Use of Waste and By-Products in Highway Construction

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The technologies for using many waste materials including industrial, domestic, and mining/metallurgical wastes were developed by the Federal Highway Administration during the 1970s. Studies on fly ash, bottom ash, incinerator residue, sulfate wastes, digested sewage sludge, coal mine refuse, waste rubber, and cement manufacturing wastes have been completed. Materials investigated were stabilized with various binders including lime, lime-fly ash, asphalt cement, and portland cement. Both laboratory evaluations and field tests were performed. Many of the systems evaluated developed strength and other physical properties adequate for use in embankments, subbases, and bases. Some materials (e.g., fused incinerator residue) were technically adequate for use in bituminous concrete-wearing surfaces. While the emphasis of the research was on engineering behavior, assessments of economic and environmental factors were made in some cases. Information generated should be of interest and of use today when more and more emphasis is being placed on saving the environment from further desecration.

The FHWA has had an interest in waste and by-product utilization since the mid 1950s. Early work concentrated on the properties and utilization of various fly ashes and fly ash-containing systems (*1,2*). In the early 1970s, several events gave impetus to the development of a comprehensive research program on waste and by-product utilization in highway construction. First, the president, in his 1970 Environmental Message, stated the need to encourage more recycling and requested the Council on Environmental Quality to develop proposals in this area. Second, the Oil Embargo of 1973 demonstrated the need to conserve energy and to develop alternative materials to supplement or replace asphalt cement. Finally, a large by-product utilization demonstration project at Dulles International Airport was sponsored by FHWA (*3,4*) that demonstrated that many by-product materials had potential for use as paving binder and aggregate supplements or replacements. On the basis of those and other events (e.g., the Clean Air Act of 1970) the FHWA developed a research program entitled "Use of Waste Materials for Highways."

FHWA's research program was designed to evaluate a wide spectrum of by-products that, in general, were technically promising as aggregate or binder supplements or replacements. Economics and environmental concerns were also considered. In some cases, materials with little or no potential for use as a highway material (e.g., sewage sludge) were evaluated to address an immediate, critical, and specific highway problem.

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This paper will describe research and development efforts undertaken by FHWA and others to develop the technologies needed to utilize wastes and by-products in highway construction. A tabulation of various materials investigated is given in Table 1 (recycled asphalt cement and portland cement concrete pavements are outside the scope of this paper).

INDUSTRIAL WASTES

Sulfate Wastes

Transpo 72

A large-scale waste utilization project was constructed in connection with Transpo 72, an International Transportation Exposition held at Dulles International Airport in 1972. Approximately 90,700 tonnes of primarily waste products were used in constructing a 40.5 hectare parking lot. The basic composition used consisted of fly ash, dolomitic lime, sulfate wastes [acid mine drainage (AMD), flue gas desulfurization sludge (FG), and fluorogyp (FLG)], limestone aggregate, and water. The dry ingredients were formulated as follows: 80.5 percent fly ash, 15 percent limestone aggregate, 2.5 percent dolomitic lime, and 2 percent sulfate waste. In addition to the fly ash-lime-sulfate-aggregate-water system, other materials tested included crushed glass, shredded tires, incinerator residue, and crushed storage batteries. Figures 1 and 2 present the plant layout for the production of the lime-fly ash-sulfate-aggregate material and the paving operation, respectively. The demonstration project indicated that satisfactory mixtures of the waste materials could be produced in a portable plant and that a suitable pavement could be constructed. However, localized failures indicated that further study was needed to develop the optimum conditions for compaction and strength development in the field. Additional studies involving multiple waste utilization follow.

Lime-Fly Ash-Sulfate Technology

On the basis of the Transpo 72 demonstration and the work of Minnick (*5*), the FHWA sponsored a comprehensive laboratory study of lime-fly ash-sulfate mixtures. This study, conducted by the Gillette Research Institute, developed the technology required for the use of sulfate wastes in highway construction, primarily in base courses and embankments. A comprehensive evaluation was made of the pertinent properties of mixtures composed of a variety of sulfates, fly ashes,

TABLE 1 MATERIALS EVALUATED IN FHWA RESEARCH AND DEVELOPMENT PROGRAM ON WASTE AND BY-PRODUCT UTILIZATION

Industrial	Municipal/Domestic	Mining
Sulfate Wastes	Incinerator Residue	Coal Mine Refuse
Cellulosic Wastes	Sewage Sludge	
Wood Lignins	Scrap Rubber	
Bottom Ash		
Fly Ash		

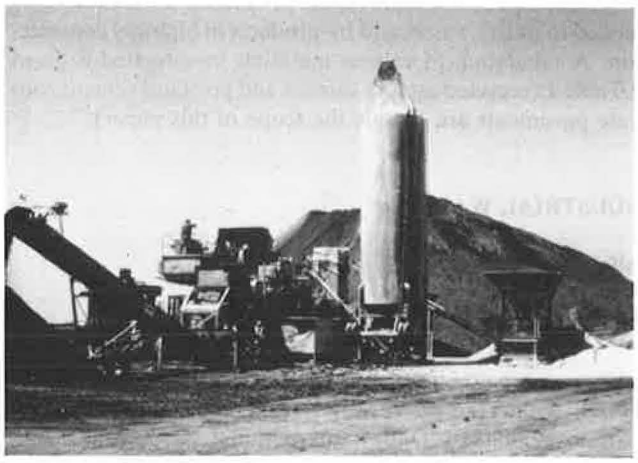


FIGURE 1 Transpo 72 plant layout for lime-fly ash-sulfate waste-aggregate pavement mixture preparation.

