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16. Abstract

A total of thirty nine case histories from sixteen states in the U.S., Canada and England on the use of recycled materials in highway embankments since 1965 have been documented. Recycled materials have been successfully used in highway embankments. Fly ash (Type A), tire chips and wood chips are the three most frequently used recycled materials in highway embankments. In the 1970's and 1980's fly ash was popular, but in the last five years tire chips have become more popular in embankment construction. Compared to fly ash, both tire chips and wood chips can be used as lightweight fill.

Information on the availability of recycled materials such as tire chips, coal ash and gypsum in the State of Texas has been summarized. Large quantities of recycled materials in Texas are available for use in embankments. Limited laboratory tests were performed on random samples of selected recycled materials with and without mixing with Texas clayey soils. Using the EPA and TNRCC leaching tests, leachability of contaminants from the recycled materials were evaluated. The recycled materials that were tested can be characterized as Class 3 waste, which is non-hazardous and non-toxic. The behavior of mixtures of recycled materials was also studied. Based on this study it is concluded that recycled materials can be used in highway earth embankments, but field verification is recommended before large-scale use commences. A specification for using recycled materials in highway embankments was developed and is included.

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RECYCLED MATERIALS IN EMBANKMENTS, EXCEPT GLASS

Project No. 01351

Final Report

Texas State Department of Highways and Public Transportation

by

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Report No. CIGMAT/UH 96-1

January 1996

ENGINEERING DISCLAIMER

PREFACE

This research project was undertaken with the primary objective of developing a specification for the use of recycled materials (except glass) in highway embankments. This was accomplished by first conducting a literature review on the use of recycled materials in earth embankments and documenting the available recycled materials in Texas. A significant effort was made to document case histories on the use of recycled materials in earth embankments. Based on the case studies and available materials in Texas, potential recycled materials for use in Texas were selected for further evaluation. Limited laboratory tests were performed to verify the engineering and leaching properties of the selected recycled materials. The behavior of the recycled materials with simulated Texas soils (20% clay) was also evaluated. Based on this information, a specification for the use of recycled materials in earth embankments was developed.

This report was prepared to summarize the information collected during the study. A total of 39 case histories from 16 states in the U.S., Canada and England on the use of recycled materials in highway embankments since 1965 have been documented. Physical and mechanical properties of several recycled materials have been documented. Information on the availability of recycled materials, such as tire chips and coal ash, in the State of Texas has been summarized.

Recycled materials have been successfully used in highway embankments. Fly ash (Type A), tire chips and wood chips are the three most frequently used recycled materials in highway embankments. Coal mine wastes have also been used. In the 1970's and 1980's fly ash (Type A) was popular, but in the last five years tire chips have become more popular in embankment construction. Compared to fly ash, both tire chips and wood chips can be used as lightweight fill.

In Texas, more than 65 million tires are present in landfills, and about 18 million tires are disposed each year, of which 7 million are effectively recycled. There are twenty-two TNRCC approved tire processing plants in Texas. Of the 6.5 million tons of fly ash produced in Texas annually (total of 17 locations), only 1.6 million tons is recycled. Of the 4 million tons of bottom ash and 3 million tons of flue gas desulfurization (FGD) material produced in Texas, only a small amount is utilized. Also, 3.6 million tons of construction debris are produced each year, with a very small quantity being utilized. Hence, large quantities of recycled materials in Texas are available for use in embankments.

Limited laboratory tests were employed to characterize the performance of recycled materials with and without Texas clayey soils. Leaching of metals and organic compounds from the recycled materials are not well documented. Using the EPA and TNRCC leaching tests, leaching was evaluated for recycled materials available in Texas. Mixing recycled materials such as fly ash and tire chip have not been studied. Hence, limited tests on combined recycled materials were performed.

ABSTRACT

A total of thirty nine case histories from sixteen states in the U.S., Canada and England on the use of recycled materials in highway embankments since 1965 have been documented. Physical and mechanical properties of several recycled materials have been investigated and reported. Recycled materials have been successfully used in highway embankments. Fly ash (Type A), tire chips and wood chips are the three most frequently used recycled materials in highway embankments. Coal mine wastes have also been used. In the 1970's and 1980's fly ash was popular, but in the last five years tire chips have become more popular in embankment construction. Compared to fly ash, both tire chips and wood chips can be used as lightweight fill.

Information on the availability of recycled materials such as tire chips, coal ash and gypsum in the State of Texas have been summarized. In Texas, more than 65 million tires are present in landfills, and about 18 million tires are disposed each year, of which 7 million are effectively recycled. There are twenty-two TNRCC-approved tire processing plants in Texas. Of the 6.5 million tons of fly ash produced in Texas annually (total of 17 locations), only 1.6 million tons is recycled. Of the 4 million tons of bottom ash and 3 million tons of flue gas desulfurization (FGD) material produced in Texas, only a small amount is utilized. Also, there are 3.6 million tons of construction debris produced each year, with a very small quantity being utilized. Hence, large quantities of recycled materials in Texas are available for use in embankments.

Limited laboratory tests were performed on random samples of selected recycled materials with and without combination with Texas clayey soils. Using the EPA and TNRCC leaching tests, leachability of contaminants from the recycled materials was evaluated. The recycled materials that were tested can be characterized as Class 3 waste, which is non-hazardous and non-toxic. The behavior of mixtures of recycled materials was also studied. Based on this study, it is concluded that recycled materials can be used in highway earth embankments, but field verification is recommended before large-scale use commences. A specification for using recycled materials in highway embankments was developed and is included.

SUMMARY

The disposal of solid waste has become a major problem over the past few years in the United States. Millions of tons of non-hazardous solid waste materials are produced each year, and Texas is one of the largest producers. Recycling and usage of these waste materials for various applications, especially in highway construction, is on the increase around the nation. Proper usage of these recycled materials may lead not only to considerable cost savings but also to the solution of environmental problems. Because highways require large volumes of construction materials, highway agencies have become frequent participants in efforts to recycle and reuse waste materials.

The use of recycled materials in embankments in Texas will become popular only if there is better understanding of the material behavior, its durability and chemical stability under various loading and environmental conditions. Also, the availability of the material in large volumes at a very reasonable cost will determine the success of recycled material applications in earth embankments.

In this study, a total of thirty nine case histories from the U.S., Canada and England on the use of recycled materials in highway embankments since 1965 have been documented. Physical and mechanical properties of several recycled materials described in the literature have been summarized in this report. Recycled materials have been successfully used in highway embankments. Fly ash (Type A), tire chips and wood chips are the three most frequently used recycled materials in highway embankments. Coal mine wastes have also been used. In the 1970's and 1980's fly ash was popular, but in the last five years tire chips have become more popular in embankment construction. Compared to fly ash, both tire chips and wood chips can be used as lightweight fill.

