Noble of the Research Council staff concluded that "Red Dog" is adequate as a road building material but is inferior to sound, quarried, crushed and graded stone.(3) It was noted that the base courses built in the Salem District with "Red Dog" had performed well. However, Noble found that the material was not as widely distributed throughout the Virginia coal mining region as is commonly thought. The cost of hauling is an important factor in the use of any aggregate, and since "Red Dog" is found mostly in those areas of the state that have readily available sources of good aggregate, it does not offer large economic advantages over conventional materials. Other potential uses of "Red Dog" listed by Noble are as a shoulder dressing; for sanding during the winter, (after crushing); and as a skid resistant aggregate, provided it has sufficient durability.

The report recommended that materials engineers and design engineers should be encouraged to consider the use of "Red Dog" and mine wastes in the Department's highway construction and maintenance programs, with the reservation that such use should be consistent with the Department's policy of providing a quality product as economically as possible. It was emphasized that this encouragement should not be construed as pressure to use such materials. In general, the conclusions reached in this report are supported by those from other, more extensive studies conducted elsewhere.

The slate residues in Nelson County are being used in base courses with good results. There is also available a fine slate dust, collected from bag houses, that may have a potential for use as a mineral filler or that possibly would have pozzolanic characteristics. A study of crushed slates used as the coarse aggregate

for concrete was conducted at the Research Council in 1966 by McGhee and Ozol.[4] Their report concluded that on the basis of the laboratory tests made and petrographic examination, it was advisable for the Department to consider approval of the Arvonia slate as an acceptable aggregate. It was stated that such approval, contingent upon the ability of the slate producer to consistently produce sound aggregate of the proper gradation, should provide an economical source of good concrete aggregate for the area since other aggregates had to be hauled considerable distances. Experimental construction on a bridge deck was recommended in the report, but apparently this recommendation was not followed. Whether or not such use of slate would be economical under present conditions was not determined.

The material cited in the FHWA report as being waste rock and tailings from the open pit feldspar mine is regularly crushed and sold mostly for private uses as crusher run material. There is also a fine sand available from a kyanite mining operation which may have a potential use, but it is generally finer than materials suitable for highway construction. The principal use at present is in brick manufacture.

Other quarry wastes were reported as available in several districts. Limestone screenings passing the 3/8 in (9.5 mm) sieve are available in the Salem and Bristol Districts. This material has been used by blending with others to form base material meeting dense-graded aggregate (21-A) specifications and has performed well. It has also been used as a base course material on a secondary road. Fine sand tailings are available in the Richmond District as a waste of the Feldspar Corporation, Montpelier, Virginia.

In the evaluation of the usefulness of any mining or quarry waste, the gradation and properties of the material must be compared to the needs of the project. Where such products are physically sound and durable and can be blended with other materials which may or may not conform to specifications so that the resulting blend does conform, no problem would be expected from the use of such blends in base courses or surface layers. In some cases the materials or blends may not conform to standard specifications but would be adequate for specific projects as fills or embankments or for applications in building low volume rural roads. Decisions on such use require project-by-project evaluation and would most likely be based primarily on whether significant savings would result from the use of the alternative materials.

In general, the results of both the FHWA study and the survey conducted for this report indicate that the usefulness of good grade mineral wastes or by-products is recognized in Virginia and such materials are being used where they can economically compete with other products.

Metallurgical Slags

Metallurgical slags are described in the Executive Summary of the FHWA study.[5] It is pointed out that although they have different origins, they are all related in that they are derived from elevated heat treatment of ores and are formed under similar cooling and processing conditions. Three basic slag types were evaluated for the FHWA report. These are blast furnace slag, steel slag, and nonferrous (heavy metal) slags. Blast furnace slag has universal acceptance as a construction material and is widely used in highways. However, at the present time the material is not available for general use in highway construction in Virginia.

Steel slags vary considerably in composition, depending on the type of furnace being used. Steel slags usually have good abrasion resistance and angular shape. Their major disadvantage is that they have a tendency to expand because they contain large amounts of unslaked lime (CaO) and magnesia (MgO). While the unslaked lime will hydrate fairly rapidly (within a period of weeks), the magnesia hydrates very slowly, which results in volume changes that may continue for many years. Some efforts have been made to age steel slags in such a manner that the hydration reactions are accelerated and as a result the expansion occurs prior to use. In such cases the product is generally acceptable for construction. At present such products are not being generated in Virginia and are not available for use.

Slags from the smelting of non-ferrous metals such as copper, lead, nickel, phosphate and zinc ores are useful where available, but none are available in Virginia.

Lime Wastes

Large volumes of waste products are available in Virginia from at least two lime manufacturing companies. These consist of waste lime — primarily incompletely burned material removed from kilns because of breakdowns or other problems. This is uneconomical to rework as a raw material. The stack dust and slurry removed from scrubbers are also available. Some small use of this material for soil stabilization has been made in local low volume roads near the plant but no "commercial" development has been attempted. After storage, this material reverts back to calcium carbonate to a large extent, thus it may not have sufficient chemical activity to serve as a substitute for lime in stabilization projects, where specification requirements must be met. No record was found of controlled tests of the residues for this purpose.

The residue from the scrubbers contains gypsum ($CaSO_4 \cdot 2\ H_2O$) or other forms of calcium sulfate and, consequently, the material is of a type studied under an FHWA contract, the results of which are given in the reports annotated in Section 4 of the Bibliography in the Appendix. The reports by Nebgen, Edwards and Weatherman, (Bibliography reference 4-2)[6,7] and the report by Smith and Kawam (Bibliography reference 4-3)[8] would be of special interest to those interested in possible applications of this type of material. The possibility exists of using the wastes available in Virginia in fills or embankments, if there is a need for such material within reasonably short distances from the stockpile.

Agricultural and Forestry Wastes

The agricultural and forestry wastes of potential interest in highway construction and maintenance are bark and sawdust and by-products of the paper industry. Barks can be utilized as mulches for landscaping applications. The usefulness of sawdust as a light-weight fill for bridge abutments, etc. has been evaluated by the FHWA.[9] (see Annotated Bibliography reference 8-2.)

Numerous attempts have been made to sell the lignin residues from paper mills as soil stabilizing agents. Despite claims of promoters, the permanent usefulness of such materials is still questionable. Virginia has constructed experimental projects using several trade name materials of this type, but none have been found to provide cost-effective performance.

An inquiry to one major paper mill in Virginia found that at present they have a waste material composed of very short fibers that are removed from their waste liquid by filtration. This amounts to about 20 tons per day and is being disposed of in landfill. Some has been used experimentally in agricultural applications, primarily as a mulch. There is also some consideration being given to burning the material as fuel, but the high water content of the stockpile leaves a very low net fuel value.

Based on conditions in 1975, shredded bark was reported to be economically competitive as a mulching material for side slopes, etc. in cuts (see Table 1). However, more recent information by one company in Virginia is that under present conditions bark is more valuable as a fuel source when facilities for using it exist at the plant where it is generated. Consequently, at the present time there appears to be no buildup of waste from this source in Virginia which could be economically used in highway construction or maintenance.

Residue From Burning Coal

The residue from burning coal is the most widely available industrial waste in the eastern part of the United States. The residue is available in three forms: fly ash, bottom ash and boiler slag. Although active marketing of the material in Virginia for use in highway construction is somewhat limited at present, the prospects are that increasing amounts of ash will become available because of both the pressures to burn more coal in industrial activities and the need to collect the fly ash to avoid air pollution. A third factor is the ongoing efforts to increase utilization of the ash. Considerable research has been conducted on the use of these materials, especially fly ash. The National Ash Association was organized in 1968 to promote the use of ash and to assist in the development of information on its properties and technological potential. Five symposiums on the utilization of coal ash have been held over the past 12 years.(10-14) At each of these symposiums, papers were presented on all phases of ash production, utilization and research. In general, most of the emphasis has been on fly ash, but bottom ash and boiler slag have been given attention. A total of 205 presentations were made at these five symposiums. Several state-of-the-art reports are also available for different aspects of usage. For information concerning highway use the Implementation Package 76-16, "Fly Ash as a Highway Construction Material", published by the FHWA, U. S. Department of Transportation, provides a good summary of highway applications and guidelines.(15) Use of fly ash as a stabilizing agent in conjunction with lime is covered by NCHRP Synthesis Report No. 37, "Lime-Fly Ash Stabilized Bases and Subbases", published by the TRB in 1976.(16)

These and other reports establish the usefulness of fly ash in a number of highway applications. However, in general such reports are likely to underestimate some of the problems and restraints that make the routine use of fly ash in highway construction more difficult than might appear on the surface.

Fly Ash Marketing Problems

The problems of marketing fly ash as a pozzolan are discussed by Hyland in a paper presented at the Third International Symposium on Fly Ash Utilization.(17) He points out a number of difficulties that must be overcome before fly ash can be made available to the user. Hyland cautions the power plant executive that instead of a "gold mine" of potential profits, the ash may be a "malignant cancer" that must be controlled to ease suffering. The power company should not expect to make money by selling fly ash, but should be able to save money by reducing or eliminating disposal costs and by avoiding environmental problems. Hyland recognized that the power plant is in the business of manufacturing kilowatts not fly ash — but must be willing to establish a system for handling the ash in such a way that it is reusable.

The "easiest" disposal, which is often dumping fly ash along with bottom ash and boiler slag in a settlement pond, cannot be utilized if the fly ash is to be sold as a pozzolan. In such cases the cost of reseparating and drying the fly ash sufficiently for reuse makes the recovery uneconomical.

Hyland recommended that a special marketing company be organized for selling fly ash and developing marketing expertise. Such selling effort must emphasize the quality and economy of fly ash concrete and the particular benefits it offers. Characteristics of fly ash concrete such as better workability, pumpability, water tightness and resistance to aggressive waters must be demonstrated to the potential customer.

Hyland also discussed problems associated with trucking fly ash from the power plant. He indicated that some truckers refused to haul fly ash because of loading and handling problems. Station supervisors must be willing to cooperate with haulers by not tying up trucks and promptly cleaning up spills, etc. Also, arrangements must be made for having suitable ash available when needed. Hyland recommends that 1,000-ton (900,000 kg) silos be available for storage. A minimum of 300 (270,000 kg) tons should be on hand at the initiation of any project. Hyland emphasized that it must be understood that marketing fly ash as a pozzolan for use in concrete is a specialized job requiring special knowledge and good technical backup. The other partner in the marriage, the electric utility, is the production facility, and like all good production plants it must exercise good quality control practices and meet shipping schedules. Then, and only then, can fly ash be marketed successfully.

With respect to highway uses of fly ash, Hyland points to the very limited progress despite considerable research by state highway organizations and urging by the FHWA. He indicates that a concerted effort is needed to promote greater use in this area.

Difficulties in Using Fly Ash in Highway Construction

While part of this apathy of highway builders towards the use of fly ash as a pozzolan may be due to a reluctance to change, it also partly results from the difficulties created by the use of a new material. Some of the points to be considered are summarized below.

Fly Ash Characteristics

The characteristics of fly ash vary considerably depending on the type of coal burned and the manner in which the ash is removed from the stack. Accordingly, all fly ashs are not suitable for all purposes.

When fly ash is to be used as an admixture for concrete or for fly ash-lime or fly ash-cement stabilization of soils, the pozzolanic nature of the fly ash is of considerable importance. The American Society for Testing Materials (ASTM) has adopted a specification for pozzolans, C-618, for use in concrete which includes fly ash as one acceptable type. Conformance to this specification generally assures satisfactory properties of the material. Companies marketing fly ash will provide materials conforming to this specification, but all fly ash collected does not meet this specification.

When fly ash is used in concrete, the carbon in the fly ash can affect the air entrainment properties of the concrete and this effect must be carefully evaluated. Variability in carbon content can also result in a nonuniformity of concrete color that may be unacceptable from the aesthetic viewpoint for structures or for blocks. However, this effect is not serious for base courses or surface pavements.

When fly ash is used in fill or embankments, the stability of the compacted mass is of major concern. Accordingly, the self-hardening properties of the material may be important.

Availability at Time and Point of Use

Fly ash is produced continuously but highway work is done intermittently. Consequently, fly ash must be stockpiled at its source or removed to a storage area immediately after generation. Although more power producing companies are developing an interest in disposing of ash in such a way that it is usable for other applications, many still dispose of fly ash, bottom ash, and boiler slag together in settlement ponds. When this is done, the material becomes difficult and uneconomical to use in most highway applications, especially if the fly ash and bottom ash must be reseparated. As of 1978 estimates of the amount of the three types of ash being utilized were around 21%, a substantial increase over the 12% utilized in 1966. However, the 1978 estimates show that only about 13% of the fly ash was being utilized. This is in contrast to about 50% utilization in England, 73% in France, and 84% in Germany for the same year.

Only one installation in Virginia is now regularly marketing fly ash. That is the Clinch River Plant of the Appalachian Power Company (American Electric Power Service Corporation). However, fly ash is commercially available in most areas of the state from power plants in North Carolina, West Virginia or Maryland.

Changes Required in Design and Control

When fly ash is used in concrete, the mixture should be designed for optimum characteristics. Consequently, substitution of fly ash for cement is not done on a 1:1 basis — often the weight of the fly ash is as much as 1.5 times the weight of the cement replaced. This need for redesigning the concrete, and for controlling an additional material (fly ash), as well as taking special precaution to assure adequate air entrainment, tends to discourage the use of fly ash concrete. Taking everything into account, there is often only a small economical advantage to fly ash concrete. Thus, unless improvements can be expected from the standpoint of the durability or other properties of the concrete, there is little incentive for its use.