FIGURE 2 Transpo 72 paving operation (compaction).

and limes. Properties of sulfate wastes are given in Tables 2 and 3. Compositions and properties of the mixtures studied are given in Tables 4 and 5, respectively.

One of the more significant observations, in keeping with some of Minnick's findings (*5*), was that sulfate waste can serve to enhance the strength characteristics of lime-fly ash mixtures. Specifically, modest additions of sulfate will increase the rate of strength gain and will also increase the final strength. Increased early strengths are due to the formation of ettringite. Figure 3 illustrates the effect of gypsum on strength development in a lime-fly ash mixture moist cured for 7 and 28 days. Mixtures of the type represented in this figure, in addition to having acceptable strength properties, had high California Bearing Ratios, low permeabilities, and slightly less than adequate durability properties.

The following conclusions were reached:

1. Properly proportioned, compacted and cured mixtures produce a strong, rigid material that may be used in applications such as embankments, subbases, and bases.
2. Compacted lime-fly ash-sulfate formulations are normally lighter in weight than most compacted soils and would be a real advantage on soft, compressible ground.
3. Mixtures studied were quite impervious, indicating that selected formulations can be employed in dikes, lagoons, and levees.
4. Durability of the mixtures, as was measured by freeze-thaw and wet-dry tests, was poor for 7 days curing at 23°C. Durability of compacted mixtures for pavement components must be considered in cold climate applications.

The study delineated the range of formulations that could be prepared with acceptable strength, permeability, and leachability properties (*6–8*). Later research on fly ash-lime-phosphogypsum mixtures confirms and amplifies the results obtained by the Gillette Research Institute. Laboratory studies indicated the following composition as being highly satisfactory for subbase construction: 91 percent fly ash, 4 percent quicklime, and 5 percent industrial gypsum (phosphogypsum) (*9*). This mixture, prepared in a continuous mixing plant, has been successfully used in road installations in several locations in France, the earliest in 1969, and has performed well for several years.

Remedial Treatment of Soils

Research by Midwest Research Institute was performed to evaluate the feasibility of disposing sulfate waste in soils and the use of various power plant and other sulfate wastes for soil stabilization. This research consisted of a laboratory study to evaluate the effects of sulfate (sulfite) wastes on the engineering properties of fine-grained soils. The various sulfates studied included (a) phosphogypsum (PG) derived from treating phosphate rock with sulfuric acid to produce phosphoric

TABLE 2 PROPERTIES OF SULFATE WASTES

	Waste Source						
	Acid Mine Drainage	Rutile Mfgre	HF By-Product	FGD(1)[a]	Spent Pickle Liquor[b]	FGD(2) Lime-stone	FGD(3) Lime
Physical form and color	reddish brown slurry	grey solid dispersed in green soln.	white lumpy solid	thick grey slurry	reddish brown	--[c]	--
sulfate form	$CaSO_4 \cdot 2H_2O$	$CaSO_4 \cdot 2H_2O$	$CaSO_4 \cdot 2H_2O$+ $CaSO_4$	$CaSO_4$+ $CaSO_3$	$CaSO_4 \cdot 2H_2O$	$CaSO_4$+ $CaSO_3$	$CaSO_4$+ $CaSO_3$
"Impurities"	$Al(OH)_3$ $Fe(OH)_3$ $CaCO_3$	TiO_2	CaF_2	Fly Ash SiO_2 Al_2O_3	$CaCO_3$	Fly Ash SiO_2 Al_2O_3	Fly Ash SiO_2 Al_2O_3
pH	9.6	2.5	9.0	11.3	8.7	--	--
Free H_2O %[d]	57	41	0	24	63	--	--

[a] FGD: flue gas desulfurization waste.
[b] Pickle liquor: a waste product resulting from the cleaning of metals with acid.
[c] data unavailable.
[d] Free water: any water which is not combined as water of hydration.

TABLE 3 PARTIAL CHEMICAL ANALYSIS OF SULFATE WASTES (OXIDES, PERCENT BY WEIGHT)

	Waste Source							
	Acid Mine Drainage	Rutile Mfgre	HF By-Product	FGD(1)	Spent Pickle Liquor	FGD(2) Lime	FGD(3) Lime-stone	Phosphogypsum
SiO_2	1	17	12	19	1	4.9	1.8	0.3
FeO_3+Al_2O_3	7	4	2	18	9	4.0	2.0	0.7
CaO	7	20	54	28	16	43.2	25.0	40.4
SO_3	4	13	43	5	1	5.9	6.4	54.3
SO_2	--[a]	--	--	--	--	33.0	11.6	--

[a] data unavailable

acid, (b) sulfates from flue gas desulfurization, (c) acid mine drainage wastes, and (d) spent bed material from the fluidized bed combustion of coal (SBM). The wastes were evaluated for their effects on the strengths, consistency limits, freeze-thaw durability, and volumetric stability of 30 soil samples representing the predominant soil series indigenous to various waste sources.