Information on the availability of recycled materials such as tire chips, coal ash and gypsum in the State of Texas has been summarized. In Texas, more than 65 million tires are present in landfills and about 18 million tires are disposed each year, of which 7 million are effectively recycled. There are twenty-two TNRCC-approved tire processing plants in Texas. Of the 6.5 million tons of fly ash produced in Texas annually (total of 17 locations), only 1.6 million tons is recycled. Of the 4 million tons of bottom ash and 3 million tons of flue gas desulfurization (FGD) material produced in Texas, only a small amount is utilized. There are also 3.6 million tons of construction debris produced each

year, with a very small quantity being utilized. Hence, large quantities of recycled materials in Texas are available for use in embankments.

A laboratory study was performed on fly ash, bottom ash, scrubber base (equal mix of FGD and fly ash), tire chips and fluorogypsum available in Texas. Limited laboratory tests were performed on random samples of the selected recycled materials with and without combining them with Texas clayey soils. Using the EPA and TNRCC leaching tests, leachability of contaminants from the recycled materials was evaluated. The recycled materials that were tested can be characterized as Class 3 waste, which is non-hazardous and non-toxic. Also, the behavior of mixtures of recycled materials was studied. It is concluded that recycled materials can be used in highway earth embankments, but field verification is recommended before large-scale use is initiated. A specification for using recycled materials in highway embankments was developed which is presented in this report.

IMPLEMENTATION STATEMENT

The results of this study show that the recycled materials can be used in highway earth embankments. Large volumes of recycled materials are available in Texas, and these materials can be used in embankments. The specification developed in this study will be useful in planning for the field verification studies.

The following factors should be noted in the implementation of the specification and in developing future field verification studies. (1) Long-term behavior of embankments with recycled materials and Texas soils in various embankment configurations must be understood. (2) Long-term risk to the environment from utilizing recycled materials in this application needs to be evaluated. (3) Quality of recycled materials changes from batch to batch must be developed, and a quality control plan must be devised. (4) This specification does not address safety problems or environmental concerns, if any, in handling the recycled materials; hence, appropriate safety and health practices must be established. (5) Separate specification for each type of recycled material must be developed.

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CHAPTER ONE. INTRODUCTION

The disposal of solid waste has become a major problem over the past few years in the United States. Millions of tons of non-hazardous solid waste materials are produced each year, and Texas is one of the largest producers. Recycling and usage of these waste materials for various applications, especially in highway construction, is increasing around the nation. Proper usage of these recycled materials may lead not only to considerable savings but also to the solution of environmental problems. Because highways require large volumes of construction materials, highway agencies have become frequent participants in efforts to recycle and reuse waste materials.

The use of recycled materials in embankments in Texas will become popular only if there is better understanding of the material behavior, its durability and chemical stability under various loading and environmental conditions. The availability of the material in large volumes at very reasonable costs will determine the success of any given recycled material application.

In this study, an extensive literature review on the use of recycled materials in constructing embankments was completed. Availability of recycled materials and their location and volume in Texas has been documented. Areas needing additional research/information to develop specifications have also been identified.

OBJECTIVES

The objectives of the research were:

(1) To conduct an extensive literature review on potential application of recycled materials in embankments for roadway construction. Develop a summary report to include such information as (a) most feasible and promising recycling materials for embankment applications, (b) typical properties of the recycled materials, and (c) availability of each of these materials on a statewide basis.

(2) To conduct laboratory tests to fill in missing information.

(3) To develop performance-based specifications for embankments with recycled materials.

The objectives as stated above were achieved in three phases. In PHASE I a literature review was undertaken to indicate the potential for recycled materials in highway embankment construction. Available recycled materials in Texas were also identified and quantified. In PHASE II additional laboratory tests were performed for waste materials available in Texas. In PHASE III a specification was developed for the use of recycled materials in earth embankments.

ORGANIZATION

A summary of the literature review on the use of recycled materials in earth embankments is presented in Chapter 2; emphasis is placed on the type of recycled material, configuration for embankments, construction methods adopted, cost of construction and materials, specifications on recycled materials and quality control. The physical and chemical properties of various recycled materials used in embankment construction are summarized, and recycled materials available in Texas and their current applications are also summarized. In Chapter 3, laboratory test results on the engineering properties and leachability of recycled materials available in Texas are presented. A specification for the use of recycled materials in earth embankments is presented in Chapter 4. Chapter 5 summarizes the conclusions of the investigation.

CHAPTER TWO. LITERATURE REVIEW

A total of 39 case histories from 16 states in the U.S., Canada and U.K., on the use of recycled materials in the highway embankments have been documented. Information collected on embankments constructed since 1965 are summarized in Table 2.1 and further details on each embankment are provided in Appendix A1. The literature review focused on the following:

• Potential waste materials: Information on the potential waste materials in highway embankment construction and their relative advantages and disadvantages.

• Popular configuration for embankments: Major categories are summarized graphically in Fig. 2.1, with different waste materials, dimensions and necessary soil cover.

• Construction methods adopted by other state DOTs: The construction methods which are already in use in various state DOTs and their relative merits.

• Properties and testing methods: Engineering and environmental properties of various waste materials.

• Availability and relative cost in Texas: An inventory showing the availability of various waste materials in Texas, and their relative cost.

• Specifications developed by the other state DOTs: A summary of the specifications developed by the other state DOTs for using waste materials in embankment construction.

Each case study is documented in the Appendix A1 and documented as follows: "Case study [A].B/C" where A is the reference number as documented by the UH researchers; C is the year of construction and B is the serial number for the embankment constructed in year C. Fly ash (Type A or Class-F), tire chips and wood chips are the three most frequently used recycled materials in highway embankments. Coal mine wastes have also been used. In Table 2.1 information on the type of highway, quantity of waste materials used, and cost of materials and project costs are summarized. Fly ash

Type A and Type B as specified by TxDOT material specifications: D-9-8900 closely represents fly ash Class-F and Class-C (ASTM C 618) respectively. Figure 2.2 shows the distribution of projects over the years with the type of recycled materials used. Clearly in the 1970's and 1980's fly ash (Type A or Class-F) was popular, but in the last five years tire chips have become very popular in embankment construction. Tire chips also have an added advantage over fly ash because they are lightweight and have been used in cases where the foundation soils are very soft and weak. It should be noted that large deflections in the embankments have been reported with tire chips and wood chips during the initial few months of operation.