The Department's 1977 and 1978 experience with fly ash concrete in Waynesboro and Augusta County illustrates the types of problems that arise which tend to discourage general acceptance of the material. In experimental construction, fly ash concrete was used in curbs, gutters, and drop inlets. Generally, the strengths of test cylinders were satisfactory but on one day they were very low. Laboratory tests showed that the cylinders with low strengths had high void contents from an undetermined cause. Whether or not the fly ash introduced uncontrollable factors is not known, but such abnormal behavior discourages experimentation. In the same locality(but on another contract) unusually large amounts of scaling occurred on some inlets, even though the majority of the inlets were satisfactory. In this case, laboratory tests revealed very low air contents and unsatisfactory air void systems for the affected inlets. Based on known difficulties with air entrainment for some fly ash concretes, it is likely but not certain that the fly ash was the cause of the inadequate air content.

Performance of Virginia Projects Utilizing Fly Ash in Base and Subgrade Stabilization

In the late 1950's the Department conducted experiments with fly ash and lime as a stabilizing agent for subgrades and base courses. Generally, the lime-fly ash treated sections were included along with cement treated sections and sections treated with lime alone. The major emphasis of these experiments was on effective means of stabilization rather than the use of fly ash, per se.

Experimental projects were constructed in four localities. These are described in a report by Nichols and consisted of the following.(18)

1. A base stabilization project on Rte. 622, Warren County. This was constructed in May 1955 and the experimental feature was the use of lime-fly ash. Two sections were constructed, one using 5% lime and 15% fly ash and the other 3% lime and 9% fly ash. The untreated material was crushed limestone (soil aggregate grading c).

2. A base and subgrade stabilization project on Rte. 460, Dinwiddie County. This project was constructed in August 1956. The experimental features included 3 sections of natural soil treated with 5% lime, 5% cement, and 3% lime plus 9% fly ash, respectively. Two sections included treatment of the top 6 in (150 mm) of soil aggregate base on untreated select blanket subgrade with 5% lime and 9% fly ash and with 5% cement.

3. A base and subgrade stabilization project on Rte. 58, Patrick County. This project was partly constructed in August 1956 and completed in May 1957. The study involved treating 10 sections of native subgrade soil in lieu of using select blanket. Treatments included two sections with 3% lime, two with 5% lime, two with 3% cement, two with 5% cement, and two sections with a combination of 3% lime and 9% fly ash. In addition, 6 sections were constructed with the top 6 in (150 mm) of soil aggregate base over untreated subgrade treated with the additives. These last 6 involved two sections with 5% cement and one section with 3% cement; one section with 5% lime; one section with 3% lime and 9% fly ash; and another section with 5% lime and 9% fly ash.

4. A base course project on Rte. 641 in Isle of Wight County. This project was designed primarily to compare the performances of cement and lime treatments. However, 10% fly ash was added to two short stretches of the lime treated base section.

Nichol's 1959 report summarized the behavior of these projects up to that time.[18] He reported that the Warren County project had been evaluated by visual inspection only. No defects were noted in the treated sections, while on the rest of the project a substantial amount of skin patching had been done on the bituminous penetration surface course. On the Dinwiddie County project the road was subjected to traffic during the winter prior to the application of the sand asphalt surface course. This resulted in severe alligator cracking of the penetration treatment with the notable exception of the two sections in which the lime-fly ash and cement

were used in the base. Some cracking was noted in the sections with additives in the subgrade, although it was less severe than the distress on the subgrade that was not treated. CBR values for treated sections were higher than for untreated sections, ranging from 20-60. The 3% lime - 9% fly ash section had generally lower CBR values than other treated sections. One spot was found in the 3% lime - 9% fly ash section where the CBR value was 7, indicating a lack of stabilization at this spot. This may have resulted from poor distribution of the lime. The 500-ft (152-m) section of the lime-fly ash treated soil aggregate base performed quite well.

Tests made at the Research Council in 1972 on cores taken from the projects in Dinwiddie County (Rte. 460) and in Isle of Wight County (Rte. 641) indicated good strengths for the lime and fly ash sections. On Rte. 460, the core strengths ranged from 322 lb/in^2 to 676 lb/in^2 with an average of 528 lb/in^2 (2,218 kPa to 4,657 kPa with an average of 3,638 kPa). The strengths of soil cement cores from the same project ranged from 248 lb/in^2 to 734 lb/in^2 with an average of 475 lb/in^2 (1,709 kPa to 5,057 kPa with an average of 3,270 kPa). On Rte. 641 the strengths ranged from 825 lb/in^2 (5,680 kPa) to 1,289 lb/in^2 (8,880 kPa) with the average of 5 cores being 1,013 lb/in^2 (6,980 kPa). The strengths of cores from the cement stabilized sections ranged from 344 lb/in^2 (2,370 kPa) to 797 lb/in^2 (5,491 kPa) with the average of 3 cores being 509 lb/in^2 (3,507 kPa). A fourth core from this section had a strength of only 10 lb/in^2 (69 kPa) and this value was discarded.

In addition to these projects, lime-fly ash combinations as used in "Poz-o-Pac" were included along with other stabilization techniques in an experiment conducted on Rte. 20 in Orange County, Virginia. The work was done by state forces. It began in 1962 and final surfaces were not completed until 1964 because of interruptions for higher priority work.[19] The major objective of this experiment was to determine an economical design for lightly traveled primary highways which must carry heavy but infrequent traffic loadings. On this project the lime-fly ash (Poz-o-pac) stabilized section provided greater strength than the crushed stone or cement treated and lime treated sections. Unfortunately, it was also more costly than the other materials.

Although the reports of these projects indicate that lime-fly ash sections performed satisfactorily, the lime alone (in clay soils) or cement alone usually performed equally as well. Since lime-fly ash treatments were reported to be more expensive than those with lime alone or cement, there has been very little incentive to use lime-fly ash techniques. Patent rights on certain lime-fly ash combinations also have deterred the general use of this technique.

Since it requires about 6 million Btu's (6.3 trillion Joules) to manufacture 1 ton (1,000 kg) of lime and lime is in short supply, at present, it is not likely that the costs relative to that of other techniques will change substantially. However, some efforts are being made to market a product utilizing cement kiln dust and fly ash in Ohio, Pennsylvania and a few other states. This material, which has been patented by Nicholson Industries, Inc., Toledo, Ohio, substitutes cement kiln dust for lime in the usual fly ash-lime pozzolanic mixture, and when used with aggregate in the proper proportions, provides a concrete of sufficient strength for use in bases and subbases for highway construction. The advantage, of course, is that two waste products are being employed so that the energy for production of the mixture is minimal. Transportation costs, as usual, tend to control the economics in any specific project. Under present circumstances the availability of both fly ash and cement kiln dust are not favorable for applications in Virginia.

Potential Utilization of Fly Ash in Highway Construction

Despite the problems cited and the limited promotional efforts on the part of fly ash marketers to utilize fly ash in highway construction in Virginia, design and construction personnel should keep in mind the possibility of using both fly ash and bottom ash where favorable supply and economic conditions exist. The National Ash Association reports that as of 1977, ash from the burning of coal was the sixth most abundant natural resource in the country; and, as previously stated, the supply is likely to increase. There is an interest at the federal governmental level in promoting the use of fly ash in concrete, both as a means of conserving energy — by reducing the amount of portland cement needed in construction — and as a means of avoiding environmentally undesirable accumulations of the material. The report prepared by Gordian Associates, Inc. for the Department of Energy and entitled "Potential for Energy Conservation Through the Use of Slag and Fly Ash in Concrete" provides an excellent review of its subject and suggests a national program to promote increased commercial use of fly ash.[20] The report also recognizes the major difficulties likely to be encountered (see Annotated Bibliography Reference 2-12).

In view of the considerable amount of knowledge that exists concerning fly ash and bottom ash and the efforts being made to increase their use, the Virginia Department of Highways and Transportation should consider using these products as alternatives to using conventional materials under the proper circumstances. In this respect, neither fly ash or bottom ash should be viewed as a material to be shoveled up at the nearest power plant, but rather

as an alternative supply of usable resources that would be purchased to meet suitable specifications after proper processing by a supplier. Under such conditions, fly ash and bottom ash would compete with alternative materials on the basis of their merits and economics.

No attempt will be made in this report to cover in detail the various potential applications of fly ash since such information is already available in other reports. However, the following summary should be helpful as a guide to those interested in specific uses.

The potential uses of fly ash vary from high volume uses to additives in portland cement or soil stabilization. The Implementation Package 76-16 published by the FHWA discusses the techniques involved in the following six applications.[15]

1. Lime stabilized fly ash mixes and lime cement stabilized fly ash mixes.

2. Stabilized fly ash pavements.

3. Fly ash and lime-fly ash in stabilized soil pavements and soil modification.

4. Fly ash embankments.

5. Fly ash in a structural backfill.

6. Fly ash in grouting.

In addition to these uses, fly ash is used as a pozzolan additive in portland cement concrete to substitute for a portion of the cement. It is also used as an ingredient in pozzolanic cements meeting ASTM specifications. Some fly ash has also been used as a filler in the construction of asphalt pavements.

A summary of each of the major uses taken primarily from FHWA Implementation Package 76-16 follows.

Lime or Cement - Fly Ash - Aggregate Mixtures
(See Chapter III of reference 15)

Lime-fly ash-aggregate (LFA) mixtures are blends of mineral aggregate, lime, fly ash and water, combined in proper proportions which when compacted produce a dense mass. Lime-cement-fly ash aggregate mixtures (LCFA) are similar mixtures in which the lime

has been partially substituted for cement. Complete substitution of cement for lime is usually done for the purpose of accelerating the rate of strength gain of the mixtures, especially for late season construction. The substitution of cement for lime is not on a one-to-one basis. Most mixtures require more cement than lime to achieve the same ultimate results.

LFA and LCFA mixtures are used as base or subbase courses. Wearing surfaces must be applied over them to protect the material from the abrasive effects of traffic, weathering, and water infiltration. They can be used under either concrete or asphalt surfaces. Appropriate design procedures and criteria are available for pavement systems ranging from low-volume roads to heavy-duty pavements. Low-volume roads may require only a seal coat, whereas 4-6 in (100-150 mm) of asphalt concrete may be needed on heavy-duty pavements.

The strengths of cores taken from LFA and LCFA bases after 1 year generally range from about 500 lb/in^2 to 1,000 lb/in^2 (3,450-6,890 kPa), although cores with strengths greater than 3,000 lb/in^2 (20,680 kPa) have been attained from a number of sites.

The key to good performance with LFA and LCFA materials is good mix design with adequate quantities of lime and fly ash. Thorough blending of the components with good compaction to yield high relative in-place densities is also essential to good performance. Late season construction should be avoided since warm temperatures are needed to accelerate the lime-fly ash pozzolanic reaction that provides strength. Excessive moisture combined with freezing and thawing and high concentrations of salt can be particularly damaging.

Chapter III of Implementation Package 76-16 provides case histories of a number of installations of LFA and LCFA and guidelines for their design and construction.[15]

Stabilized Fly Ash Pavements
(See Chapter IV of reference 15)

Stabilized fly ash base and subbase courses are unique in that the fly ash acts both as a pozzolan and as an aggregate. The fly ash and stabilizer (lime or cement) function mechanically much the same as a fine-grained soil cement, except that the natural pozzolanic reaction between the fly ash and the stabilizer continues to produce an increase in strength over a long period of time. Generally, the amount of lime or cement used will be about one part of lime or cement to 10 parts of fly ash.

Certain chemical and physical characteristics of the fly ash influence the degree to which it can react with the lime or cement. This reactivity determines not only the ultimate strength which a stabilized fly ash achieves, but also the rate at which the strength gain takes place. Although many fly ashes possess self-hardening properties, the strength does not develop rapidly enough and is not adequate for pavement applications; consequently, lime or cement must be added. It is noted, however, that fly ashes from which the calcium oxide has been leached out, as in the case of lagoon or stockpiled ashes, have somewhat reduced reactivity. High carbon content in the fly ash is also detrimental to the pozzolanic reaction, thus fly ash produced from older plants (usually high carbon) do not work as well as fly ash from newer units (low carbon).

The construction of stabilized fly ash bases or subbases would be economical where the fly ash did not have to be moved great distances. Such use is relatively new in the United States, but stabilized fly ash bases have been used in Great Britain for nearly 15 years. The French have used fly ash in pavement construction since 1957. They have found that fly ash-cement mixes used as subbase on a number of major highways are superior in quality and economy to locally available paving materials. In the United States, test sections in Missouri and West Virginia are performing well.

Chapter IV of Implementation Package 76-16 provides case histories of installations in England and West Virginia.[15] Design criteria and procedures for both cement stabilized and lime stabilized fly ashes are also provided.

Fly Ash and Lime-Fly Ash in Stabilized Soil Pavements and Soil Modification (See Chapter V of reference 15)

Although the use of lime-fly ash aggregate mixtures or cement-lime-fly ash aggregate mixtures as previously discussed under Section 1 provide materials of high strength, lime-fly ash-soil mixtures are also useful in certain applications and can provide economical and energy-saving alternatives through the use of in situ materials. In particular, fine grained soils such as silts and clays can be stabilized by this technique. This procedure is particularly useful in constructing base courses for secondary roads, parking lots, and other locations where heavy traffic loads are not anticipated. It can also be useful for subbases beneath conventional pavements and for subgrade improvements to provide additional support for the pavement or to remedy undesirable subgrade conditions to expedite construction.