Analysis of the results indicated that PG, FG, and AMD had little effect on mixture properties. However, when those wastes were used in combination with lime, lime-fly ash, or cement kiln dust, higher strengths were achieved than when lime was used with the test soils. The higher the sulfate content of the waste, the stronger the mixture. In summary, the results demonstrated that PG, FG, and AMD can be used to enhance

TABLE 4 FORMULATIONS USED IN EVALUATING PROPERTIES OF WASTE SULFATE: FLY ASH-LIME MIXTURES

Waste Type	Calcitic Lime, percent	Waste, percent	Fly Ash, percent
Pure Gypsum	4.7	9.3	86.0
Acid Mine Drainage	5.0	15.0	80.0
HF By-product	4.0[a]	11.0	85.0
Titangypsum	5.0	12.0	83.0
FGD (2)	5.0	19.0	76.0
FGD (3)	5.6	32.8	61.6

TABLE 5 PROPERTIES OF WASTE SULFATE: FLY ASH-FLY ASH MIXTURES

	Compressive Strength kN/m^2			Tensile Strength kN/m^2			Permeability, x 10^6cm/sec at 20 °C		CBR percent	
	7days	28days	91days	7days	28days	91days	7days	28days	7days	28days
Pure Gypsum	3651	13918	15813	782	1654	3583	3.79	9.45	346	617
Acid Mine Drainage	2756	5030	7648	482	1171	1275	2.51	7.72	208	381
HF By-product	3307	7269	7992	586	1033	689	7.19	4.27	300	487
Titangypsum	2170	7889	7820	379	1344	1550	5.02	0.82	350	-- [a]
FGD (2)	2790	4237	9715	482	872	1137	16.5	17.0	226	335
FGD (3)	1240	5202	7407	139	1102	1447	36.1	5.91	126	376

Samples moist cured at 23 °C.
[a] Data unavailable.

the rate and magnitude of strength development of soil-lime mixtures. Results with SBM indicated that it is equally effective as lime for soils treated in this study. Results of the research are given in three reports (*10–12*).

Lime and Cement Kiln Dusts

Waste material from lime and cement manufacture accumulates at a rate in excess of 18 million tonnes a year. Some of those materials are recycled, used for acid effluent neutralization, used in landfill stabilization, or used in soil stabilization, but most (approximately 70 percent) of the material is landfilled. To promote more widespread utilization of those materials, the FHWA conducted a study to determine the effectiveness of substituting kiln dusts for hydrated lime in lime-fly ash-aggregate (LFA) road bases (*13*).

A large selection of lime and cement kiln dusts (KD) and fly ashes (both class F and class C) was obtained and characterized chemically and mineralogically. Optimum kiln dust/fly ash ratios were established, and engineering properties were evaluated. Engineering properties of kiln dust-fly ash-

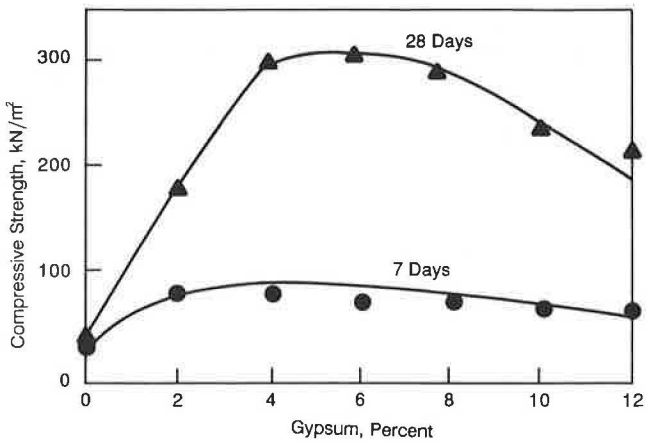


FIGURE 3 Variation in strength of lime-fly ash mixtures with varying gypsum content for 7 and 28 days curing.

aggregate (KDA) mixtures evaluated included compressive strength, durability, dimensional stability, autogenous healing, and resilient modulus.

Conclusions of the study are as follows:

1. KD are generally capable of being substituted for hydrated lime in LFA road base compositions. The possible exceptions are cement KD with high sulfate or alkali content or lime KD with very high levels of free lime.
2. KDA mixes generally develop higher early strength than do conventional LFA mixes and provide equal or better durability and volume stability characteristics. KDA mixtures are capable of autogenous healing although not as strongly as in LFA mixtures.
3. Generally, concentrations of KD required are higher than lime, meaning that greater quantities of KD are needed to react with fly ash.

The final report for the study provides detailed recommendations with regard to KD and KDA evaluation and mixture design procedures. Included in the recommendations are KD screening tests, KD-fly ash-aggregate mixture design, logistical considerations, and mixing and placement considerations.

Cellulosic Wastes

The possibility of using cellulosic wastes as a pavement binder material was investigated in a contract with SUNTECH, Inc., of Marcus Hook, Penn. (*14*) to develop and evaluate processes for converting cellulosic and related wastes into road binder materials and to evaluate the performance of such materials alone and in mixtures with aggregates.