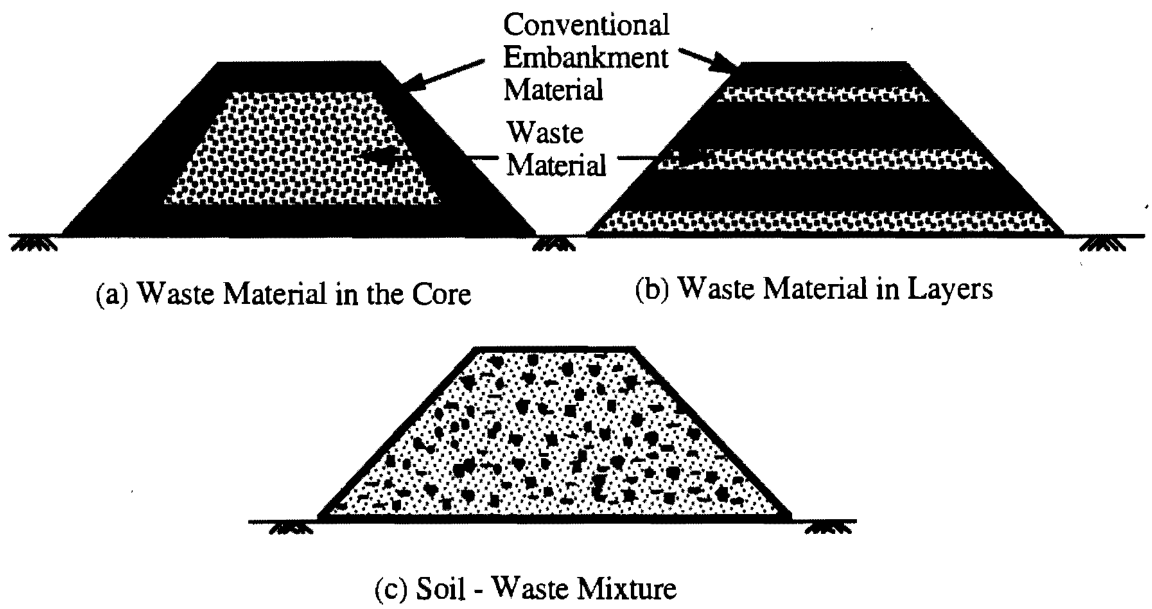


Figure 2.1 Typical Embankment Cross Sections

Figure 2.3 shows the frequency of use of the three types of embankment configurations. Type A has been the most frequently used because the waste material is placed in the core with the help of geotextiles. The top soil cover helps to distribute the loads, and the side slope soil cover helps reduce water infiltration into the embankment core and helps in stabilizing the slope with vegetation. However, Edil et al. (1994) studied the performance of Type A and C configurations with tire chips and concluded that the Type C configuration performed better than the Type A configuration. For Type C, the researchers used a 50/50 sand-tire chip mixture.

Table 2.1. Recycled Materials in Embankments: Summary of Case Studies

No /Year	County or City	State or Country	Highway	Recycled Materials				Quantity Cu.Yards (Size)	Cost $/Cu.Yard	Remarks	Case No.
				Tire	Fly Ash	Wood	Others				
1/65	Waukegan	Illinois	Local		X Class-F			5500	not available	Type A. Experimental project. Embankment 200 ft long, 6 ft high. Internal friction angle 25^{o}. Pneumatic rollers were used.	[13]
1/67	South Heights	Pennsylvania	Local		X Class-F			190,000	not available	Type A. Embankment was 800 ft long and 75 ft high. Fly ash was placed in 12-in. lifts and compacted with 6.5-ton compactor. Side slope was 3H:1V. Unit weight of fill, 67-71 pcf. Fly ash had no cohesion (c=0) and the internal friction angle was 30^{o}.	[17]
1/71	Waukegan	Illinois	Expressway		X Class-F			246,000	not available	Type A. 10-ton vibratory drum roller. Compacted in 6 in. lifts. Unit weight 85-92 pcf with optimum moisture content 20-26%.	[14]
1/74	Luzerne Co.; Wilkes-Barre	Pennsylvania	Expressway				X Coal mine refuse	1,500,000	not available	Type A. 2,344 ft long with maximum width and height of 472 ft and 57 ft respectively. Needed a lightweight fill. Lift thickness was less than 8 in. Uniform grain size. Specific gravity was 2.15. Friction angle from CU tests varied from $25\text{-}33^{o}$, and the cohesion was 1-10 psi. D-8 and D-9 bull dozers were used to spread the materials. Compacted with steel drum vibratory compactor and steel drum roller. Compacted densities varied from 102-118 pcf with moisture content of 10-15%. Sulfate and pH were monitored.	[20]

2/74	Cambria Co.	Pennsylvania	US 219				X Coal mine refuse	200,000	$1.25	Type A. 1000 ft. long with a height of 18 ft. Well-graded material with specific gravity 1.61-1.84. Unit weights varied from 84 to 95 pcf. Angle of internal friction varied from 33 to 42^{o}, and cohesion varied from 0-14 psi. Extraction study (BS 1377 test method) showed 0.02% sulfate.	[21]
3/74	Durham Co.	England	Local				X Unbur-ned colliery shale		not available	Type A. 1150 ft in length and 14 ft high. Compacted in 15 in. lifts using Bomag 7.8 Mg double vibrating roller. 6 passes gave an average dry unit weight of 115 pcf.	[23]
1/76	Milwaukee	Wisconsin	Local		X Class-F			100,000	not available	Type A. Embankment was 900 ft long and 25 ft high. Envelope of cohesive material and pavement drainage system were provided to prevent infiltration of moisture and leaching of fly ash. Fly ash was compacted in 6-in. lifts with a rubber tired roller. SPT tests show blow counts from 60 to 150 blows/ft.	[18]
2/76	Raymond	Washington	SH 101			X Saw--dust		100,000	(Savings of $250,000)	Type A. 600 ft long. Triaxial and direct shear tests indicate an angle of internal friction of 31-50^{o}, and 35^{o} was used for design. In place density was 60 pcf. Water draining from the fill was normal after 1 year. Average life of 15 years.	[22]
3/76	Bristol and Somerset	England	Motorway 5		X			1,025,000	not avaialable	Maximum height of embankment was 20 ft.	[24]
4/76	Madien	West Virginia	US 60		X Class-F			27,000	not available	no details available	[30]
1/78	Carbo	Virginia	SH 665		X Class-F			300	not available	no details available	[28]
2/78	Norton	Massachusetts	Local		X Class-F			5,000	not available	no details available	[33]
1/79	Eagan	Minnesota	SH 13		X Class-C			350,000	not available	Only 80% of the emankment was fly ash.	[34]