Combinations of lime and fly ash can be used as an alternative to cement or lime-soil stabilization of soils. There are two primary mechanisms by which all three of these stabilizers can improve

a soil for engineering applications. These are: (1) improvement of the soil's inherent properties, such as decreasing its plasticity index, improving drainage characteristics, and decreasing volumetric shrinkage; and (2) cementation of the individual soil grains to produce an increase in both strength and durability characteristics.

In lime stabilization, a marked improvement in the properties of many soils occurs. In addition, the lime reacts with any pozzolanic material present in the soil and results in cementation action.

In cement stabilization, the cement reacts with water to produce certain compounds which are effective in cementing the soil particles together. The strength development does not depend upon the chemical interaction between the cement and the soil. However, the lime released during the cement hydration process may modify the soil's properties and can react with any pozzolanic material in the soil to produce further cementation.

Lime-fly ash stabilization produces improvements in soil properties because of the presence of lime, and also results in significant cementation from the reaction between lime and the pozzolanic fly ash. The cementation process is somewhat similar to that in cement stabilization in that the process does not depend on interaction between the admixtures and the soil, although the presence of pozzolanic material in the soil can modify the lime-fly ash reaction.

Although different soil types may react differently to various stabilization procedures, it is often possible to attain greater strengths and improved durability with lime-fly ash stabilization than with lime alone. In locations where lime is cheaper than cement, lime-fly ash can often produce material of comparable long-term strength and durability at a reduced cost when compared to cement stabilization.

Chapter V of Implementation Package 76-16 covers case histories of installations in Alabama, North Dakota, Missouri, and England.[15] Also included are mix design concepts and strength and durability criteria.

Fly Ash Embankments

The utilization of fly ash as borrow material in embankments results from two primary factors: the lightweight of fly ash and its relative economy as compared to that of natural borrow materials.

The low unit weight is particularly advantageous in situations where a fill or embankment must be placed on relatively weak subsoils. The average range of compacted dry unit weights for fly ash, 70-95 lb/ft^3 (1,120-1,520 kg/m^3), represents a considerable reduction in the surcharge placed on in situ materials. Conventional materials have dry unit weights in the order of 100-130 lb/ft^3 (1,760-2,080 kg/m^3). The potential economy will depend primarily on how far the fly ash must be moved in comparison with the movement required for other suitable material.

One of the most significant characteristics of fly ash embankments is the strength developed. Well-compacted fly ash will exhibit strengths comparable to those for soils normally used in earthfill operations. In addition, many fly ashes possess self-hardening properties which can result in the development of shear strength higher than those encountered in many soils. The addition of lime or cement can induce hardening in fly ashes that may not self-harden. By using this technique significant increases in shear strength can be realized in relatively short periods of time and, if this increased strength is taken into consideration in the design of the embankment, the use of fly ash can represent a distinct economy over the use of other embankment materials.

In general, fly ash has been shown to be a suitable material for embankment construction. It can be handled as easily as natural soil and thus presents no problem in its utilization that cannot be solved through proper design and good construction techniques.

The first documented use of fly ash in an engineered fill occurred in Great Britain in the late 1950's. After trial embankments were successfully constructed, Great Britain incorporated fly ash into its massive motorway construction program (similar to the U. S. Interstate System). The use of fly ash made it possible for the British to construct miles of high speed, divided highways over areas of poor subsoil where the use of heavier fill material would have been impractical. Other European countries have also made extensive use of fly ash for embankments. This usage accounts to a considerable extent for the large percentage of available fly ash being utilized in European countries. The Implementation Package 76-16 provides case histories of a limited number of installations in this country and Europe.[15] Discussions of shear strength, compressibility, frost susceptibility, capillary action, erodability, and leaching from the design viewpoint and recommended construction procedures are also included in the implementation report.

Fly Ash as a Structural Backfill

Fly ash has been successfully used as structural backfill for bridge abutments, walls, and other types of retaining structures. Its success in this application results from its lightweight, good shear strength characteristics and, in some cases, its self-hardening properties. Actual research and data collection for this application are limited, but field reports to date have said it has been highly satisfactory. Its use in Great Britain is reported to achieve smooth transitions from approach slabs to bridge decks by eventual elimination of the noticeable "bump" which so often occurs at the junction of the two as a result of differential settlement. Case histories of installations in England and guidelines for design and construction are included in the implementation report.

Fly Ash in Grouting (See Chapter VIII of reference 15)

Fly ash has been used extensively for years in grouting operations for foundations, stabilization, subsidence prevention, void filling, and other uses relating to building construction. It was natural, therefore, that such usage be extended to similar situations for highway-associated structures. The objectives of using grout are generally to (1) increase strength, (2) reduce permeability, (3) reduce compressibility, or (4) fill undesirable voids. The fineness of fly ash and the predominantly spherical shape of the particles enables grouts incorporating fly ash to be pumped more easily than those containing only sand or cement. Partial replacement of either cement or sand by fly ash improves pumpability and injection by keeping the grout in suspension. Case histories are included in the implementation report, including one incident of use in West Virginia in which a fly ash-cement slurry was used to stabilize the bridge approach slabs on Interstate 79 structures. This grout consisted of two bags of fly ash to one bag of cement with two shovels of bentonite clay or local shaley clay and one shovel of calcium chloride mixed with sufficient water to obtain the slurry.

Discussions of several type grouts including those containing only fly ash, lime-fly ash, portland cement-fly ash, portland cement-fly ash-clay and portland cement-fly ash-sand are presented in the implementation report.[15] Construction procedures are reported to be the same as procedures used for non-fly ash grouts.

Fly Ash as a Pozzolanic Material in Portland Cement Concrete

In addition to the uses of fly ash covered in the FHWA implementation report discussed in the preceding sections, fly ash is utilized as a pozzolanic addition in portland cement concrete. When so used the fly ash replaces a portion of the cement. When the portland cement hydrates, calcium hydroxide (lime) is formed and this

then reacts with the silica in the fly ash (in the presence of water) to form calcium silicate hydrates similar to the reaction products of portland cement. These products add to the strength and durability of the concrete. Consequently, a relatively large proportion of the portland cement can be replaced with fly ash without adversely affecting the ultimate strength and durability of the concrete. However, the rate of strength development may be slower. The greatest use of fly ash concrete in the United States has been in the construction of dams where low heat of hydration was desirable. Considerable research has been conducted by highway agencies on the use of such fly ash in pavements, primarily as a means of eliminating the danger from expansive reactions between alkalies in the cement and reactive silica. However, except for special experimental construction, Alabama is the only state that has made extensive use of fly ash concrete in highways. Experimental sections were constructed in Virginia around 1955 and a recent laboratory study at the Research Council has evaluated fly ash concrete as a possible replacement for concrete with Type II cement.[21]

An evaluation of the field performance of the fly ash concrete placed in 1955 was recently made by Ozyildirim.[22] This installation included sidewalk, curb, and gutter. In the two experimental mixtures 20% and 33% of Type II cement by weight was replaced with fly ash. The control sections used concretes containing all Type II cement. The early tests — up to 1 year — showed that even though the fly ash concretes had lower strengths at 28 days than the controls, at 90 and 365 days their strengths were higher than those of the controls. The strengths of cores from all concretes taken in 1979 after 23 years' service were significantly higher than the 1-year strengths. The fly ash concretes had average strengths slightly less than that of the control for the 20% replacement and essentially equal to that of the controls for the 33% replacement. It was observed, however, that the fly ash concretes scaled to a greater degree than the control concrete. It is also noted that the fly ash used in this experimental project had a relatively high carbon content (9.5% to 11.4%). This is higher than desirable because of the difficulties in entraining the proper amount of air in the concrete. However, whether or not this characteristic affected the results of this project is not known.

A report of the laboratory studies made to evaluate possible alternatives to Type II cement is also available.[21] This study showed that fly ash concrete with Type I cement compared favorably with concrete prepared with Type II cement. The strength and durability were satisfactory, but as indicated by the earlier study, it was found that fly ash concrete may be more susceptible to surface scaling than concrete made with Type II cement.

Potential Regulatory Problems by Classification of Fly Ash as a Hazardous Material

One problem has recently arisen which, if not resolved, will hinder further development of ways to utilize fly ash. This problem was summarized by Faber in the opening session of the Fifth International Ash Utilization Symposium. He stated that:[23]

> The good news is that power plant ash is becoming available in greater quantities in more locations, the quality is improving, and acceptability continues to increase. The bad news, in the form of a regulatory cloud, threatens to invalidate a decade of accomplishments and virtually destroy the marketability of these recyclable coal by-products.
>
> The ominous threat is contained in proposed Environmental Protection Agency guidelines governing the definitions and control of hazardous wastes under the Resource Conservation and Recovery Act of 1976 (RCRA).
>
> Preliminary regulations have classified coal ashes, at least by implication and association, under a "special category" umbrella, as a "hazardous waste". If this position stands, utilization as we now know it will no longer be possible. The ash industry feels that the EPA has acted in an indiscriminate manner without scientific data.
>
> In fact, the inclusion of ash in the RCRA guidelines has conservatively destroyed twenty percent of our growth for the next five years.

The background for this statement was explained in more detail by several other speakers at the symposium. Pound discussed the economic and environmental aspects of some of the problems in handling fly ash either for disposal or reuse. He covered four points:[24]

1. dust (particulate emission)
2. sulfur oxides and alkalies
3. nitrogen oxides
4. trace elements and radioactivity

Most of these problems are well known and have been effectively dealt with in handling fly ash over the past 20-25 years. Effective ways to control dust and to prevent leaching of soluble materials into streams or ground water have been devised. The newly recognized concern is the radioactivity of some fly ashes — derived from the parent coal. This is a very low level radiation similar to that of a number of natural materials. However, the proposed EPA definition of a hazardous material includes all materials having a radium - 226 (^{226}Ra) emission greater than 5 picocuries per gram (5×10^{-12} curies per gram). Tests on 18 fly ashes reported by Morris and Bobrowski showed that statistically the level of radiation for the fly ashes from the 8 western coals tested would be expected to be in the range of 4.6 ± 2.3 picocuries per gram.(25) Actual test results ranged from 2.7 to 8.8. For the fly ashes from 10 eastern coals the expected level was reported as 5.4 ± 2.4 picocuries per gram. Actual test results ranged from 2.4 to 10.0 for this group. The experimental error for the determination was reported to be about 20% based on replicate determinations with one fly ash.

It is emphasized that a picocurie is a very small unit of radioactivity. It is one trillionth (10^{-12}) of a Curie, which is a measure of radioactivity based on radium. Thus it can be stated that a substance with a radioactivity of 5 picocuries per gram contains the equivalent of 5 trillionths (5×10^{-12}) of radium. In more familiar terms, this means that a fly ash with a radioactivity of 5 picocuries would have the equivalent of 1 pound of radium in about 1 billion tons of fly ash (1 gram in about 5 trillion kilograms).

There is no evidence that any use of fly ash has resulted in health hazards and the limits proposed by the EPA are believed to be ultraconservative. However, as discussed by several authors, even the mention of radioactivity is sufficient to cause potential users to shy away from using ash. At the symposium Kinder discussed the potential impact of the proposed regulations on the recovery and utilization of ash.(26) In his view, the present EPA approach would end most of the present uses of utility by-products (coal ashes). He points out that private industry, local governments, and their insurers would avoid any reuse involving a by-product which the EPA labels "hazardous", even if the product is, in fact, environmentally safe. He also points out that costs resulting from regulatory requirements would make much of the present practice uneconomical. Similar thoughts were expressed by Price in an article in Modern Concrete, based on a report prepared for the EPA by Gordian Associates.(27) As he states, even the mention of radioactivity at any level is sufficient to curtail interest in the use of the product.

At the time this report was prepared the matter had not been resolved. The EPA has held several hearings on the proposed regulations and strong objections to the present proposals have been registered by a number of those involved in the power plant industry or with promoting the use of coal ash as a by-product. Information received from the EPA is that new regulations concerning this matter will be issued December 31, 1979. From the standpoint of the Virginia Department of Highways & Transportation, it is believed that desirable experimentation with possible uses of fly ash and bottom ash should continue, since there is no evidence of any real health hazard from the radiation levels in question. However, it would be wise for the Department to withhold any strong effort to promote the use of fly ash until the EPA's position has been clarified — and hopefully modified.

Municipal Wastes

The products considered to be municipal wastes are incinerator residues, building rubble, old asphalt pavement, old portland cement concrete pavement, discarded automobile tires, and miscellaneous products such as used lubricating oil and sewage sludge.