A detailed evaluation of the supply, availability and geographic distribution of cellulosic wastes was made. Various wastes evaluated included agricultural wastes (crop residues, animal manure, foresting wastes), manufacturing wastes (food processing and wood and paper industry), and urban refuse (municipal solid waste and manufacturing plant trash). Following this evaluation, a consideration of process feasibility (e.g., pyrolysis, liquefaction, and hydrolysis) was made. Secondary processes such as distillation, extraction, air blowing, hydrotreating, and blending (with asphalts) were also considered. Finally, a study of product performance was made and involved previously reported results plus extensive experimental studies needed to complete the evaluation. After completing the survey, process feasibility study, and product performance evaluation, the following conclusions were drawn:

1. An estimated 74 $\times$ 10^9 kg/year of cellulosic waste is available for processing.
2. Pyrolysis is the preferred method for converting cellulosic waste to substitute binder material.
3. Pyrolysis products are not suitable for direct use in highway binder applications. Rheological properties do not meet performance criteria, and the products are not compatible with asphalt.
4. Hydrogenation of wood pyrolysis products improves their compatibility with petroleum asphalt.
5. A pyrolysis-hydrogenation procedure could be cost effective in a 909 tonnes/day waste-processing facility.
6. Hydrogenated pyrolysis oil is suitable for use as an extender of asphalt in paving operations.
7. The durability of a wearing surface mixture containing hydrogenated pyrolysis oil was not significantly different from that containing the reference asphalt cement.

Wood Lignins

Wood lignin is high-volume waste produced in the manufacture of paper products. An examination of the feasibility of converting lignin to a highway binder material was investigated in a study entitled, "Evaluation of Wood Lignin as a Substitute or Extender of Asphalt" (*15*). The study evaluated the use of lignin in three different applications: (a) alone as a substitute for asphalt, (b) as an extender for asphalt in hot mixes, and (c) as an extender of emulsified asphalt in conjunction with rubber in cold mixtures.

Principal conclusions of the study follow:

1. The utilization of wood lignin alone as a substitute paving binder is not feasible, and the conclusion was reached after an extensive program of chemical and physical treatments ("formulations").
2. Using lignin material to extend asphalt seems feasible with a 30 percent replacement possible with no sacrifice in physical properties. Paving mixtures prepared with lignin-asphalt material require a slightly higher binder content than does conventional asphalt cement concrete.
3. Suitable lignin-asphalt binder formulations were prepared from lignins from both major manufacturing processes (i.e., kraft and sulfite processes).
4. Because lignin-asphalt binders are somewhat stiffer than asphalt alone, precoating of the coarse aggregate is recommended, and also permits a reduction in binder content.
5. Coal tar, coal, kraft liquor, or carbon black generally enhance the reaction between lignin and asphalt and allow a lower binder content.
6. Kraft lignin appears to be suitable as a partial replacement of asphalt in emulsified asphalt paving mixtures.

7. Kraft lignin appears to be insoluble in asphalt.
8. Lignins are environmentally stable from a leaching standpoint.
9. On the basis of laboratory mixture characterization, on a comparison of expected behavior by using elastic layer theory, and on the predictive computer program, VESYS IIM, it appears that pavement mixtures using lignin-asphalt materials can be designed to match those from conventional materials.

Bottom Ash

Problems associated with using various power plant bottom ashes in pavement construction were comprehensively investigated in the laboratory to evaluate the feasibility of using bottom ashes as a partial or full substitute for natural aggregate in bituminous mixtures and to develop detailed guidelines for implementation of the findings.

Detailed results of the study and recommended guidelines for the selection of materials, testing, mixture design, evaluation of performance parameters, and quality control are summarized in two publications (*16,17*). The principal conclusions follow:

1. Bottom ash-asphalt mixture properties are dependent on ash content. In general, as the ash content is increased, the optimum asphalt content is increased, the mixture density is decreased, and the voids and voids in mineral aggregate are increased.
2. In bituminous mixtures the mixture stability of ash-containing compositions decreases up to an ash content of about 30 percent, and further additions do not effect significant changes in the stability.
3. Resilient moduli for ash-aggregate-asphalt mixtures are low and Poisson ratios are approximately equal when compared with standard asphalt mixtures.
4. Fatigue life and fracture toughness of ash-aggregate-asphalt mixtures increase with ash and asphalt content, and rutting susceptibility and plastic deformation also increased with higher ash and asphalt content.
5. Ash-aggregate-asphalt mixtures have a high resistance to moisture damage (immersion-compression) and environmental conditioning (samples were tested dry, saturated, and after freeze-thaw cycles).
6. It was concluded from the data and test results presented that the properties of most wet and dry bottom ashes can meet performance specifications for conventional aggregates and that those materials can be used successfully in pavement construction.

Fly Ash

As was mentioned previously, FHWA has had a long-standing interest in fly ash and fly ash–containing systems. The use of fly ash alone or in combination with, for instance, lime, sulfate wastes, or soils, has been described in many FHWA publications based on staff, Highway Planning and Research (HP&R), contract, and NCHRP studies.

Guidelines designed to promote the use of fly ash in highway construction and maintenance were developed for FHWA by General Analytics, Inc. (*18*). The guidelines provide details and examples of the use of fly ash in various highway applications such as pavements, embankments, backfills, and grouts.

FHWA's Demonstration Projects Division in 1981 initiated Demonstration Project No. 59, "The Use of Fly Ash in Highway Construction" (*19*), to promote the use of fly ash in various applicable types of highway construction processes. This project offered technical assistance and financial incentives to states willing to construct and evaluate pilot demonstration projects. As part of the technical assistance, an informative booklet, *Fly Ash Facts for Highway Engineers*, was prepared and given distribution (*20*). To date, approximately 20 projects have been constructed.