2/79	Windsor	Ontario, Canada	Local		X Class-F			113,000	not available	Embankment was 100% fly ash.	[36]
1/80	Joseph City	Arizona	SH 40		X Class-F			60,600	not available	no details available	[31]
1/81	Avon	Ohio	SH 480		X Class-F			30,000	not available	no details available	[32]
1/82	Sarnia	Ontario, Canada	Highway 402		X Class-F Bottom ash			300,000	not available	Type A. Embankment was 26 ft high with a base layer of bottom ash (3 ft), fly ash core and a bottom ash cap. Maximum dry density, 76 pcf	[19]
1/83	Gallia Co.	Ohio	US 35		X Class-F			27,000	not available	no details available	[29]
1/84	Sarnia	Ontario, Canada	Highway 402		X Class-F			80,000	not available	Embankment was 100% fly ash.	[35]
1/85	Flying V	Wyoming	US 85			X Wood chips		40,000	$3.00	no details available	[25]
1/86	Hoquiam	Washington	SH 109			X Wood chips		Quantity not available. (Wood fibers were 1/2 to 2-in. in length.	(project cost: $972,221. Cost savings of $500,000 with alternative technology).	Type A. Geotextile was used in 6 layers. 13.5 ft high embankment. Lift thickness for the wood fiber was 1 ft. Unit weight was 37 to 39 pcf.	[10]
1/87	Benewah Co.	Idaho	Airport			X Wood chips		Quantity not available (Wood chips were 1 in.)	$3.00	Type A. D7 dozer. Unit weight, 55 pcf. Friction angle was 10^{o} and 30^{o} at 5% and 20% strain respectively. Maximun settlement of 6 in. in 32 months.	[11]
1/90	Ramsay Co./ St. Paul	Minnesota	CR 59	X		X Wood chips & Tire chips		Quantities not available for wood chips 4,725 (tires chips) (3 in.x 3 in.)		Type B. Geotextiles were used to encapsulate fill. Wood chips were placed a foot above water table. Tire chips (3 in. x 3 in.) were placed over the wood chips. Steel wires were embedded in the chips. D8 dozer.	[1]
2/90	Eden Prairie Co./ Minneapolis	Minnesota	Local	X				4,100 (6-8 in. wide and 12-24 in. long)	not available	Type A. Geotextiles were used. Comapcted in 2-3 ft lifts with D8 dozer. Compacted density of 40-45 pcf. Road settled 0.9 in. in one year.	[3]

3/90	Roseburg	Oregon	US 42 (raised 4 ft. and widened to 20 ft.)	X				12,800 (580,000 tires) (80% to be < 8 in. and 50% to be > 4 in. maximum size ws 24 in.)	$15.00 (material) Construction cost: $ 4.17	Type A. Geotextile was used. 2 to 3 ft lift. D8 dozer. Unit weight, 45 pcf. After 3 moths of traffic unit weight 52 pcf. Material transported from 150-250 miles.	[8]
4/90	Dane Co./ Madison	Wisconsin	Local	X			Tire-sand mixture (50/50)	not available	not available	Type A, B & C. Demonstration study. 8 sections, each 20 ft. long and 6 ft. high. Compacted 1 ft-lifts of tire chips and sand. 12 ton sheeps foot roller with vibratory capabilities. Vibration did not improve compaction. Unit weight of tire chips varied between 20-30 pcf. Chip-sand, 75 pcf. Leaching tests were done. Chip-sand mix performed best.	[12]
5/90	Middlesex	Vermont		X				2,738	not available	To flatten slope. Used as side slope fill. Compacted using 5 ton dozer. Specific gravity of chips was 1.2. Field unit weight 47-56 pcf.	[15]
1/91	Benton Co./Rice	Minnesota	CR 21	X				52,000 tires (Allowable cip size was 8 sq.in. Longest length 12 in.	not available	Required lightweight embankment. Geotextiles used to confine the tire chips. 3.5 ft of granular soil was used to cap the fill.	[2]
2/91	Orange Co.	North Carolina	SH 54	X				1,250	$20.00 (including transport and placement)	Type A & C. Average of 25% tire chips with a maximum of 40%. Chip size 1 to 3 in.	[7]
1/92	Prior Lake	Minnesota	Local	X				9,600 (4 in.)	not available	Type A. Geotextiles used. Tire chips were placed over a foot of wood fiber fill. D8 dozer.	[4]
2/92	Lake Co./ Finland	Minnesota	SH 7	X				3,900 (4 x 12 in to 1/4 tire)	not available	Type A. Geotextiles used. After 2 years no noticeable setttlement.	[5]

3/92	Milka Co.	Minnesota	Local	X				3,000	not available	Type A. Geotextiles used. Excessive settlement was reduced by 40-50%.	[6]
4/92	Adam Co.	Colorado	US 76 (200 ft.) (Light-weight fill was required)	X				10,000 (500,000 tires) (4 in chips)	Free material. Transporta-tion cost = $60,000 for project	Type A. Geotextiles used. 5 ft high and 300 ft wide. D8 dozer. Tire chips were compacted in 2-ft layers. To speed up settlement additional soil was added on top and later removed.	[9]
1/93	York Co./ Williamsburg	Virginia	CR 199	X			Tire-Soil Mixture (50/50)	56,000 (1.7 million tires) (Chips were 40 sq. in. and maximum length was 10 inches.)	Total cost $1,129,688 Cost overrun was $425,509	Type C. Experimental project. Chips were mixed with soil (50/50) with a D8 dozer. Also sheeps foot rollers were used. 2 ft layers were compacted. Soil was silty sand. Tire-soil unit weight was 70 pcf. Embankment instrumented with earth pressure cells and settlement sensors. Settlement at the end of construction was 132 mm. Monitoring wells were used to evaluate water quality.	[16]
2/93	Pine City	Minnesota	US 35	X				18,200 (1,000,000 tires)	not available	No details available	[37]
3/93	E. Foston City	Minnesota	Local	X				1,500 (80,000 tires)	not available	No details available	[38]
1/94	Sheridan-Beckton	Wyoming	SH 331			X Wood chips		6,300	$6.19	No details available	[26]
2/94	Double Nickle	Wyoming	SH 28	X				13,000	$26.10	No details available	[27]
3/94	Taylor Falls	Minnesota	Local (TH 95)	X				2,000 100,000 tires		No details available	[39]