Incinerator Residues

The FHWA has conducted an evaluation of the usefulness of incinerator residues for highway construction. It has also investigated the possibility of preparing synthetic aggregate from the residue by complete burning and fusion of the residue to form a glassy product.[28] As indicated in the Bibliography, several reports of these studies are available (see Section 5).[28-31] Report No. FHWA-RD-77-150[30] provides guidelines for the use of incinerator residue as highway construction material. This report shows that as of 1975, five incinerators were operating in Virginia. The location and capacity of each of these is given in Table 3. As indicated, four of the five are in the Tidewater area of the state. At present, these residues are being disposed of in landfills and there is no apparent advantage to the Department of Highways & Transportation in attempting to make use of this material. Efforts are under way to recover resources and energy from such wastes in the southeastern part of the state. A regional solid waste management group is considering the problems for the area. In general, however, their thinking is that most of the municipal wastes and household trash and garbage, as well as fly ash and bottom ash from various power plants, will be placed in landfills. Efforts are now being directed toward recovering the energy in the trash and garbage by burning. The residues from this activity are also placed in landfills. The Norfolk Naval Base now has an installation for generating steam by burning its own waste. The steam is used for heating ships in port and buildings on the base. Another installation under construction is a jointly funded project between the City of Hampton and the federal government. Sixty percent of the funds are being provided by Hampton, 30% by NASA, Langley Field, and 10% by the Langley Air Force Base. Expected to be completed in June 1980, this installation is expected to generate 36 million lb (16 million kg) of steam

annually, which will be sold to NASA at Langley Field and will provide an estimated payment to the City of Hampton of $150,000 annually. This will result in an estimated yearly saving of 2 to 2.5 million gal. (7,600 to 11,400 m^3) of No. 6 fuel oil. All of the combustible waste from NASA and other federal installations in the area will be burned at the incinerator, as will about 70% of the waste from the City of Hampton. The total refuse to be handled will average about 200 tons (180,000 kg) daily, 7 days a week. One hundred seventy-five tons (157,500 kg) will be from the city and 25 (22,500 kg) from the federal installations. The residue from the incinerator will be heated to about 1,800°F (approximately 1,040°C), thus it will be essentially sterile and free of all organic material. Plans are that the residue, approximately 1/7 of the solid refuse by weight, will be placed in the Hampton landfill. The federal landfill in the area will be closed. The placing of the relatively low volume of sterile residue in the landfill will extend the life of the fill and also eliminate dangers from ground water contamination that now exist.

The residue from the incinerator is expected to be partially fused but will contain large metal pieces that would make it unsuitable for use in highway construction. The officials in charge of the project indicate that their estimates show that under present circumstances it would not be economically feasible to process the product for use other than in landfill. However, should conditions change — such as an acute aggregate shortage or exhaustion of landfill area — the possibility of utilizing this 20-30 tons (18,000-27,000 kg) per day as a source of aggregate for highway bases should not be overlooked.

Table 3

Operating Municipal Incinerator Plants
in Virginia as of 1975
(Source: Reference 30)

Location	Year Built	Refuse Capacity (Tons per 24/hr day)	Furnace Type & Grate
Alexandria #2	1966	300	Cont./Rocking
Newport News	1968	400	Cont./Trav.
Norfolk	1946	400	Batch/Mech.
Norfolk	1968	360	Cont./Recip.
Portsmouth	1963	350	Batch/Rocking

Old Concrete Pavements

Old concrete pavements have been successfully crushed and used as aggregate in highway construction. Crushing is simplified when reinforcing steel is not present, but a number of projects have been built in which the steel has been removed manually without extreme difficulty after partial crushing.(32) This material has been used successfully elsewhere as aggregate in bituminous mixes as well as aggregate in new concrete, but no use in Virginia was reported in the replies to the survey. However, disposal of concrete rubble was considered a growing problem in some areas. In particular, the necessary removal of large areas of concrete sidewalks because of uneven settlement and undermining can at times create a disposal problem. The possibility of crushing such materials at or near the job site for reuse should be explored. Although the crushing operation itself may require energy equivalent to that required for crushing new stone, the saving in costs and energy by not having to move the old concrete to a disposal area and bring in new material may provide overall economy. Eliminating the need for new aggregates for the work would, also provide conservation of natural resources as well as monetary saving. Because of the national interest in concrete pavement recycling and interest within the Department a state-of-the-art report on recycling portland cement concrete pavements has been prepared and published as a special report of this project.(33)

Asphalt Pavement

Recycling asphalt pavements is not always considered to be waste utilization. The chief motivation for recycling generally is to conserve energy and materials as well as save money. Nevertheless, the recycling is related to waste utilization in that it avoids the generation of a waste material that would otherwise have to be disposed of. In the United States there is considerable interest in recycling asphalt pavements and the technology is rapidly developing. Much of the early efforts have been to devise procedures for heating the reclaimed material along with new asphalt or "rejuvenators" and mixing with new aggregates. Avoidance of atmospheric contamination from heavy smoke and excessive particulate matter has been one of the major efforts in this work. Procedures and equipment are now available that can provide adequate mixing without excessive exhausts. Guidelines for recycling pavement materials of all types and using different techniquesare being developed by the Texas Transportation Institute as a project of the National Cooperative Highway Research Program (NCHRP).

Interim guidelines for recycling have been included in a draft report of this project dated November 1978.[34] This draft indicates that the final report will include guidelines to —

1) point out the potential advantages of recycling;

2) assist in making a preliminary analysis of recycling as an alternative and to identify suitable methodology;

3) provide guidance and criteria for making a detailed analysis of cost, energy, materials design, structural design, construction specifications, and quality control; and

4) recommend a scheme for evaluation of results to see how well recycling compares to conventional methods of rehabilitation.

The final report of this project is expected to be available sometime in 1980.

The FHWA has also sponsored a demonstration project for asphalt recycling (Demonstration Project 39) and several reports of individual projects are available. A summary of the general findings from this project concerning hot asphalt recycling is available.[35] This report shows that essentially all the projects conducted showed savings of dollars, energy, and resources by comparison with similar projects using new materials.

Asphalt pavement recycling efforts in Virginia have been limited to a few experimental efforts. A report by Hughes summarizes the major project conducted to date.[36] In general, most Virginia maintenance of asphalt pavements involves overlay work so that no waste is being generated. Where removal of old pavement is required because of stripping or other deficiencies, efforts are made to utilize the removed material in rural low volume roads, or shoulders, etc. There is a need, however, to continue the evaluation of new equipment and new technology as it develops, and plans are under consideration for additional work in this area utilizing a modified drum mixer for heating the recycled material.

Discarded Automobile Tires

The disposition of worn out vehicle tires which are discarded at the rate of about 100 million per year is a problem in all areas

of the country. Such tires create problems in landfills and cannot be burned in open fires because of air pollution. Numerous uses of the ground rubber from such tires have been devised but the removal of the rubber from the tire and other necessary processing generally make the material expensive compared to the usual ingredients in asphalt pavements. For this reason, substantial improvement in performance is needed in order for such operations to be cost-effective. For pavements, the most successful application has been in a specialized seal coat such as first developed by Charles H. McDonald and used extensively on city streets in Phoenix, Arizona. This process is described in Implementation Package 73-1 published by the FHWA.[37] In this application about 25% ground rubber from old tires is mixed with 75% asphalt at a temperature between 350° and 450°F (177°-232°C). Kerosene may be added to reduce the viscosity for spraying. The time of mixing depends somewhat on the temperature but may be on the order of 30 minutes and is controlled by the experience of the engineer on the job. The rubber is partially dissolved in the rubber-asphalt mixture. It is applied to the cleaned and patched road surface at the rate of about 1/2 gal/yd^3 (1.6 l/m^2) and cover stone, precoated with asphalt, is applied at about 38 lb/yd^2 (12 kg/m^2). The stone is a nominal 3/8 in (9.5 mm) chip (70%-100% passing 3/8 in). For more detail on the process see reference 37.

To promote this use as well as other ways to use discarded tires in highway construction the FHWA is conducting a demonstration project (No. 37). The September 1979 status report on the project shows that 23 states, including Virginia, are participating in this project with one or more experiments.[38] Twelve states have projects involving the use of the rubber-asphalt as the binder for seal coats. Sixteen states have projects involving the use of the ground rubber-asphalt mixture as a stress relieving interlayer between the old pavement and a new overlay. One state has used the rubber-asphalt in a waterproofing membrane for a bridge deck. One state has used the mixture to encapsulate subgrade and one state (California) has used the old tires (split longitudinally) as a reinforcing medium in embankment construction. The construction techniques for each project may vary to some extent but most of the seal coat experiments and interlayers have been built by one specialized company. That company's techniques are summarized in general terms below.

For seal coats:

> Twenty-five percent by weight of ground rubber is added to hot asphalt cement and allowed to "cook" for about one hour in order that the rubber will dissolve to the maximum extent possible. The time required varies with the asphalt being used and is controlled by

the specialized company's engineer on the basis of his judgement. Before the binder is spread, kerosene is also added to reduce its viscosity. The stone chips are of the usual size used for seal coating. They are applied as quickly as possible after the binder is spread on the road and rolled immediately with pneumatic rollers.

For interlayers:

The rubber-asphalt binder is prepared as for seal coats. When an overlay is to be applied immediately, only a sand blotter is used to cover the binder. In some applications a normal chip seal will be built and the overlay applied at a later date. In some cases this may be as much as a year later.

A report describing the specific construction conditions and the materials used will be prepared for each experimental project by each state. The performance of each project will be monitored. As of September 1979, in addition to the project status report, reports are available from Colorado,(39) Oklahoma,(40) South Dakota(41) and Texas.(42) The Virginia experiment involves chip seals constructed on sections of state Rtes. 684 and 738 near Richmond. Conventional chip seals are used as the control sections. The construction of these projects was completed in September 1978. At present the seal coats are performing satisfactorily under relatively heavily loaded trucks. However, a report on the project is not yet available and no conclusion can be drawn as to its cost-effectiveness. It should be noted that special expertise and equipment are required for such applications and general use would be most likely through specialized companies rather than the producers of conventional asphalt paving mixtures.

The major advantage claimed for both the rubber-asphalt seal coat and the interlayer type of construction is that they prevent reflective cracks. The seal coat is reported to be especially successful in overlaying pavements that exhibit severe fatigue or alligator cracking. It also provides good skid resistance if high grade, polish resistant aggregate is used. In a number of applications the ability to correct problems with a thin surface treatment rather than a conventional 1 1/2 in (38 mm) or thicker overlay is economical because of the saving resulting from not having to adjust manhole covers or curbs.

The California project involves the use of old tires in a unique manner.(43) In this application the old tire is split longitudinally. The side wall sections are then laid flat in a special configuration on successive layers of an embankment as it is constructed. They add strength to the embankment in the same

way as the strips used for "reinforced earth" construction. This project is described in Annotated Bibliography reference 8-7. The feasibility of an experimental project using split tires in this manner is now under consideration in Virginia.

Discarded automobile tires have also been used experimentally in crash cushions[44] (see Annotated Bibliography reference 8-3).

Used Lubricating Oil

Used lubricating oil can be diluted and used as a dust preventative. However, dilution requires the use of a petroleum distillate and, consequently, disposal of the waste in this fashion does not tend to be desirable either from the environmental or the energy viewpoint. Collecting and burning the lubricating oil as an energy source, however, recaptures the energy and in some areas where appreciable quantities of such oil is available this procedure or reclaiming is desirable. Considerable effort is now being directed towards reclaiming and reuse of the oil as a lubricant. The EPA estimates that nearly 500 million gal (2 million m^3) of used oil are released directly into the nation's environment each year. In the past the principal drawback to reclaiming much of this oil has been the cost of collecting it from many scattered sources — filling stations, etc. However, the present high cost of lubricating oils is such that the process can be economical even under these conditions.

Sewage Sludge

The disposal of sewage sludge is a problem in a number of large municipal areas. Although it has been shown that this material makes a good fertilizer, there is considerable public objection to its use because of its odor and for psychological reasons. There is also some concern about the eventual buildup of toxic metals in the soil if continued applications are made in the same soil.

The possibility of utilizing sewage sludge as a fertilizer for highway slopes and other landscaping was investigated by the Research Council in 1975. An unpublished report by Sherwood[45] discusses the extent of the problem and some possible means of utilization. The report states that in the Washington, D. C. area alone 1,000 tons (900,000 kg) per day of sludge was being produced with substantial increases being expected. It was estimated that by 1983 the amount would be 3,500 tons (3.2 million kg) per day. Disposal costs in 1975 were reported to be as high as $70 per ton in some areas. The nutrient composition of sewage sludge is such

that it can supply elements needed for good growth although not in the same ratio as commercial fertilizer. Also described in the report is the method used for applying the sludge to the soil, which consists of plowing it in to avoid odors. A method of composting for eventual use as a fertilizer was also described. Because of the environmental and possible health factors involved, Sherwood's report recommended that the policies of the State Health Department and the Water Control Board be determined before any use by the Department. This recommendation led to Parker's study and report.[46]

He reported that a commission was then considering establishing regulatory control on the use of sewage sludge in land applications. It was determined that the regulations being considered would rule out much of the potential applications on highway right-of-ways. Representatives of the State Health Department and the Water Control Board also discouraged such use by the Department of Highways and Transportation. In addition, Parker's economic analysis showed that the Department would save very little money, if any, by such use. Although about $200,000 a year is spent for fertilizer, the cost of the extra manpower and equipment to utilize sewer sludge in lieu of the fertilizer would equal or exceed this amount. Accordingly, Parker recommended that the Department not become involved in the use of sewage sludge. This recommendation was followed and no experimental use of the sludge on Virginia highways has been made.