In response to Congressional requirements and incentives (*21–23*) and an Environmental Protection Agency Guideline (*24*), discriminatory clauses against the use of fly ash in portland cement concrete (PCC) have been removed. All states now allow the use of fly ash in PCC on federal-aid projects. Instructions to effect implementation of Section 117(f) of the Surface Transportation and Relocation Act of 1987 (*23*), which provides for increase in the federal-aid matching ratio for highway projects using significant amounts of fly ash or bottom ash, are given in FHWA Notice N 5080.109 (*25*). Also, guidelines and recommendations for the use of fly ash and bottom ash in bases and embankments are given in FHWA Technical Advisory 5080.9, *Use of Coal Ash in Embankments and Bases* (*26*).

In 1982, FHWA's Eastern Direct Federal Division administered a $19 million road building project for the Federal Aviation Administration and involved a 6.0-km extension of the Dulles Access Highway from its terminus at Route 123 to its intersection with I-66. Special features of the project included the use of 37,000 m^2 of 15-cm lime-fly ash base and the use of fly ash–modified concrete for the substructure of the eastbound bridge of Old Chain Bridge and Route 123. Details of the project are given in the literature (*27*).

From those examples it is apparent that FHWA's involvement in fly ash use has been continuous and comprehensive, encompassing research, implementation, demonstration, and significant construction projects. This interest will continue, especially with the recent groundswell of concern for increased use of by-products and recovered materials.

MUNICIPAL/DOMESTIC WASTES

Incinerator Residue

Several studies were performed and demonstration projects built to evaluate the technical merits of using incinerator residue as a total or partial aggregate replacement in paving mixtures. (ASTM Committee E-38 defines incinerator residue as all of the solid material collected after an incineration process is completed, comprising ash, metal, glass, ceramics, and unburned organic substances. Residue is the solid material remaining after burning.) Additionally, a process was developed for fusing incinerator residue to produce a high quality aggregate material (*28,29*). Material produced by using this process performed well in a bituminous surface course installation in Harrisburg, Penn. (*30*).

A comprehensive effort addressing the potential for using incinerator residue in various highway applications was completed in December 1976 (*31,32*). In this study a nationwide survey of incinerator locations and types was made, samples of residues were collected and were characterized physically and chemically, bituminous mixture designs were developed for base and surface course application, and field test installations were made. Those installations were experimental wearing surfaces composed of a 50-50 blend of residue and natural aggregate. The installations were placed in Philadelphia, Penn.; Delaware County, Penn.; and Harrisburg, Penn. (Table 5). The first two installations performed satisfactorily during the monitoring period (1 year), and the Harrisburg installation suffered considerable stripping of asphalt from the residue. None of the test installations was subjected to heavy traffic. Evaluation of those demonstration test results, along with literature and test evaluations of other possible applications, including portland cement mixes, lime- and cement-stabilized incinerator residue for base course applications, controlled fill, and subgrade use, resulted in the following recommendations:

1. Incinerator residue compositions can be mixed, placed, and compacted by using conventional bituminous construction apparatus and procedures.
2. Residues should be well burned out (less than 10 percent loss on ignition).
3. Bituminous paving mixtures for base course applications composed of approximately 50 percent natural aggregate and 2 percent lime hold the most promise for residue use.
4. Incinerator residue can be used in lime- or cement-stabilized base course mixtures.
5. The use of incinerator residue in portland cement mixtures is not recommended (excessive volume changes result from the reaction of aluminum to produce hydrogen).

Several installations using incinerator residue as an aggregate were made (Table 6) before, and subsequent to, this study. Details of those installations are given in the literature (*33–38*). Figure 4 presents the paving operation at the Washington, D.C., site.

Sewage Sludge

Sewage sludge, after some form of primary treatment including digestion, consists of a low solids content dispersion of variable viscosity, depending on the moisture content. It is generally dark brown or black in color, and, although it may contain up to 10 weight percent of twigs, cigarette butts, and rubber, it frequently has the appearance of a fairly homogeneous suspension. Sewage sludge generally has a solids content between 5 and 10 percent by weight, although some lagooned sludges may have over 40 percent solids. Table 7 presents data obtained from lagooned sewage sludge from southwest Philadelphia lagoons. This material was of interest

TABLE 6 INCINERATOR RESIDUE TEST INSTALLATIONS

Project	Date	Residue Percent	Asphalt Cement Percent	Lime Percent	Length Meters	Thickness Centimeters	Performance
Houston, TX	1974	100	9.0	2.0	61	15 base	excellent
Phila., PA	1975	50	7.4	2.5	30	3.8 surface	acceptable
Delaware Co., PA	1975	50	7.0	2.5	18	3.8 surface	acceptable
Harrisburg, PA	1975	50	7.0	2.5	73	3.8 surface	poor
Harrisburg, PA fused residue	1976	100	6.7	0.0	55	3.8 surface	excellent
Washington,D.C.	1977	70	9.0	2.0	122	11.4 base	good
Lynn, MA	1979	50	6.5	2.0	approx. 1610	3.8 binder and surface	excellent