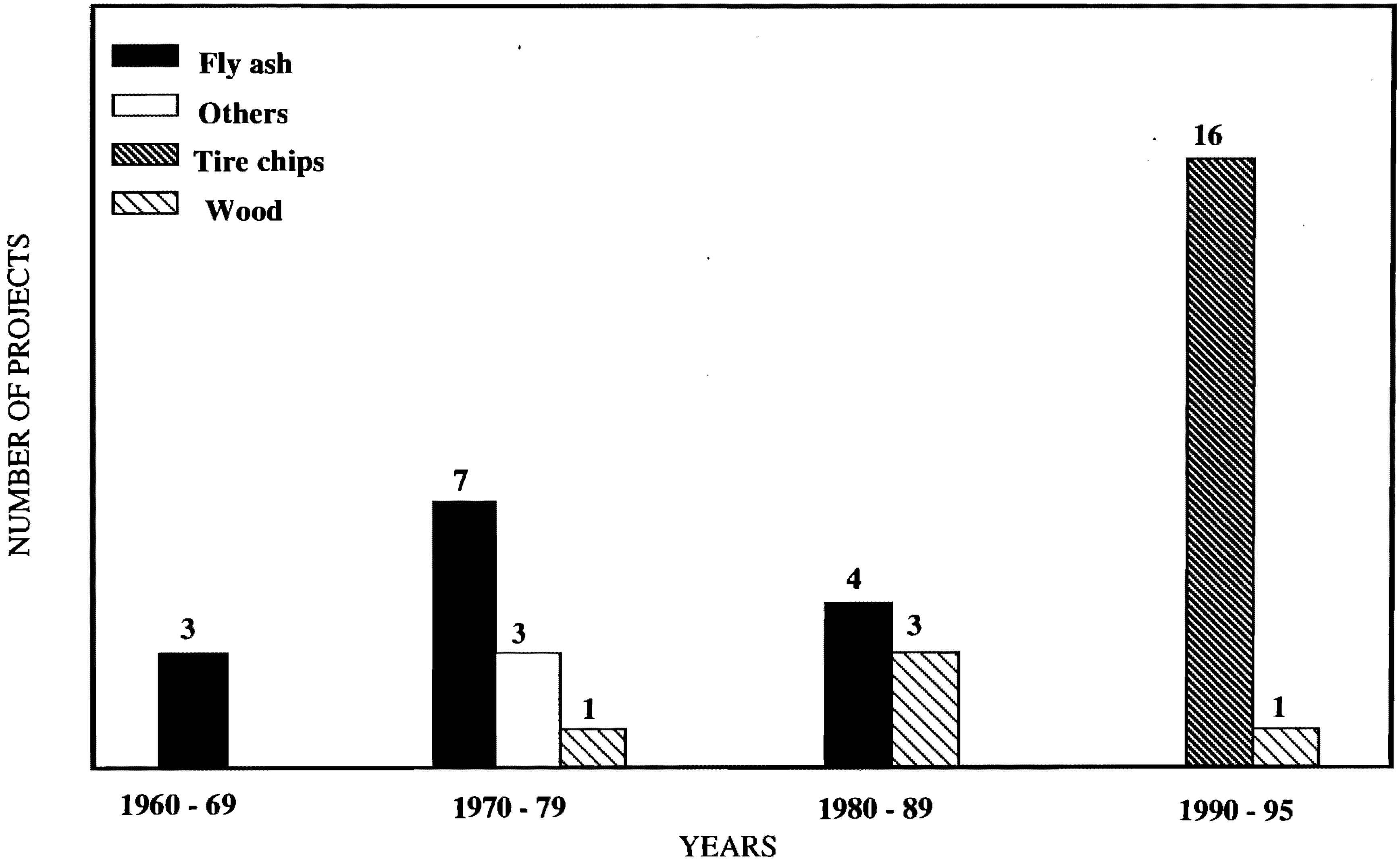


Figure 2.2. Distribution of Embankment Projects Over the Years Based on the Type of Recycled Material