Because of a special situation in Philadelphia, where the right-of-way for Interstate 95 was to go through an area where sewage sludge had been ponded for a number of years, the FHWA sponsored research on the problems associated with the use of sewage sludge. The report of this work indicates that several combinations of sewage sludge, soil, lime, fly ash and sulfate wastes, provide suitable embankment materials with no indications that problems would arise from leaching or permanent odors[47] (see Annotated Bibliography reference 8-4). However, the report recommended covering the material containing sludge with at least 3 ft (1 m) of good soil to avoid any possible freeze-thaw damage. Even though the FHWA report indicates that the technology is adequate to utilize sewage sludge in this manner, it is believed that consideration for its use in highway construction should be given only in special cases where a highway facility is to be built over a previous disposal area and removal and relocation of the sludge would be costly.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of this review of national and international literature concerning the potential for utilizing wastes and by-products for construction of transportation facilities in Virginia, and the survey of availability of such wastes and by-products, the following conclusions and recommendations are warranted.

1. A number of solid waste products are technologically suitable for use in highway construction and the cost of such products at the point of origin may be very low — or even negative where the originating source must pay to have the material removed. However, such materials are often not economical to use since the cost of processing them and hauling the product to a highway job site exceeds the cost of processing and hauling conventional materials.

2. For Virginia conditions the utilization of solid wastes or by-products does not offer an economical alternative to the use of conventional aggregates. Generally those mineral wastes having a potential for use in highway construction have been tested by the state and, although in a number of cases suitability from the technological viewpoint has been demonstrated, the costs or the nonavailability of the waste sufficiently close to the points of need generally rule out their economical use.

3. There is a possibility that some wastes can be successfully utilized in highway construction as a means of avoiding environmentally undesirable accumulations. However, such accumulations do not now appear to be a serious concern within the state.

4. The continuing development of technology to utilize fly ash and other products from the combustion of coal, coupled with the likelihood of increasing supplies of such products, makes continuing test and experimentation with the products desirable. However, the state's role should be one of evaluation of processed products and the development of suitable tests and specifications as an alternative construction material and technique rather than the development of ways to use just any fly ash or bottom ash. An important activity in this regard is to keep abreast of the findings of national and international research programs.

5. Experimentation should be accelerated within Virginia for recycling both asphalt and portland cement concrete pavements to avoid generation of wastes products and to possibly save energy and conserve the supply of new aggregates.

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APPENDIX

AN ANNOTATED BIBLIOGRAPHY ON THE UTILIZATION OF WASTE AND BY-PRODUCT MATERIALS IN CONSTRUCTION OF TRANSPORTATION FACILITIES

The reports annotated in the following pages do not constitute a complete listing of all available reports. However, it is believed that each subject is covered in sufficient detail to give the reader some insight into major advantages and disadvantages of utilizing waste products for highway construction. It is noted that many of the reports annotated in Section 1 represent a synthesis of data from a number of reports and contain numerous references not annotated for this bibliography. References 1-7, 1-12, 1-14, 1-21, 2-2, 2-8, 2-12 and 5-4 are summary reports that should be of special interest.

Section 1 — General Surveys and Summaries

1972

1-1 Gedney, D. S., "Solid Waste in Highway Embankments", presented at Annual AASHO Conference, Phoenix, Arizona, November 1972.

Paper reviews potential uses and problems for using waste materials in highway embankments. It is concluded that a number of such wastes could be disposed of in embankments, provided proper attention is given to the special properties of the wastes.

1973

1-2 Jimeron, G. David, and W. V. Wyatt, "The Location and Potential Highway Use of By-Products in Arkansas", Arkansas State University, State University, Arkansas, 72467 (NTIS Acquisition No. PB 230.953).

This is a study made for the Arkansas State Highway Department. An extensive survey was made of companies in Arkansas to determine the types and amounts of wastes generated, and a list of possible uses is given. A list of waste products in use by other states is included.

1-3 Halstead, W. J., and R. H. Brink, "Potential Uses of Solid Waste in Highway Construction", 1973.

Summarizes findings of NCHRP project on Potential Replacements for Highway Aggregates. Describes project

utilizing lime, fly ash, and sulfate sludge. Also, discusses use of incinerator residue in base courses. The possibility of satisfactorily and safely disposing of sewage sludge by its incorporation into embankments is also covered.

1975

1-4 Emergy, J. J., "McMaster University, Hamilton, Ontario, Canada, "Waste and By-Product Utilization in Highway Construction", Resource, Recovery and Conservation 1, 1975.

Examines potential of a number of waste products available in Canada. Contains 64 references.

1-5 Halstead, W. J., "Materials Options with Respect to Energy Related Shortages", American Highway and Transportation Magazine, Vol. 54, No. 3, July 1975.

Paper discusses the problems and promises of substitute materials for coping with energy related shortages. Short-range possibilities discussed are (1) greater use of reclaimed materials, (2) greater use of in-place stabilization techniques, (3) greater use of cold-construction techniques, that is, emulsion mixes instead of hot mix, and (4) use of emulsion in lieu of cutbacks. Long-range possibilities are (1) use of sulfur as a binder, (2) development and use of a resin using wood products, and (3) development and use of by-product binders derived from the production of gasoline and fuel oil from oil-shale deposits.

1-6 Walters, R. O., and R. H. Cassellius, "Evaluation of Solid Waste Materials for Highway Uses", Investigation No. 638, Minnesota Department of Highways, Minneapolis, Minnesota, 1975.

Report deals with three main waste materials available in Minnesota. These are taconite tailings, wet bottom boiler slag, and fly ash. A general evaluation of uses of these materials was made and results summarized. An evaluation of properties that make them adaptable to use is included as well as some test results. It is shown that taconite tailings are acceptable for construction. Use in bituminous surfacing, bases, and fills is feasible. Tailings are also very useful as a deicing sanding material since they have good abrasion and dark colors. They are also useful in seal-coating because of their good skid resistance. Their use is limited by shipping costs.

Boiler slag (bottom ash) from coal burning electric generating plants accounts for about 25% of total ash production. Mostly available near urban areas. Has been used as seal-coat aggregate, sanding and deicing aggregate, bituminous paving aggregate, and in fills or base courses. Has been used (outside Minnesota) as filter media in water treatment, drainage material, and as a component of brick manufacture (up to 24% boiler slag). Also used as sandblasting grit and as roofing granules for shingles. Material is economically competitive unless long hauling or extensive processing is required.

Fly ash accounts for about 65% of the total ash products. Utilization of fly ash in concrete is discussed. Its usefulness to increase sulfate resistance of the concrete as an anti-corrosive additive (keeps pH high to avoid corrosive environment), as a means of decreasing volume change, and as a replacement for part of the cement is discussed. Its potential as a filler in bituminous mixtures and its suitability as a fill material is also discussed. Soil stabilization is also included as a potential use. Fly ash can also be used as the pozzolanic component of Type IP cement.

1976

1-7 Miller, R. H., and R. J. Collins, "Waste Materials as Potential Replacements for Highway Aggregates", NCHRP Report No. 166, Transportation Research Board, Washington, D. C., May 1976.

Thirty-one materials were evaluated and classified as either industrial, mineral, or domestic wastes. Four classes were established. Those in Class I have maximum potential. Class II contains those materials which require more processing or whose properties are not as adequate as those in Class I. Class III contains those with less promise than ones in Classes I and II but which might be used in isolated situations. Class IV materials showed little or no promise. The estimated quantities of each waste evaluated are given as well as source, location, physical state, and current or potential uses.

1-8 Collins, R. J., and R. H. Miller, "Availability of Mining Wastes and Their Potential for Use as Highway Material", Vol. 1 — Classification and Technical and Environmental Analysis", FHWA-RD-76-106, Federal Highway Administration, Washington, D. C., May 1976.

Study was performed to determine availability of mining and metallurgical wastes in the United States and to assess their potential for use in various aspects of highway construction. A comprehensive literature survey was made to develop information on locations, amounts, and uses of various mining and metallurgical wastes. Volume 1 contains classification and environmental analysis.

1-9 Collins, R. J., "Availability of Mining Wastes and Their Potential for Use as Highway Material, Volume II — Location of Mining and Metallurgical Wastes and Mining Industry Trends", FHWA-RD-76-107, Federal Highway Administration, Washington, D. C., May 1976.

This is Volume II of same study as above (Reference 1-8). This volume lists amounts and shows locations of all major sources of mining wastes in the United States. Individual state maps and names and locations of companies generating wastes are included.

1-10 Collins, R. J., "Availability of Mining Wastes and Their Potential for Use as Highway Material, Volume III — Annotated Bibliography", FHWA-RD-76-108, Federal Highway Administration, Washington, D. C., May 1976.

Volume III of same study as the previous two references, 1-8 and 1-9. This volume contains a brief summary of 80 of the most pertinent references on the subject of mineral waste utilization.

1-11 Forsyth, Roy A., and J. P. Egan, Jr., "Use of Waste Materials in Embankments", California Transportation Laboratory Report (prepared for presentation at 55th Annual Meeting of Transportation Research Board, January 1976).

Case histories of California use of wastes in embankments are cited. The three types of uses covered are: (a) wood wastes (tree stumps, logs, etc., from clearing); (b) sanitary landfill wastes; and (c) non-biodegradable wastes (discarded tires). Construction guidelines and theoretical considerations are presented.

1977

1-12 Collins, R. J., and R. H. Miller, "Availability of Mining Wastes and Their Potential for Use as Highway Material — Executive Summary", FHWA-RD-78-28, Federal Highway Administration, Washington, D. C., September 1977.

This executive summary constitutes the final report of the subject study and presents the major findings and conclusions in a concise manner. (Previous reports are FHWA-RD-106, 107, 108, references 1-8, 1-9 and 1-10.)

1-13 Clifton, J. R., P. W. Brown, and G. Frohnsdorff, "Survey of Uses of Waste Materials in Construction in the United States", NBSIR 77-1244, National Bureau of Standards, Washington, D. C., July 1977.

This report is the result of a survey of the amounts and methods of disposal of major mining, industrial and municipal wastes available in the 48 conterminous states of the United States. Included are present and potential uses of the wastes as construction materials. Only small amounts of the 3 billion (2.7 trillion kg) tons of waste material generated annually in the United States are now being used but the low level of use does not yet reflect the advances being made in converting wastes into viable construction materials. In several cases, construction materials produced from wastes have been at least the technological equivalent of materials produced from virgin resources. (Paper is U. S. contribution to RILEM Symposium by correspondence on the use of waste materials in the construction industry.)

1-14 Organization for Economic Cooperation and Development, "Use of Waste Materials and By-Products in Road Construction", Paris, September 1977. (Report prepared by an OECD Road Research Group — Dr. Clay Ormsby of FHWA was chairman of the group.)

This report summarizes the availability and use of waste materials for road construction in 12 countries (Belgium, Canada, Denmark, Finland, France, Germany, Italy, Netherlands, Spain, Switzerland, United Kingdom, and United States). The report reviews the use of materials from mining and quarry wastes and products, metallurgical wastes and by-products, industrial wastes and by-products, municipal wastes, and agriculture and forestry wastes and by-products.

Specific attention was directed to economic, environmental, and energy considerations. The conclusions were supplemented with a summary table indicating established or potential highway construction uses for each type of waste material.

1-15 Dunn, J. E., "Stretching Our Aggregates Reserves", Transportation Research News, No. 72, September-October 1977.

Discusses various factors leading to aggregate shortages in some areas and possibilities of alternatives such as synthetic aggregates or upgrading poor aggregates. The potential advantage of underground mining of aggregate in a close to urban area is also discussed.

1-16 Subcommittee on New Highway Materials, "Ways to Use Waste Products in Highway Construction", prepared by Task Force 16, Joint Cooperative Committee of AASHTO, AGC, and ARTBA, 1977.

Report is a short description of potential uses for certain waste products. The utilization of fly ash, scrap rubber, incinerator residue, stack dust from lime manufacturing plants, and bottom ash and boiler slag is discussed.

1-17 Sherwood, P. T., L. W. Tubey, and P. G. Roe, "The Use of Waste and Low-Grade Materials in Road Construction 7, Miscellaneous Wastes", 1977.

This report deals with miscellaneous wastes that for one reason or another have less potential for use as highway construction materials than those described in other reports of this series. The wastes considered are: cement-kiln dust, slate waste, demolition waste, metallurgical (nonferrous) slags, waste rubber, and waste glass.

1978

1-18 Duft, B. L., H. Levine, and A. McLeod, "A Study of the Feasibility of Utilizing Solid Wastes for Building Materials: Phase I — Summary Report", EPA-600/z-78-091, Environmental Protection Agency, Municipal Environmental Research Lab, Cincinnati, Ohio, April 1978.

A comprehensive literature search was conducted. The data were reviewed and evaluated for potential matrix, reinforcement, and filler candidates. The more promising candidates were evaluated with limited laboratory studies. From these studies two types of matrices —

furfural, phenolic and inorganic — were selected for further study. Seven reinforcement candidates and five filler candidates were selected for evaluation with the two matrices.

The selected reinforcement candidates are glass roving, waste paper, rice hulls, bark, wood chips, plastic scrap, and cotton waste.

The selected filler candidates are fly ash, plastic scrap, wood bark, rice hulls, and sawdust.

1-19 Bassi, I. J. S., "Industrial Wastes are Potential Cement", Rock Products, August 1978.

The difficulties of developing increased capacity for production of hydraulic cement in India are discussed. Extremely high capital investment costs coupled with low profit making capacity creates the problem. Author suggests greater use of waste products in manufacturing slag cements and pozzolanic cements may provide some economic relief. Such waste products are available in India. The potential roles of slag, fly ash, carbonate and lime sludge, by-product gypsum and kiln dust are discussed.

1-20 Colony, D. C., "Industrial Waste Products in Pavements: Potential for Energy Conservation", University of Toledo, Toledo, Ohio, January 1979. (Paper presented at the Transportation Research Board, Washington, D. C., January 1979.)