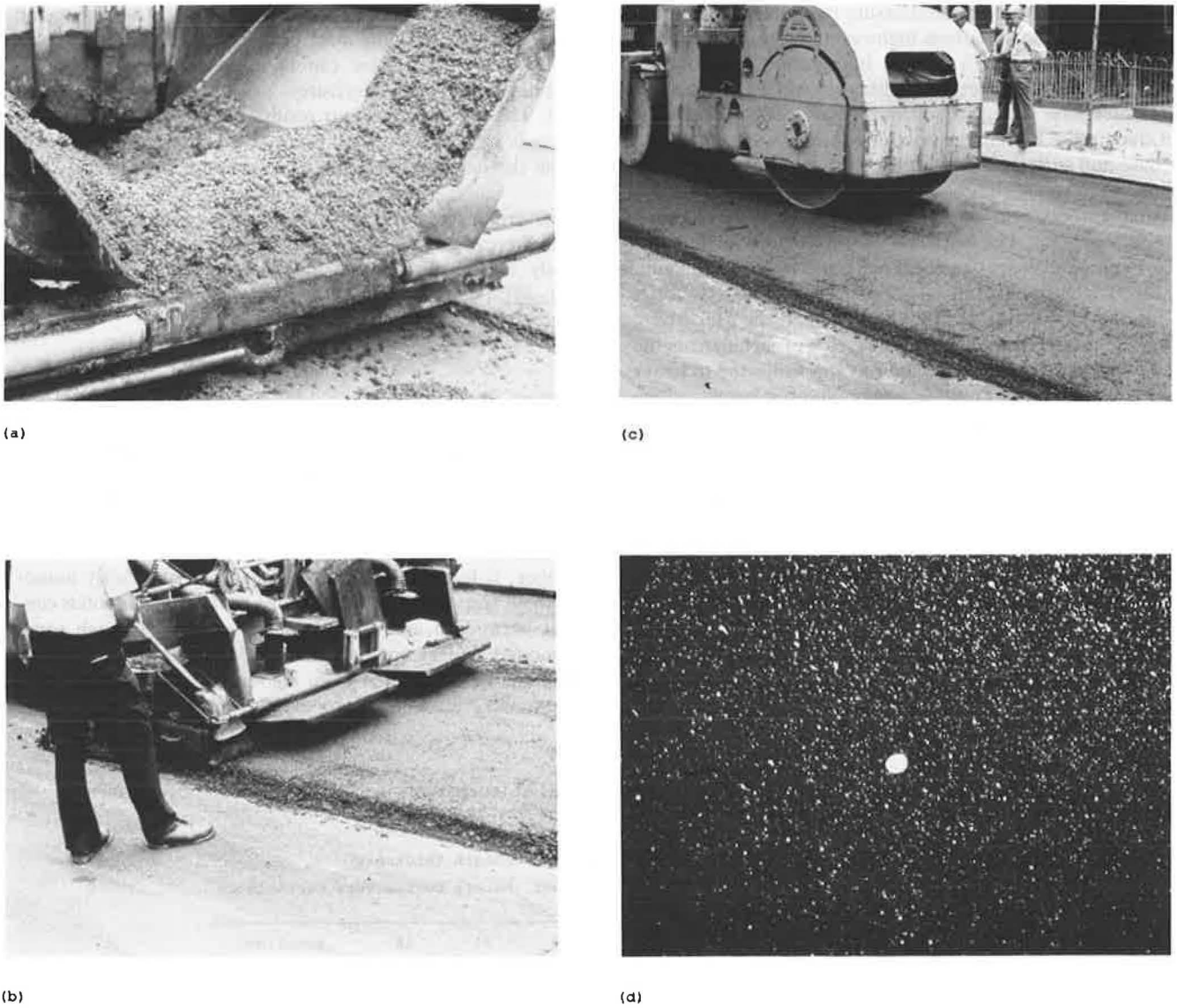


FIGURE 4 Paving with municipal incinerator residue, Washington, D.C. (a) Paver. (b) Placement. (c) Compaction. (d) Finished base (close up).

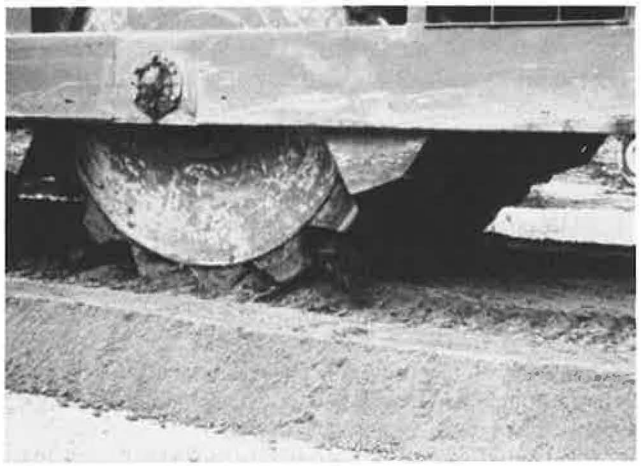
TABLE 7 TYPICAL ANALYSIS OF SEWAGE SLUDGE FROM PHILADELPHIA LAGOONS

Solids, percent		23.45
Ash, percent		13.58
Volatile solid, percent		41.61
Heat of Combustion, cal/gm		1995
Oil and Grease, g/kg		55.38
Zn, ppm	Zn^{2+}	2637
Cu, ppm	Cu^{2+}	809
Cr, ppm	Cr(VI)	1458
Pb, ppm	Pb^{2+}	1713
Cd, ppm	Cd^{2+}	22
Hg, ppm	Hg^{2+}	196

because a proposed roadway was to be built across the lagoon and it was theorized that the sewage sludge might have some use as a highway construction material. Laboratory tests incorporating digested sewage sludge in lime-fly ash sulfate mixtures were performed first by I.U. Conversion Systems, Inc. (*39*) of Plymouth Meeting, Penn., and later by the FHWA. Compositions were developed that had strengths adequate for embankment construction, low permeabilities, and, after suitable curing periods, acceptable leaching characteristics.