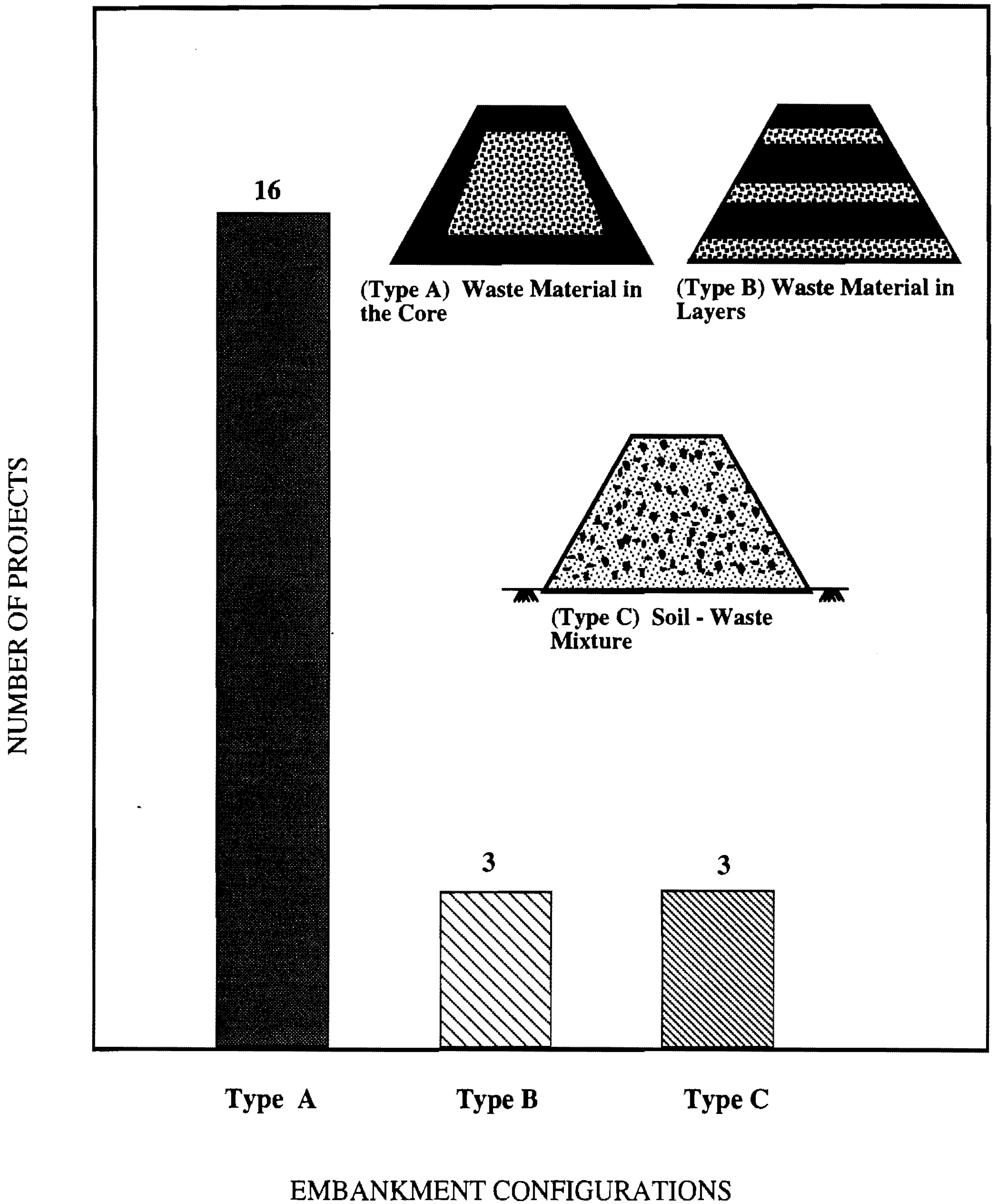


Figure 2.3. Distribution of Embankment Projects Based on Type of Configuration

Table 2.2. Properties of Recycled Materials

Recycled Material	Composition	Soil		Properties						Remarks	References (see Bibliography)
		Yes	No	Size	Specific Gravity	Friction Angle	Cohesion	Max.Dry Density	TCLP*		
Tire chips	Rubber, Sulfur		X	1/2"- 3"	0.88-1.36	19°- 25°	1 - 2 psi	38 - 43 pcf	Organic and metal ion leachates	For embankments, chip sizes larger than 3 in. are needed. According to the TNRCC**, the tire chips cannot be greater than 9 sq. in.	Humphrey (1993); Edil (1994); Ahmed (1991)
Tire chips	Sand / Tire chips	X 40% chips and 60% soil		1/4"- 1"	same as above	36°	6 psi (up to 15 psi confining pressure)	70 pcf	Same as above	This mixture can form a very good drainage layer at the base of the embankment.	Edil (1994); Ahmed (1991)
Tire chips	Borrow / Tire chips (sandy silty clay) (CL-ML)	X (50/50)		1/4" - 1"	same as above	32°	5 - 9 psi (confining pressure 4.5 - 28.8 psi)	75 pcf	Same as above	Ideal for lightweight fill, and settlements are less than for fills of pure tire chips.	Ahmed (1991)
Bottom ash	SiO_2, Al_2O_3, Fe_2O_3 and small quantities of CaO, MgO, K_2O, Na_2O		X	Well graded size distribution ranging from fine gravel to fine sand.	2.0 - 3.4	46° - 50°	1.5 - 3.0 psi	60 - 116 pcf	Ground water monitoring for presence of potential metal ion leachates	Good drainage layer for embankments. It can be used as a soil cap over embankments. It can also be used as an embankment material.	Lovell (1991;) Seals (1972)
Fly ash	SiO_2, Al_2O_3, Fe_2O_3, CaO		X	Particle size lies between silty sand and silty clay	2.3 - 2.6	30°- 42°	10 - 15 psi (confining pressure 10 and 15 psi)	77 - 89 pcf	Same as above	Fly ash has been found to be a very good fill material where fly ash is readily available in large quantity.	DiGioia (1972)

* Toxicity Characteristics Leachate Procedure (EPA)

** Texas Natural Resource Conservation Commission

Waste Material	Composition	Soil		Properties						Remarks	References
		Yes	No	Size	Specific gravity	Friction Angle	Cohesion	Max.Dry Density	TCLP		
Coal Mining Waste	Unburned coal, Pyrites and Mixed with Soil.	X		uni-formly graded Has less than 25% fines	1.61 to 1.84	33° - 42°	0 - 14 psi	84 - 95 pcf	sulfate leachates might be expected due to the reaction of water and pyrites.	Coal mine refuse forms a very good embankment material. It should be placed in such a way that it does not get into contact with ground water. The embankment needs to be encapsulated in a cohesive soil cover.	Pierre and Thompsun (1979)
Fluoro-gypsum	Pure Calcium Sulfate (anhydrite)		X	Similar in gradation to silty fine sand and sandy silt. Has >65% fines	not available	40° (eff-ective)	14 psi (effective)	96 pcf (average)	concerns for sulfate leachates might hinder its use.	Due to hight shear strength and relatively low weight, gypsum(calcium sulfate) forms a very good embankment material. Sulfate leachates can be controlled by encapsulation	D. N. Little (1987)
Wood Waste	Wood Chips, Sawdust.		X	These particles vary from 0.25 to 0.75 in.	1.0 to 1.2	10° - 30°	4 - 8 psi	30 - 39 pcf.	Ground water monitor for potential organic leachates from the wood fiber fill is required.	This material forms a very good lightweight material for embankments. The embankment should be made anaerobic by the provision of cohesive soil cover and geotextiles all around it in order to prevent any decay.	Allen and Kilian (1993)

Properties of Recycled Materials

In Table 2.2, typical properties of recycled materials reported in the literature are summarized. The properties with soil mixtures are also included. The strength parameters (cohesion and friction angle) for the recycled materials are reasonable and in the author's opinion the materials can be used in embankments with and without mixing them with soil. Information on the leachability of wastes such as metals and organics from the recycled materials are very limited. Additional information on the properties of recycled materials are summarized in Appendix A2.

Recycled Materials in Texas

The availability of recycled materials in the State of Texas is summarized in Table 2.3. Tire chips currently produced in Texas are mainly used in boilers for tire-derived-fuel. More than 65 million tires were shredded in Texas over the past two years, with only 15% of those shreds being marketed. Twenty to twenty-five million additional tires remain in landfills. About 18 million tires are disposed of each year in Texas, of which 7 million are effectively recycled. There are twenty-two TNRCC-approved locations that process tires.

Of the 6.5 million tons of fly ash produced in Texas (in 17 locations), only 0.8 million tons is recycled. Of the 3 million tons of bottom ash and FGD produced in Texas, only a small amount is utilized; Also, there are 3.6 million tons of construction debris produced each year, with a very small quantity being utilized; hence, large quantities of recycled materials are available for use in embankments. Additional information on the availability of recycled materials in Texas is summarized in Appendix A3.

Summary and Conclusions

Based on the literature review, the following observations can be advanced.

(1) Recycled materials such as fly ash, tire chips and wood chips have been used with and without mixing with soil in highway embankments. Fly ash (Type A) has been used exclusively. Coal ash (fly ash, bottom ash), fluorogypsum and used-tires are available in large quantities in Texas.

Table 2.3. Summary of Recycled Materials in Texas

Recycled Material	Quantity Available (millions)		Quantity Used (millions/year)	Source		Cost	Current Applications	Remarks	Reference
	Total	Annual Prod		Number	Locations				
Tires (Number of tires)	55 (shredded) and 25 (whole)	18	7	22	Lubbock, Abilene, Tyler, El Paso, Odessa, Waco Beaumont, Corpus Christi (one each); Duncanville (3); Houston (6); San Antonio (5)	$5-$25 per cubic yard (0.5 to 3 inch) $40-$50 per cubic yard (< 0.25 inch)	Rubber-modified asphalt, tire-derived fuel, retreading.	Used in cement kilns. Exported to other states.	*Scrap Tire Market Study, TNRCC **.*
Fly ash (tons)		6.5	0.8	16	Houston, San Antonio, Victoria, College Station, Amarillo, San Miguel, Tolk.	$17-$23 per ton	Concrete construction, grouts, agriculture, waste treatment.	50% of CCBP* produced in Texas.	*Texas Recycles 2: Marketing our Neglected Resources.*
Bottom Ash (tons)		3.8	0.5	17	Same as above and another location Limestone	$5 per ton FOB (Freight on Board)	Agriculture, wall board, road base.	28% of CCBP* produced in Texas.	*Texas Recycles 2: Marketing our Neglected Resources.*
FGD (ton)		3.0	0.06	10	Same as above but not including Victoria, San Antonio, Amarillo.	$7 per ton/FOB	Agriculture, wall board, road base.	22% of CCBP* produced in Texas.	*Texas Recycles 2: Marketing our Neglected Resources.*
Construction and Demolition Debris (C & D) (tons)		3.6	Not available	318 Landfills	Throughout Texas	Highly variable	Low-cost houses.	Components are Wood (47%); Rubble, Aggregate and Ceramics (24%); Metals (6%); Paper (3%); others (20 %)	*Texas Recycles 2: Marketing our Neglected Resources.*

* Coal Combustion By-Products
** Texas Natural Resource Conservation Commission

(2) Three types of embankment configurations have been used. Placing the recycled material in the core of the embankment is the most popular. Use of tire chips will result in a lightweight embankments. Short-term and long-term settlements in embankments in which tire chips are used are not well documented.

(3) Use of recycled materials can either increase or decrease the cost of earth embankment construction. Transportation cost is an important factor influencing the project cost.