This paper emphasizes the problems associated with the use of many waste materials in highway construction. It is pointed out that some materials such as fly ash (as a pozzolan) and blast furnace slag have desirable properties that favor their use in some applications even in the absence of environmental or energy considerations.

The total energy required to construct and maintain a pavement is estimated by consideration of the energy required in the various stages of construction and service. The total life cycle is considered as the time required for the pavement to reach a PSI of 2.5. One of the conclusions drawn is that pavements constructed utilizing waste products must have a pavement service life nearly equal to the life obtainable with conventional materials

in order to save any energy. At present, the relatively low cost of the energy saved restricts the range of feasible waste products. However, if the energy crisis deepens (and costs increase) the number of feasible products would increase. A recommendation is made that products somewhat beyond the current limits of economic marginality should be investigated in anticipation of the increasing importance of energy conservation.

1-21 Transportation Research Board, "Recycling Materials for Highways", National Cooperative Highway Research Program, Synthesis of Highway Practice — Report No. 54, Washington, D. C., 1978.

This synthesis report brings together much of the present information concerning the use of recycled materials in highway construction. "Recycled" as used in the report includes the utilization of waste materials such as mine tailings, etc. The report discusses different categories of recycling. They are: (a) the procedure used, (b) type of materials, and (c) the structural benefit to be gained. The report discusses procedures for surface recycling, in-place and base recycling, and central plant recycling. Consideration is given to both asphalt and portland cement concrete pavements, metal guardrails, and waste materials such as fly ash, sulfur, mining waste, slag, glass, tires, and incinerator residue.

It is concluded that:

- Pavement recycling and the use of waste material can reduce aggregate requirements in some areas.
- Specialized pulverization equipment is available for in-place recycling operations.
- Hot central-plant recycling of asphaltic concrete has been accomplished by several processes without air pollution.

1-22 Sherwood, P. T., and P. G. Roe, "Imported Fill for Earth Works: Case Studies of the Use of Waste Tips or Borrow-pits", Transportation Research Laboratory - S411, Crowthorne, Berkshire, England.

This report describes a study of the benefits and disbenefits that have occurred in a number of road projects where waste materials were either used or considered for

use as a source of bulk fill materials. The case studies showed that where waste materials occur in close proximity to a road site their use should be considered if environmental gains can be achieved. However, there is no simple solution to the question as to whether or not waste tips (piles) should be used in preference to borrow-pits as the source of bulk-fill material. Borrow pits are not always environmentally harmful and the use of wastes can give rise to problems which may outweight the benefits of using them. Each case must, therefore, be treated on its merits. (Author's abstract)

Report gives consideration to differences in costs for construction projects — primarily fills and embankments — when wastes are utilized and when more conventional materials would have to be obtained from borrow pits. The positive values from partially or completely removing old waste tips (piles) are considered. Citizens' objections to hauling wastes through residential areas become a factor in a number of incidents. Whether or not a site containing waste is to be reclaimed or not is also an important consideration. Dual bids were taken on most jobs — one showing costs if wastes were utilized and the other showing costs if wastes were not utilized. Decisions were then based on overall effectiveness from the standpoint of residual effects on the environment as well as costs.

Section 2 — Fly Ash and Bottom Ash

1967

2-1 Faber, John H., John P. Capp, and John D. Spencer, "Fly Ash Utilization — Proceedings Edison Electric Institute — National Coal Association — Bureau of Mines Symposium, Pittsburgh, Pennsylvania, March 14-16, 1967", Information Circular 8348, U. S. Department of the Interior, Bureau of Mines, Washington, D. C., 1967.

Proceedings contains 27 formal presentations on all major phases of fly ash production, utilization, and research. Paper by Hester of Alabama State Highway Department covers use in base course stabilization, concrete bridges, and concrete pavements. Approximately 200 miles of concrete pavement containing fly ash have been constructed in Alabama (first use was in 1954). During past

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six years (as of 1967) all bridges were constructed using Type II cement and fly ash. Good sulfate resistance obtained but freeze-thaw damage and deicing salt damage can be severe where entrained air may be low.

1970

2-2 Capp, John P., and John D. Spencer, "Fly Ash Utilization — A Summary of Applications and Technology", Information Circular 8483, U. S. Department of Interior, Bureau of Mines, Washington, D. C., 1970.

This information circular summarizes the major uses of fly ash and prospects for utilization in agriculture and in brick and mineral wool manufacture. Technological aspects of utilization are discussed and references are given to the work of many of the leaders in the fields of fly ash production, processing, and utilization. Seventy-nine references are included. Subject areas included are physical and chemical characteristics of fly ash, use in cement and concrete, use in lightweight aggregate concrete, use in soil stabilization and base course construction. Use as mineral filler, use in agriculture, use in brick manufacture and feasibility for use as a raw material in manufacturing mineral wool.

2-3 Faber, John H., Neil H. Coates, and John P. Spencer, "Ash Utilization — Proceedings: Second Ash Utilization Symposium", Information Circular 8488, U. S. Department of Interior, Bureau of Mines, Washington, D. C., March 1970.

Proceedings contain 23 formal presentations on all phases of fly ash production, utilization, and research. Highway related paper discusses use of fly ash as a bituminous filler.

1973

2-4 Moulton, L. K., R. K. Seals, and D. A. Anderson, "Utilization of Ash from Coal-Burning Power Plants in Highway Construction", Department of Civil Engineering, West Virginia University. (Highway Research Record No. 430, Transportation Research Board, Washington, D. C., 1973.)

The summary of the report states:

"Although more laboratory and field research will be required in order to provide a sufficient store of knowledge to justify generalized acceptance of bottom

ash and fly ash as highway construction materials, the experience described herein shows that much of the ash produced by coal-burning power plants can be utilized in one form or another in highway construction. As ash production increases and supplies of natural aggregates diminish in the years to come, it will become increasingly more desirable to utilize bottom ash and fly ash in a more productive manner. This will require the modification of existing materials and construction specifications to permit the use of ash in a variety of highway applications, with the provision that the resulting performance be equal to, or better than, that obtained with conventional construction materials. If this can be done, it will constitute a significant contribution to the conversion of a burdensome solid waste into a valuable national resource.

1974

2-5 Faber, John H., William E. Eckard, and John D. Spencer, "Ash Utilization — Proceedings: Third International Ash Utilization Symposium — March 13-14, 1973", Information Circular No. 8640, U. S. Department of the Interior, Bureau of Mines, Washington, D. C., 1974.

Proceedings include 26 formal papers on all phases of ash production, utilization, and research. Papers of interest to the highway industry include: (1) "Specifications and Methods for Using Fly Ash in Portland Cement Concrete" by Mielenz; (2) "Utilization of Ash in Stabilized Base Construction" by Barenberg; (3) "Marketing Powerplant Aggregates as a Road Material" by Blocker and others; (4) Factors Affecting Pozzolan Marketing" by Hyland; (5) "Bottom Ash and Boiler Slag" by Moulton.

1975

2-6 Sherwood, P. T., "The Use of Waste and Low-Grade Materials in Road Construction: 3, Pulverized Fuel Ash", TRRL Laboratory Report No. 686, Transportation and Road Research Laboratory, Crowthorne, Berkshire, England, 1975.

Report provides information on the characteristics and uses of pulverized fuel ash (fly ash) in England.

1976

2-7 Transportation Research Board, "Lime-Fly Ash-Stabilized Bases and Subbases", NCHRP Synthesis Report No. 37, Washington, D. C., 1976.

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This report describes current technology for the construction of stabilized bases and subbases using lime-fly ash-aggregate materials. Typical specifications for mixing and placing the materials are described.

2-8 Meyers, J. F., R. Pichumani, B. S. Kapples, "Fly Ash as a Construction Material for Highways", Implementation Package 76-16, U. S. Department of Transportation, Federal Highway Administration, June 1976.

This report summarizes the possible uses of fly ash in highway construction.

It is shown that the pozzolanic properties, light unit weight, and good shear strength of fly ash have led to its utilization as a highway construction material in several areas of this country and in several European countries.

The pozzolanic properties of fly ash which enable it to react with lime to form cementitious products have made fly ash a good quality base or subbase course material when used with lime or cement. Strength and durability criteria have been developed. Construction procedures utilize standard equipment and techniques for central mixing or mix-in-place operations.

Fly ash is used as embankment or structural backfill material over weak or compressible soils because of the reduced surcharge that results from its light unit weight. In addition, its good shear strength properties result in low compressibility and good stability characteristics. Economics can be realized in the design of retaining structures backfilled with lightweight fly ash.

Fly ash improves the flow properties and strength characteristics of grouts. It can be used alone for void-filling or used in conjunction with portland cement, lime, clay, sand, and gravel to develop grouts for applications related to highway structures.

2-9 Faber, John H., Allan W. Babcock, and John D. Spencer, "Ash Utilization: Proceedings Fourth International Ash Utilization Symposium — March 24-25, 1976", Report No. MERC/Sp-76/4, Energy Research and Development Administration, Morgantown, West Virginia, 1976.

Proceedings include 58 presentations on all phases of ash production, utilization, and research. Papers

of particular interest to the highway industry are: (1) "Bottom Ash Use in Black Base and Bituminous Surfacing" by Majidzadeh and Bakowski, (2) "Use of Power Plant Aggregate in Asphaltic Concrete" by Ulsman, Usmen and Anderson; (3) "Soil Stabilization Using a Western Coal High Calcium Fly Ash" by Thornton, Parker and White; (4) "Poz-o-Blend — The Second Generation Poz-o-Pac" by Minnick; (5) "Fly Ash for Construction of Highway Embankments" by Bacon; (6) "Low-Cost Pavements Utilizing Power Plant Ash" by Clayton; (7) "Lime-Fly Ash Soil Stabilization" by Greenwell and Pizella.

1978

2-10 Usmen, M., D. A. Anderson, and L. K. Moulton, "Applicability of Conventional Test Methods and Material Specifications to Coal-Associated Waste Aggregates", (Presented at the 57th Annual Meeting of Transportation Research Board, Washington, D. C., January 1978).

Report notes behavior of boiler slags and bottom ashes when tested in accordance with standard methods of tests and notes differences of behavior that may negate the normal criteria for judging acceptability. In particular, it is noted that the surface texture and pore structure of bottom ash and boiler slag and the slaking of coal mine refuse complicate the determination of bulk specific gravity and absorption. It was also shown that the Los Angeles abrasion and sulfate soundness tests do not give good indications of the mechanical integrity of the coal-associated wastes and fall short of representing field conditions. The deleterious materials present in coal-associated wastes are not of the same origin and nature as those found in conventional materials, and thus are not properly accounted for by the existing test methods and material specifications. The unit weight and dry-sieve analysis are meritorious, but wet-sieve analysis produces suspect test results. The pore structure and slaking properties of the coal-associated wastes also obscure the test results on paving mixtures incorporating these materials. For example, void analyses of bituminous mixtures prepared with power plant ashes are subject to large error; existing methods of assessing moisture damage on bituminous mixtures do not properly identify potential problems associated with bottom ash; and degradation of the ash mixtures is also not properly evaluated by any of the cement test methods.

The authors note that in evaluating all new materials special attention must be given to their physical and chemical properties and how they affect design, construction or performance. Consideration must be given to modification of methods and criteria to relate to potential performance. The best guide is actual performance data when available and the experience and judgement of the materials engineer.

2-11 Levine, Sid, "Power Plant Ash — A Growing Raw Material Resource", Modern Concrete, February 1978.

Power plant ash can now be considered the sixth most abundant solid material resource in the United States. Bureau of Mines 1976 estimates of solid minerals produced show stone (890 m. tons); sand and gravel (770 m. tons); and coal (671 m. tons); iron ore (78.0 m. tons); hydraulic cement (73.6 m. tons) and coal ash (61.9 m. tons). Article reports 20% utilization in 1976, an increase of 3.6% over 1975. Continuing increase is expected.

National Ash Association classifications are given as (1) Use in Type I-P cement (ASTM C595) or mixed with raw material before forming cement clinker; (2) potential replacement of cement in concrete or concrete products; (3) lightweight aggregate; (4) stabilization for roads; (5) fill for roads, reclamation and ecology dikes; (6) filler in asphalt mix; (7) ice control; (8) blast grit and roofing granules; (9) miscellaneous.

Article describes different types of ashes and gives statistics on amounts generated, locations, and percentages of utilization for specific uses.

2-12 Price, James D., Peter Troop, and Harvey W. Gershman, "Potential for Energy Conservation Through the Use of Slag and Fly Ash in Concrete", SAN-1699-T1, U. S. Department of Energy, Office of Industrial Programs, Washington, D. C., December 1978.

The report was prepared by Gordian Associates, Inc. of Washington, D. C. for the Department of Energy. It examines the potential for conserving energy by the use of slag and fly ash, both from the standpoint of adding the materials to the concrete during mixing and also from the standpoint of blending the product with the cement. The report notes that hydraulic cement concrete is the most widely used man-made building material in the world and states that approximately 700 million tons per year

are used in the United States alone. About 84% of this use is in 3 industries: ready-mixed concrete, 63%; concrete products manufacturers, 13%; and highway construction, 8%. Manufacture of the portland cement used in this concrete required 564 trillion Btu's. This is equal to about 2% of the energy used for all U. S. industrial processes. The report contains 5 chapters. Chapter 1 is the introduction. Chapter 2 presents background information on both fly ash and blast furnace slag. This includes their respective properties, the location where the materials are generated in the United States and the current state of the art in terms of research and development.