To explore the possibility of using digested sewage sludge in road embankment construction, I.U. Conversion Systems, Inc., constructed a demonstration embankment at Bridgeport, Penn. (Figure 5) that was composed of a mixture of sewage sludge, fly ash, soil, lime, and waste sulfate. The embankment was approximately 45 m long by 2.4 m wide by 0.9 m high. The embankment was placed in five lifts, each

(a)



(b)

FIGURE 5 Test embankment construction, using sewage sludge. (a) Compaction. (b) Compaction (close up).

lift separately compacted. Cores were taken from the embankment after 90 days of curing for unconfined compressive strength, wet-dry stability, and freeze-thaw durability tests. Additional cores were taken and tested for leaching characteristics. Results of those tests showed the material to have acceptable properties with the exception of freeze-thaw resistance.

Additional detailed laboratory experiments on lime-fly ash-soil-sulfate-sewage sludge mixtures were performed by the Gillette Research Institute (*40*) and tests substantiated and amplified the information just summarized. The following conclusions were drawn:

1. Generally speaking, small but significant amounts of digested sewage sludge (e.g., 10 percent by dry weight of the mix) incorporated in lime-fly ash (or soil)-sulfate formulations and properly cured will result in products with strengths suitable for embankment construction.
2. The embankment material produced has acceptable permeability and leaching characteristics.
3. Freeze-thaw resistance and wet-dry stability of the embankment material are marginal, and, therefore, embankments constructed by using the material should be capped with approximately 1 m of soil.
4. The possible large-scale utilization of digested sewage sludge in embankments construction should be based on tests performed by using materials indigenous to the embankment test site.

Scrap Rubber

The FHWA has had an interest in the reuse of waste rubber for a number of years. Initially, assessments suggested that the small amounts, remote locations, and excessive collecting and processing costs would preclude any possible benefits that could be accrued in using waste rubber. Therefore, in the early and middle 1970s, research and demonstration studies were limited to HP&R efforts. Most of those studies were performed by the Arizona Department of Transportation and were given impetus by the pioneering work of C. H. McDonald (*41*).

In the late 1970s a demonstration project, "Discarded Tires in Highway Construction" (*42*), was initiated. By 1980, several test sections using asphalt-rubber had been constructed and included projects in which asphalt-rubber was used in chip seals, interlayers, and bridge deck sealing. Discarded tires were also evaluated for use in embankments and it was concluded in 1981 that asphalt-rubber membranes offer viable alternatives to conventional materials for rehabilitation of some asphaltic concrete pavements and that, in many cases, asphalt-rubber chip seals or interlayers can be advantageously used to ameliorate fatigue-type cracking in bituminous pavements (*43*).

A recent critical evaluation of asphalt-rubber systems was performed under a national pooled fund study (*44*). Over 200 experimental rubber-modified pavements were evaluated relative to their performance compared with control sections. The following pavement applications were evaluated:

1. Asphalt-rubber seal coats,
2. Asphalt-rubber interlayers,
3. Rubber-filled asphalt concrete,
4. Asphalt-rubber friction course,
5. Asphalt-rubber concrete, and
6. Rubber-filled friction course.

Those systems are outlined in Figure 6.

The results of the study are summarized graphically in Figure 7 (*45*). In the first two applications the experimental sections performed the same or worse in approximately 80 percent of the sections. In the third application, the experimental sections performed the same or better in approximately 95 percent of the sections. Too few sections were evaluated to permit definite conclusions in the remaining applications.

In summary, no conclusive evidence exists that asphalt-rubber systems are generally superior to conventional asphalt cement materials. It is important to note that the study was conducted on a nationwide basis. The generally favorable performance of rubber-asphalt systems in tests in Arizona is in contrast to the pooled-fund study results, suggesting that

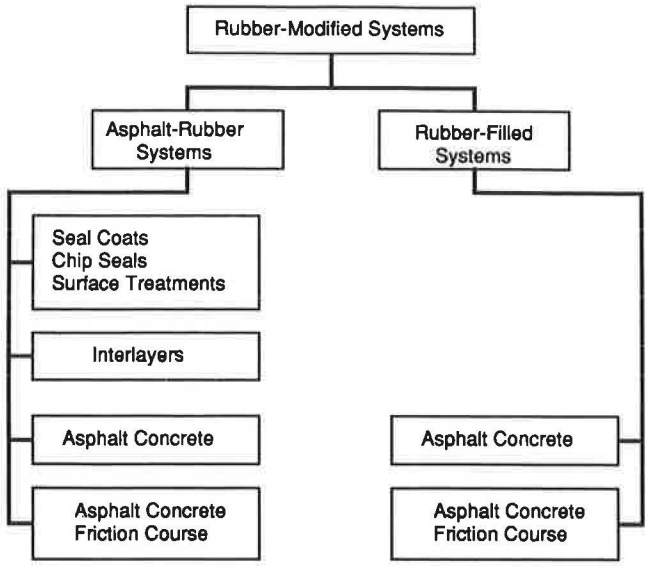


FIGURE 6 Classification of rubber-modified asphalt paving materials.