(4) Construction and demolition debris has not been used in earth embankments.

(5) Leaching of metals and organic compounds from the waste materials is not well documented.

(6) Behavior of recycled materials with clayey soils (Texas soils) has not been studied. Mixing of recycled materials may be feasible since their sources are often located in close proximity (for example, coal ash and tire chips). Behavior of such mixtures has not been studied.

(7) Coal ash, tire chips and fluorogypsum available in Texas were selected for further laboratory evaluation.

CHAPTER THREE. LABORATORY TESTS

INTRODUCTION

In order to evaluate the properties of recycled materials in Texas, several experiments were performed to characterize their geotechnical properties. Coal combustion by-products, tire chips and fluorogypsum were selected for the study. The recycled materials were obtained from various locations in Texas. The properties of recycled materials mixed with sand and simulated typical Texas soil (20% clay and 80% sand) were also determined. In many parts of Texas the soil is clayey in nature with varying amounts and types of clay. In order to simulate the affects of clay type, both kaolinite and bentonite clays were used in this study. Leachability studies were also conducted using the Toxicity Characteristic Leachate Procedure (TCLP) recommended by the EPA and the 7-Day Distilled Water Leachate Test recommended by the TNRCC to assess the environmental acceptability of the recycled materials.

EXPERIMENTAL PROGRAM

The experiments were divided into engineering properties tests and leachability tests. The properties of interest were specific gravity, particle-size distribution, index properties, compaction characteristics, permeability, unconfined compressive strength, cohesion, friction angle and stress-strain relationship. Both ASTM and TxDOT recommended tests were performed.

Engineering Properties Tests

Specific gravity: Tests were performed according to **ASTM D-854**. At least two tests were performed for each material.

Grain size distribution: Particle sizes of the recycled materials were determined using **ASTM D-421/422**. Samples of recycled materials were dried at 104°F for one day prior to testing. A Capa-700 series particle size analyzer was used to determine the particle size of kaolinite, bentonite and cement samples. The particle size analyzer uses a method of sedimentation (both the gravity and centrifuge options are available) and measures relative light absorbance/transmission at regular intervals to determine the particle size in the range of 0.05 to 300 μm.

Index properties: Atterberg limits for the recycled materials, their mixtures and in combination with soils were measured. The minus 40 fraction of the recycled materials and their combinations were tested to determine the liquid limits and plastic limits. The materials were dried at 104°F for one day before testing. The main objective of these tests was to determine how the plasticity of recycled materials varied when they were mixed with other recycled materials and Texas soils. These tests were conducted according to **Tex-104-E** for the liquid limit, and **Tex-105-E** and **Tex-106-E** were used for the plastic limit and plasticity index calculations, respectively. These tests are in conformity with **ASTM D 423/424.**

Compaction: Compaction properties were studied using the standard Proctor test method, **ASTM D 698**. Here again, the maximum dry density and optimum moisture contents for the soil, recycled materials and their mixtures were studied. Compaction behavior of pure tire chips and their combinations with sand, Texas soil and Type B Fly ash were studied using a 6 in. x 8 in. size mold and **Tex-113-E** method for compaction.

Permeability: Hydraulic conductivity tests were performed using double-ring fixed-wall permeameters that have the dimensions of a standard Proctor mold. The tests were performed at a constant inlet water pressure of 16 psi corresponding to a hydraulic gradient of 100. This test is very similar to the constant head permeability test, **ASTM D 2434,** except for the sample size. The pH of the effluent fluid was monitored throughout the test. Hydraulic conductivity tests were continued till the permeability coefficient reached a constant value.

Unconfined compression strength: Tests were conducted on freshly compacted samples. Samples were compacted in a Harvard miniature mold at the optimum moisture content. Tests were conducted according to **ASTM D 2166**.

Shear strength parameters: Cohesion, internal friction angle and stress-strain relationships of the soils and recycled materials was determined using the consolidated drained triaxial test (**ASTM D 2850**). Except for the tire chips and its combinations, with sand and Type B fly ash the triaxial test was conducted on specimens 35 mm (1.4 in.) in diameter and 70 mm (2.8 in.) in length. Behavior of the chips and their mixtures were studied using the Texas triaxial cell. Texas standard test method **Tex-117-E** was followed when Texas triaxial cells were used. Behavior of the materials was studied up to a confining pressure of 207 kPa (30 psi). Each material was tested under at least three confining pressures to determine the effective angle of internal friction and cohesion. These shear strength parameters are very important for designing embankments.

Leachability Tests

TNRCC and TCLP tests were performed on recycled materials. Leachate solutions were analyzed for metals and total organic carbon (TOC). Ordinary Portland cement was selected as a control material. The procedures followed for the TCLP test were according to the EPA standards of test procedures. Metal concentrations in the leachate solutions were compared to the TCLP limits specified by the EPA standards.

TNRCC Test (Texas Natural Resource Conservation Commission)**:** Recycled materials were mixed with distilled water in the ratio of 1:4 by weight in 2 liter bottles: 250 g of recycled material was mixed with one liter of distilled water. The Distilled Water Leachate Test in **Appendix E** of **31 TAC** (Texas Administrative Code) was continued for 7 days (Guidelines for the Classification and Coding of Industrial Wastes and Hazardous Wastes, RG-22, published by TNRCC). Although the original test was specified for 7 days, the investigators decided to continue the test for a total of 30 days. At the end of 7 days and 30 days, the leachate sample was filtered through 0.45 micron filter paper and the filtrate was analyzed for metals and total organic carbon (TOC). Passing the TNRCC test will qualify the recycled material as a Class 3 waste material that is non-hazardous.

TCLP Test (Toxicity Characteristics Leachate Procedure)**:** Tests were performed on recycled materials smaller than 9.5 mm (passing No. 10 sieve). The extraction fluid for the leachate test was selected based on the pH of the mixture of de-ionized (DI) water and recycled material. Each recycled material selected in this study was evaluated separately to select the leaching solution. All recycled material exhibited a pH of 7 or higher. Each TCLP test sample (approximately 100 g) was mixed with DI water in a 2 liter vessel, with a solid to liquid ratio of 1:20 by weight, and then agitated in a rotary tumbler at 30 rpm for 18 hours. The investigators decided to continue the test for a total of seven days. At the end of seven days, leachate samples were collected and analyzed for metals using an ICP (inductively coupled plasma atomic emission spectroscopy) device.

RESULTS and DISCUSSION

The experimental results are summarized and observations are advanced based on the test results.

Specific gravity: The specific gravity results for the recycled materials are summarized in Table. 3.1. The values are within the range reported in the literature (Table 2.2). The tire chips (without metal attachments) had the lowest specific gravity.