Chapter 3 discusses the effects that may be expected from increased fly ash and slag utilization in blended cements and concrete. The economic implications for the affected industries are discussed. The industries include portland cement manufacture, iron and steel, electric utilities, fly ash and slag processors and brokers, ready-mixed concrete producers and general contractors. Estimates of potential energy savings for various use scenarios are included. The possible environmental problems and health "hazards" are also discussed.

Chapter 4 outlines a proposed government sponsored commercialization program and discusses the potential for government procurement practice to assist in the program of utilization.

Chapter 5 constitutes the conclusions and recommendations. Of particular interest are the following selected portions of the conclusions.

1. The use of glassy blast furnace slag and fly ash as partial cement replacements either in blended cements or as admixtures in concrete present the potential for sizeable energy savings. If 40% of the 1976 cement production had been blended cements (20% fly ash or 30% slag inter-mixture), the industry would have reduced its energy consumption to a level of 5.64 million Btu's per ton of cement. Such a reduction would have equalled a saving of 16.3% over the 1972 base year, exceeding the target for a 15.7% improvement set by the Federal Energy Administration.

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2. The total availability of fly ash and slag is sufficient to produce a volume of blended cement equal to 40% of the total hydraulic cement production but neither broad consumer acceptance nor industry willingness can be assumed with respect to these ash and slag applications. First, an institutional resistance to the use of blended cements or admixtures is prevalent within much of the U. S. engineering and contracting community. In large part, this disposition reflects the lack of agreement on performance characteristics and related inadequacy of national st.ndards and test procedures for blended cements and admixtures.

   Second, the materials supply industry is not in agreement as to how fly ash and slag should be employed as cement replacements. The cement industry often cites quality control problems in the blending or admixing of fly ash or slag due to compositional variations expected of these materials. However, with the anticipated rise in cement demand, the cement industry has the opportunity to ease their capital requirements and optimize their fuel use through the ambitious developments of blended cement production.

3. Because blended cements cost about the same as portland cement, there is relatively little incentive for ready-mixed concrete producers to use blended cements, unless specifically required by specifications. On the other hand the use of fly ash and slag as a replacement for part of the cement during mixing affords an opportunity to reduce costs. (Fly ash is cited in the report as costing $7.00 per ton [$7.70 per m. ton] and cement $40.00 per ton [$44 per m. ton]. Although substitution is not on an exact 1:1 basis, this price differential provides an opportunity for significant savings in concrete production costs.)

4. Whether slags and fly ash are employed by either blending or admixing, long-term supply agreements are preferred by the slag or fly ash consumer to assure a steady supply of quality materials.

Therefore, utilization of slag and fly ash is enhanced by the brokerage of these products by firms capable of dealing in sizeable year-round quantities. Such firms can better provide a product of predictable quality by working directly with slag and fly ash generators than can individual utilities.

5. The environmental implications of the increased deployment of slag and fly ash blended cements and admixtures require further study, but are apparently not of sufficient magnitude to impinge on further market penetration.

6. If the government deems the potential energy savings to be worthy of pursuit when weighed against the economic incentives and disincentives, Gordian recommends the establishment of a commercialization program for slag and fly ash blended cements and concrete.

   The program outlined includes the following features:

   a) A drive to revise specifications to provide for technically appropriate and economically competitive applications of these materials.

   b) Encouragement of government procurement of these materials through the release of guidelines for blended cement and concrete, as well as other legislative vehicles to influence state and local use.

   c) A general information transfer and technical assistance effort aimed at national dissemination of this information to members of the engineering community as well as the construction and construction materials industries.

   d) Thorough documentation of knowledge in the literature.

   e) An effort to maintain and improve the quality of fly ash at the source by impressing upon electric utilities the valuable nature of fly ash resources.

Section 3 — Mine Wastes and Debris

1973

3-1 Hughes, Michael, and T. A. Haliburton, "Use of Zinc Smelter Waste as Highway Construction Material", Transportation Research Record No. 430, Transportation Research Board, Washington, D. C., 1973.

The products of four Oklahoma zinc smelters were studied during this investigation. The results indicated that zinc smelter wastes may be used as aggregate in particular phases of highway construction. The following conclusions were stated.

"1. When natural gradation of the smelter waste is modified by an addition of fine sand or the material is either separated or crushed and recombined to meet particular gradation requirements, it may be used in sand-asphalt mixes. Resulting stability values are above minimums of the Oklahoma Department of Highways and optimum asphalt contents are within specification limits.

2. The Hveem gyratory method appears adequate for mix design. However, the sharp angular texture of the aggregate, with resulting high angles of internal friction, causes unusual Hveem stability values.

3. Addition of zinc smelter waste to asphaltic concrete surface course mixes containing limestone aggregate susceptible to polishing should increase the skid resistance of the mix.

4. Because of cement-aggregate reactivity, zinc smelter wastes should not be used in portland cement concrete mixtures.

5. All four of the zinc smelter wastes tested appear satisfactory for use in manufacture of mechanically stabilized aggregate mixtures."

1975

3-2 Sherwood, P. T., "The Use of Waste and Low-Grade Materials in Road Construction; 2, Colliery Shale", TRRL Laboratory Report 649, Transportation and Road Research Laboratory, Crowthorne, Berkshire, England, 1975.

Report provides information on characteristics of colliery shales and discusses problems associated with their use in various road-building activities. Colliery shale is the waste product that must be removed to gain access to coal faces or that is unavoidably brought out of the pit with the coal and separated from the coal at the cleaning plant.

1977

3-3 "From Waste Banks to Highway Construction — Coal Mine Debris Finds a New Home", Transportation Research News No. 27, September-October 1977.

The Pennsylvania Department of Transportation has a program to utilize mine wastes in embankments. Two large embankments have already been constructed with mine wastes with good results.

1979

3-4 Rose, J. G., "Energy Efficient Sintered Coal-Refuse Lightweight Aggregate," University of Kentucky, Lexington, Kentucky, January 1979. (Presented at Transportation Research Board, Washington, D. C., January 1979.)

Paper describes the development and evaluation of a synthetic lightweight aggregate having particular application to the building and transportation construction industries. Bituminous coal refuse was sintered on a pilot-sized traveling grate to produce lightweight aggregate. Most of the energy required for sintering is originally a part of the waste, thus the process is economical. The aggregate was shown to have satisfactory properties for use in bituminous concrete mixes and structural lightweight portland cement concretes. Lightweight concrete would have an advantage where low thermal conductivity is of importance.

Section 4 — Sulfate Wastes

1973

4-1 Brink, R. H., "Use of Waste Sulfate on Transpo '72 Parking Lot", presented at the Third International Ash Utilization Symposium," March 1973.

Describes a project which utilized fly ash, lime, bottom ash, aggregate and waste sulfate as a surfacing material for a temporary parking lot. The mixture gave erratic behavior with failure to develop acceptable strength in some cases with good results in others. Adverse lay-down conditions and unseasonably cool weather affected the performance.

1976

4-2 Nebgen, J. W., J. G. Edwards, and D. F. Weatherman, "Use of Waste Sulfate for Remedial Treatment of Soils", FHWA-RD-76-143 and 144, Federal Highway Administration, Washington, D. C., August 1976.

The effects of waste sulfate (phosphogypsum from fertilizer manufacture, flue gas desulfurization solids, and neutralized acid mine drainage solids) on physical and strength properties of soils were studied. Waste sulfate alone had little effect on soil strengths. However, if combined with lime, higher strengths than can be obtained with equivalent lime treatment are present because of solid sulfate lime reactions. Fly ash can be used with waste sulfate/lime mixtures to further improve strength. Cement kiln dust has been shown to be an effective substitute for lime as a soil stabilizer.

Volume I, (FHWA-RD-76-143) is a discussion of results and Volume II (FHWA-RD-76-144) includes an annotated bibliography of the literature reviewed as well as test data and data analysis procedures.

4-3 Smith, L. M., and A. Kawam, "The Effect of Gypsum on Lime-Fly Ash Compositions: Literature Review and Annotated Bibliography," FHWA-RD-76-84, Federal Highway Administration, Washington, D. C., May 1976.

Report contains 65 annotated articles dealing with the use of waste sulfate and presents a short summary of the effects of gypsum (calcium sulfate) in pozzolanic mixtures. The areas covered were the strength and engineering properties of lime-fly ash, lime-pozzolan, lime-fly ash-aggregate, lime-gypsum-pozzolan and lime-gypsum-fly ash mixtures. Compound identification studies of clays, pozzolans, and fly ash with both lime and lime-gypsum mixtures were also reviewed.

The literature showed that the addition of gypsum to pozzolan or fly ash mixtures does alter its engineering

properties and could be used to advantage. Also the chemical reactions that occur in a lime fly ash-gypsum mixture are similar to those in other natural pozzolans. Therefore, it should be feasible to use waste sulfate as the source of the gypsum.

1977

4-4 Nebgen, J. W., J. G. Edwards, and D. Conway, "Evaluation of Sulfate-Bearing Waste Material from Fluidized Bed Combustion of Coals for Soil Stabilization", FHWA-RD-77-136, Federal Highway Administration, Washington, D. C., September 1977.

Report evaluates the effect of spent bed material (SBM) from fluidized bed combustion of coal on the physical and strength properties of fine-grained soils. The SBM is a mixture of lime and calcium sulfate (together with some fly ash) which results when pulverized coal is burned in a fluid bed of finely ground or calcitic dolomitic limestone (analysis of materials used: $CaCO_3$ - 3.2%; $MgSO_4$ - 9.6%, $CaSO_4$ - 15.1%; CaO - 31.9% and SiO_2 - 29.6%).

Results indicate that SBM is an excellent substitute for lime for soil stabilization. It behaves about the same as mixtures of lime, calcium sulfate, and fly ash when mixed with soil, but has the advantage of being premixed all in one component. At present fluidized bed combustion is only in pilot plant stages but when full-scale plants are operating, the material should be economical and easy to use.

Section 5 — Incinerator Residues

1974

5-1 Pindzola, D., and R. C. Chou, "Synthetic Aggregate from Incinerator Residue by a Continuous Fusion Process", FHWA-RD-74-23, Federal Highway Administration, Washington, D. C., April 1974.

Report describes a pilot plant demonstration of a system to convert municipal incinerator residues into dense road aggregates. The aggregates prepared would be suitable for bituminous construction. Potential production from a 600 ton/day incinerator (Philadelphia) was estimated to be 120 tons of aggregates per day. The plant cost was estimated to be about $300,000 (in 1974). Operating costs for the aggregate plant will be $4-$5 per ton of aggregate (1974 dollars).

1975

5-2 Haynes, J., and W. B. Ledbetter, "Incinerator Residue in Bituminous-Base Construction", FHWA-RD-76-12, Federal Highway Administration, Washington, D. C., December 1975.

Use of incinerator residue as an aggregate in a bituminous base pavement (termed littercrete) was studied. Two sections of bases were constructed with material in Houston, Texas, and bases were covered with 1-1/2 inch wearing surface. Results show that littercrete pavement meets current specifications for asphalt stabilized material and littercrete can be constructed using conventional equipment and technology. Estimated life of pavement was 10-15 years. The high cost of aggregates in certain areas makes littercrete economically feasible and there are some intangible benefits associated with the use of incinerator residues.

5-3 Collins, R. J., R. H. Miller, S. K. Ciesielski, E. M. Wallo, M. J. Boyle, D. M. Pindzola, and J. Tropea, "Technology for Use of Incinerator Residue as Highway Material", FHWA-RD-77-151, Federal Highway Administration, Washington, D. C., October 1976.

Report shows that as of 1976 there were 141 operating municipal incinerator plants in 24 states and the District of Columbia. These plants produced about 5 million tons of residue annually. Six basic types of incinerator residue were obtained in the field and subjected to extensive laboratory study. The materials were characterized and evaluated for performance in base course and wearing surface mixtures. Based on these tests, incinerator residue is not recommended for use in portland cement concrete. It is, however, recommended as an aggregate in bituminous mixtures.

Three experimental sections were placed using incinerator residue in bituminous wearing surface mixtures. The mixtures used have performed well since their placement in the latter part of 1975. Early data on skid resistance for those mixtures indicate that the addition of incinerator residue does improve pavement skid resistance.

1977

5-4 Collins, R. J., R. H. Miller, and S. K. Ciesielski, "Guidelines for the Use of Incinerator Residue as Highway Construction Material", FHWA-RD-77-150, Federal Highway Administration, Washington, D. C., September 1977.

Report gives background information on the composition and characteristics of various types of incinerator residue and suggests a classification system. The use of incinerator residue in structural fills, stabilized bases, and bituminous paving applications are discussed. Included are specific recommendations for materials handling and preparation, laboratory testing procedures, engineering properties, and design and construction procedures for these applications. Discussions of the conditions that result in either a favorable or unfavorable situation with respect to the utilization of incinerator residues are included.

1979

5-5 Teague, D. J., and W. B. Ledbetter, "Three Year Results on the Performance of Incinerator Residue in a Bituminous Base", Texas Transportation Institute, Texas A & M University, College Station, Texas, January 1979. (Presented at Transportation Research Board, Washington, D. C., January 1979.)