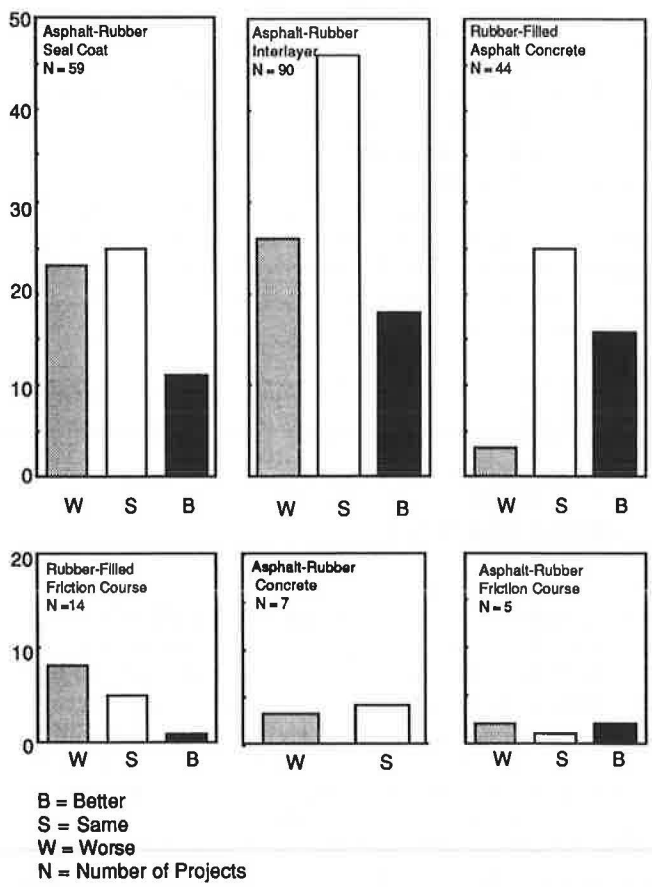


FIGURE 7 Project performance by application, in the national-pooled fund study on rubber-modified asphalt pavement tests.

climatic conditions may be of considerable importance in asphalt-rubber system performance.

MINING WASTES—COAL MINE REFUSE

Valley Forge Laboratories conducted a study, "Availability of Mining Wastes and Their Potential for Use as Highway Material" (*46–48*), to develop methods for using coal mine refuse in highway base course construction. A contract was executed to determine the potential for combining fly ash with coal refuse to form a base course material for highway construction. A survey was performed of existing information regarding the engineering properties and field testing of fly ash and coal mine refuse. Also, a nationwide survey was made to establish regions or areas of optimum use potential where the combination of economically available wastes and fly ash indicates attractive potential use of those waste materials in lieu of natural aggregates (*49*). Finally, an extensive laboratory testing program was established to study the physical and engineering properties of mixtures of coal mine refuse (CMR) and fly ash from 10 optimum use areas and a comparison of serviceability index and physical damage parameters based on the VESYS Predictive Design Procedure between crushed stone and CMR-fly ash compositions.

The major findings of the study were as follows (*50*):

1. CMR and fly ashes had physical, chemical, and engineering properties generally similar to those reported in the literature.
2. Several unstabilized CMR-fly ash compositions possessed good strengths but were not durable.
3. CMR-fly ash blends were successfully stabilized with each of the four stabilizing agents tested (portland cement, lime, asphalt cement, and emulsified asphalt).
4. Portland cement- and lime-stabilized CMR-fly ash base courses yielded thinner surface and base course layers than did crushed stone for the same loading, temperature, and subgrade conditions when evaluated by using the VESYS Predictive Design Procedure.
5. The predicted performance levels (serviceability index and physical damage parameters) of those thinner pavement layers are equal to and typically more favorable than those for crushed stone.
6. Unstabilized CMR-fly ash compositions appear to be unsuitable for highway base course application based on the results from the VESYS Predictive Design Procedure.

CONCLUDING REMARKS

The research and development efforts described in this paper were undertaken during the 1970s and early 1980s. During this period, even though there was beginning to be an increased awareness and concern regarding environmental problems, as evidenced by various pieces of legislation addressing resource recovery and hazardous materials, air and water pollution, etc., the thrust of FHWA's efforts was on the possible technical problems associated with use of wastes and by-products. Because much of the regulating legislation was in an embryonic stage in terms of implementation, the FHWA was able to develop design procedures and demonstrate the technical

viability and potential of many industrial/domestic/municipal/mining by-products without suffering unbearable regulation and delays. This is not to say that environmental impacts were not considered, just that in many cases they were not of primary concern. Thus, FHWA's efforts were not subjected to the severe scrutiny and constraints imposed by regulatory groups, environmental advocacy groups, and the general public, that are given by-product utilization today (Chesner, Warren G., *Work Plan for the Demonstration of the Utilization of Waste-to-Energy Combustion Residues as a Substitute Aggregate in Bituminous Paving Applications*, unpublished data).

Regardless of severe constraints exercised today with regard to the reuse of wastes and by-products, FHWA's past and present efforts in this area should provide valuable guidance to those wishing to ameliorate the waste problem by increased recycling (reuse). It is recognized that recycling is only part of the picture and that waste reduction at the source, incineration, and, last, limited landfilling will need to be carefully and fully integrated to prevent the world from being inundated in waste.

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