Approximately 200 ft (61 m) of roadway were constructed using incinerator residue as part of the aggregate for the base course. The project is described and the results of tests made after 3 years are given and discussed. The conclusions drawn are that after 3 years, both the littercrete and the control section are performing essentially the same. This conclusion is based on the properties of the recovered asphalts, densities and field observations, Marshall stability and splitting tensile tests. Hveem stability values for littercrete dropped significantly.

Section 6 — Concrete Rubble (Buildings and Pavements)

1973

6-1 Buck, A. D., "Recycled Concrete", U. S. Army Engineers, Waterways Experiment Station, Vicksburg, Mississippi, Highway Research Record No. 430, Transportation Research Board, Washington, D. C., 1973.

Report found crushed concrete generally suitable as coarse aggregate with some decrease in strength. Fine aggregate from waste concrete had mild undesirable effects on workability and cement content but would also be usable if effects could be reduced to tolerable level.

1977

6-2 Buck, A. D., "Recycled Concrete as a Source of Aggregate", ACI Journal, May 1977.

Paper cites general use of crushed concrete as aggregate in Europe after World War II with successful results and renewed interest in both U. S. and Europe because of need for better methods of disposal and energy conservation. Present research and current use are reviewed. Paper concludes that recycling concrete for use as aggregate in new concrete is feasible and may become routine.

6-3 Malhotra, V. M., "Use of Recycled Concrete as a New Aggregate", CANMET Report No. 76-8, Canadian Centre for Mineral and Energy Technology, Energy, Mines and Resources of Canada, Ottawa, Canada.

Test results show that satisfactory concrete can be made with aggregates prepared from recycled concrete. At high water-cement ratios, the compressive and flexural strengths of concrete made with aggregate prepared from recycled concrete are somewhat lower than the strengths of concrete made with reference aggregates. However, this difference can be overcome with suitable adjustment in mix proportions. At low water-cement ratios, strengths of the two types of concrete are comparable. The durabilities of both types were also comparable.

6-4 Frondistou-Yannas, S., "Waste Concrete as Aggregate for New Concrete", ACI Journal, August 1977.

Compares properties of concrete prepared with aggregate from old concrete and with conventional aggregate. The mechanical properties were best matched when concrete from recycled aggregate contained additional gravel. The water-cement ratio did not appear to significantly affect relative merits of the recycled product and the control.

The strength of aggregate-matrix mortar bond was reduced to about 55% to 88% of the strength of the control when coarse aggregate was replaced with pieces of old concrete. Recycled concrete was equally workable as the control. Compressive strength was at least 76% of control and modulus of elasticity was from 60% to 200% of control. It was suggested that recycled concrete is a possible substitute for aggregate in areas where concrete disposal is a problem or in areas where natural aggregates are not accessible.

Findings of other authors are reviewed and references included.

1978

6-5 Bernard, D., and G. Henderson, "The Alternate Aggregate Source — Recycled Concrete", Rural and Urban Roads, October 1978.

Cites objective of Demonstration Project 47 of Federal Highway Administration.

Indicates that the cost of production of recycled aggregate is less than the cost of producing natural aggregates. Where haul distances for natural aggregates exceed 50 miles (80 km); recycled aggregate gains the economic advantage. Energy analysis indicated that elimination of haul distances for new aggregates was the one major significant factor contributing to the energy and monetary savings. Harshness can be reduced by adding 15% to 30% natural sand in design. Water-cement ratio should not exceed 0.55. Expects better break-up process to increase use. Six-sack concretes using recycled aggregates have produced pavements with 4,300 lbs/in^2 (29,300 kPa) compressive strength and 800 lbs/in^2 (5,500 kPa) flexural strength at 28 days.

6-6 Ray, G. K., "Recycled Concrete", Modern Concrete, January 1978.

Cites location and general description of projects built in United States. Mentions need for proper mix design.

6-7 Britson, R., "Iowa Tests Concrete Recycling in Search for Low-Cost Aggregate", Rural and Urban Roads, April 1978.

Describes 3 projects in Iowa in which old concrete pavement was crushed, graded, and then used as aggregate in new concrete pavement. Mix designs were close to standard Iowa specifications. Concrete containing 564 lb/yd^3 (334 kg/m^3) of cement with 50% recycled coarse aggregate produced compressive strength of 4,300 lb/in^2 (29,300 kPa) at 28 days. Concrete containing 626 lb/yd^3 (371 kg/m^3) of cement (Iowa's C-4 paving mix) and using 40% recycled coarse aggregate produced compressive strength of 5,500 lb/in^2 (37,920 kPa). The first project is now in its second winter with no signs of deterioration.

6-8 "Landfill Avoids Concrete Waste by Aiding Recycling Operation", Rural and Urban Roads, March 1978.

Describes operation at Pontiac City, Michigan.

Landfill operation could not accept large pieces of broken concrete. However, the contractor leased an area within landfill and allowed all contractors to dump their broken concrete. He processed it by removing reinforcing steel and wood and crushing to aggregate size. He then sold aggregate to contractors as well as used it himself. Process is profitable to all. Contractors avoid about 35-mile (56-km) haul to dispose of rubble — landfill avoided problems from trying to incorporate in fill and process was profitable to crusher operator.

Article describes equipment used for crushing and handling.

6-9 Dresser, J. G., Jr., "Rehabilitation of Runway 13-31 Jacksonville International Airport", Jacksonville, Florida, (a concrete recycling project), (Presented at the Transportation Research Board, Washington, D. C., January 1978.)

Report describes the conditions leading to the decision to crush the old runway and to use the crushed materials as aggregate for a strengthened "econocrete" base. The procedures and design used are described. The project proved to be economical and feasible.

6-10 Ray, G. K., and H. J. Halm, "Energy Savings Through Concrete Recycling", (Presented at the Transportation Research Board, Washington, D. C., January 1978.)

Paper gives general overview of need for recycling and shows computations of energy used in concrete construction and estimates savings possible by recycling old pavements as aggregate in new concrete.

Section 7 — Asphalt Pavement Recycling

1975

7-1 Epps, J. A., and R. J. O'Neal, "Recycling of Pavement Materials", Cooperative Research Project 1-9-74-214, Texas State Department of Highways & Public Transportation and Texas Transportation Institute, College Station, Texas, December 1975.

Report reviews recycling projects in various states as of 1974. (Later reports probably update this information.)

1976

7-2 Fisher, D. J., "An Economic, Energy and Environmental Evaluation of Pavement Recycling", Texas A & M University, College Station, Texas, August 1976.

Report is a study by a graduate student to summarize existing literature on recycling both flexible and rigid pavements from an economic, energy, and environmental standpoint. Approximately 170 references are included.

1978

7-3 Ortegies, B., "Asphalt Recycling with a Twist", Rural and Urban Roads, January 1978.

Describes an asphalt recycling project in Iowa in which a "sprinkling" of precoated aggregate on the recycled pavement at laydown was added. This provides polish-resistant aggregate in the surface for improved traction.

The sequence of operations were:

1. Diluted asphalt primer applied to surface with distributor

2. Heater-planer heated and scarified old surface (minimum depth 1/2 in [127 mm])

3. "Cutler" repaver supplied additional heating and placed thin (3/4 in [190 mm]) new asphalt overlay

4. Sprinkle treatment spreader applied 3/4 in. (190 mm) graded sprinkle stone

5. Surface rolled — tandem steel roller for breakdown, pneumatic final intermediate roller and tandem steel finish roller

1119 7-4 Alcoke, W. H., E. G. Robbins, and J. E. Taylor, Jr., "Cold Recycling of Failed Flexible Pavements with Cement", Portland Cement Association, Skokie, Illinois, January 1979. (Report presented at Transportation Research Board, Washington, D. C., January 1979.)

Report discusses the advantages of pavement recycling of several types. Energy calculations are included for several alternatives to strengthening and rehabilitating old flexible pavements. It is shown that use of cement stabilization is economical and uses less energy than other alternatives. (Caloric energy in asphalt is included for use of asphalt stabilization and overlay.)

Report also cites a number of projects for which recycling has been used and gives cost figures.

7-5 Ingberg, R. C., and R. H. Cassellius, "Asphalt Recycling: The User's View", Minnesota Department of Transportation, Minneapolis, Minnesota (Presented at Transportation Research Board, Washington, D. C., January 1979.)

Paper reviews advantages and disadvantages of recycling salvageable asphaltic concrete and aggregate base materials. Estimates are that 325 million tons (205 billion kg) of asphalt concrete are produced each year. If only 10% to 30% of this amount is eventually salvageable, the value of the 32.5 to 97.5 million tons (29.3 to 87.8 billion kg) would range between 260 and 780 million dollars (based on 3% asphalt at $100/ton [$110 per 1,000 kg] and aggregate at $5/ton [$5.50 per 1,000 kg]).

Although costs are associated with utilizing these materials, the potential for saving is considerable. Paper shows potential savings for assumed situations with different designs. Urges that state allow use of recycled mixes as an equal to standard conventional mixes provided they meet the same design criteria as mixes made with new material. This policy would permit contractors to benefit, from lower costs of raw material as well as provide some saving to state.

Section 8 — Miscellaneous

1973

8-1 Ledbetter, W. B., "Synthetic Aggregates from Clay and Shale: Recommended Criteria for Evaluation", Texas Transportation Institute, Texas A & M University, Highway Research Record No. 430, Highway Research Board, Washington, D. C., 1973.

To develop the criteria for performance, or durability, the research was considered from four aspects: physical performance, chemical performance, mechanical performance, and volume change performance. Within the limitations imposed, the study found that sound, durable, high-quality highways and bridges can be constructed with synthetic aggregates, provided the aggregates meet certain requirements. Not all functional uses of synthetic aggregates require aggregate of the same quality, and laboratory evaluations can, with reasonable assurance, predict field performance of synthetic aggregates.

1974

8-2 Nelson, D. S., and W. L. Allen, Jr., "Sawdust as Lightweight Fill Material", FHWA-RD-74-502, Federal Highway Administration, Washington, D. C. May 1974.

Sawdust was found to be useful for fill on unstable embankments and in potential slide areas since its light weight counteracted sliding potential. A life expectancy of 15 years was reported where asphalt sealed slide slopes were used. The material would be most useful in secondary and country roads with unstable slide conditions where economics prevent major repairs.

1975

8-3 Transportation Research Board, "Crash Cushions of Waste Materials", NCHRP Report No. 157, Washington, D. C., 1975.

Old tires and cans were used in various configurations to form crash cushions. Crash tests were conducted to determine their effectiveness. Tests showed effective cushion could be designed with tires but rebound created some problems. Tire-sand cushions can also be used. Concept would remove old tires from scrap heap but other designs for crash cushions are probably superior.

8-4 Kawam, A., L. M. Smith, J. Ross, H. G. Larew, and L. Rude, "Feasibility of Using Sewage Sludge in Highway Embankment Construction," FHWA-RD-75-38, Federal Highway Administration, Washington, D. C., February 1975.

The feasibility of using sewage sludge in construction of a highway embankment was studied. Mixtures composed of lime, fly ash, waste calcium sulfate and up to 17% sewage sludge were evaluated. Two soils, one sandy and the other clayey, were used to replace 30%, 50%, and 70% of the fly ash in selected formulations.

Test results showed that satisfactory strength was obtained with no heavy metals being leached from compacted fill. Mixture was susceptible to damage by freeze-thaw.

Conclusions are that sewage sludge could be satisfactorily disposed of in this fashion with no environmental damage. However, at least 3 ft (1 m) of soil cover is needed to provide protection from freezing. It was also recommended that the sludge mixture be isolated from ground water by placing it on a layer of impervious soil at the bottom of the embankment.

8-5 "Ground Pelletized Slag Autoclaved Blocks", McMaster University, Hamilton, Ontario, Canada, 1978.

The pelletizing process developed by National Slag Limited in Canada for quenching blast furnace slag is relatively new but it is being adopted all over the world and new uses recognized. Pelletized slag is largely vitreous (glassy) and porous in structure, which makes it suitable for cement replacement when ground to adequate fineness. Partial grinding can also be employed. The rationale for partial grinding in block manufacture is to provide a high temperature (185°C) steam reaction with silica flour and the free lime released by cement and slag (silica flour is less expensive than cement and slag aggregate permits use of more silica).

Mixes incorporating slag fines as 67% of the binder resulted in strengths superior to that of the control mixes.

8-6 "Missouri Sign Reclamation Saves $120,000 in Substrate Materials", Rural and Urban Roads, September 1978.

Article describes special operation of Missouri State Highway Department. Three-man team operates plant. Old signs are cleaned, paint is removed, and the signs are rolled to remove all dents. Operation eliminated

$176,000 in purchase of new material at a cost of $54,000 (based on 30-year amortization of building cost and 10-year amortization of equipment costs). This was a $3 return for each $1 invested.

1976

8-7 Forsyth, Raymond A., and Joseph P. Egan, Jr., "Use of Waste Materials in Embankment Construction", Construction and Research Transportation Laboratory, California Department of Transportation, California Department of Transportation, Sacramento, California. (Presented at Annual Meeting of Transportation Research Board, Washington, D. C., January 1976.)

Report covers the possible use of three types of waste materials in embankments — wood waste, sanitary landfill wastes, and nonbiodegradable waste (discarded tires). Case histories of embankment construction with wood wastes — mostly stumps, logs, and tree branches, etc. from clearing operations — are given along with an analysis of the theoretical effects of tire sidewall reinforcement on earthquake resistance of embankments. Plans were reported to be under way for utilizing 1/2 tire sections (tires are split longitudinally through center of tread) in embankment construction.

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