Grain size distribution: Particle size distributions for the recycled materials are shown in Fig. 3.1. Of the materials tested, tire chips (commercially marketed as 13 mm [0.5 in.] tire chips) had the largest particles, and fly ash had the smallest. The coefficient of uniformity (C_u) and coefficient of curvature (C_c) for the soils and recycled materials are summarized in Table 3.1. Tire chips, bottom ash and fly ash were uniformly distributed, while the other materials were well-graded. Cement is used only as a comparison to other recycled materials selected for this study. Cement particle size varied from 0.8 to 100 μm, while kaolinite and bentonite particle sizes ranged from 0.1 to 6 μm. The coefficient of uniformity and curvature for cement and bentonite was 7 and 6.4, and 1.09 and 0.65 respectively. The selected sand was uniformly graded, and simulated Texas soils (sand blended with kaolinite (denoted "K") or bentonite (denoted "B") were well graded. Particle shapes and handling problems are also summarized in Table 3.1, and D_{15} and D_{85} particle sizes are summarized for the recycled materials so as to permit evaluation of these materials as filters in embankments.

Atterberg Limits: The test results are summarized in Table 3.2. Based on the index properties and particle size distribution the soils, recycled materials and their mixtures are classified in Table 3.2 according to the USCS system. The results are represented in a plasticity chart in Fig. 3.2. Liquid limits for non-plastic (NP) materials are shown in Fig. 3.3. Based on the test results the following observations can be advanced:

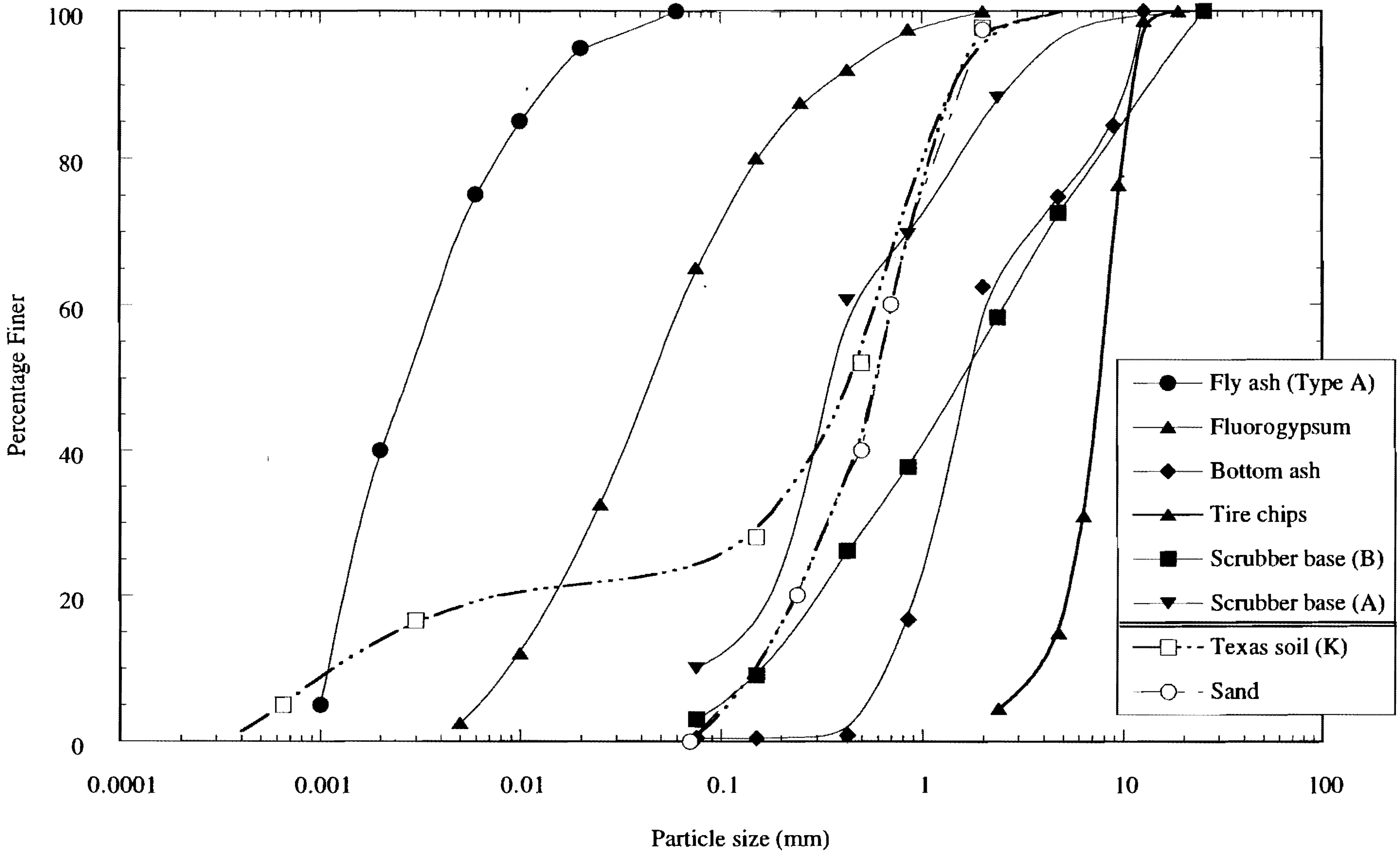


Figure. 3.1 Particle Size Distribution for Soils and Recycled Materials

Table 3.1. Summary of Specific Gravity and Particle-size Analysis

Material	Specific gravity G_S	D_{15} (mm)	D_{50} (mm)	D_{85} (mm)	C_u	C_c	Remarks
1. Soils							
Sand	2.68	0.3	0.6	1.1	2.5	1.1	Angular particles. Uniformly graded.
Kaolinite	2.60	0.0005	0.012	0.03	3.0	0.65	Very fine particles.
Bentonite	-	0.0003	0.012	0.03	6.4	0.65	Very fine particles.
Texas soil (K)	-	0.003	0.4	1.2	Gap graded > 100	-	Well (gap) graded. Angular to very fine particles.
2. Recycled Materials							
Fluoro-Gypsum	2.06	0.012	0.045	0.20	6.9	0.87	Angular particles. Well graded.
Tire chips	1.28	4.5	7.5	11	2.2	1.2	Irregular shape. Uniformly graded.
Bottom ash	2.55	0.8	1.7	9.0	3.1	1.1	Irregular /spherical shape and flat pieces. Uniformly graded. No dust problem.
Fly ash Type A *	2.52	0.0012	0.0025	0.01	3.2	0.6	Very fine particles. Uniformly graded. Gray color. Dust control needed.
Fly ash Type B*	2.56	-	-	-	-	-	Very fine particle. Yellow color. Dust control needed.
Scrubber base (A)	-	0.13	0.35	2.0	6.0	1.4	Spherical/irregular shape. Large particles break during compaction. Well graded.
Scrubber base (B)	-	0.25	1.6	11	16	0.8	Spherical/irregular shape. Large particles break during compaction. Well graded.
3. Control Sample							
Ordinary Portland cement	3.15	0.003	0.013	0.03	7.0	1.09	Irregular shape. Well graded. Gray color

* Note: Fly ash Type A and Type B as specified by TxDOT material specifications: D-9 8900 represents closely Fly ash Class-F and Class-C (ASTM C 618) respectively.

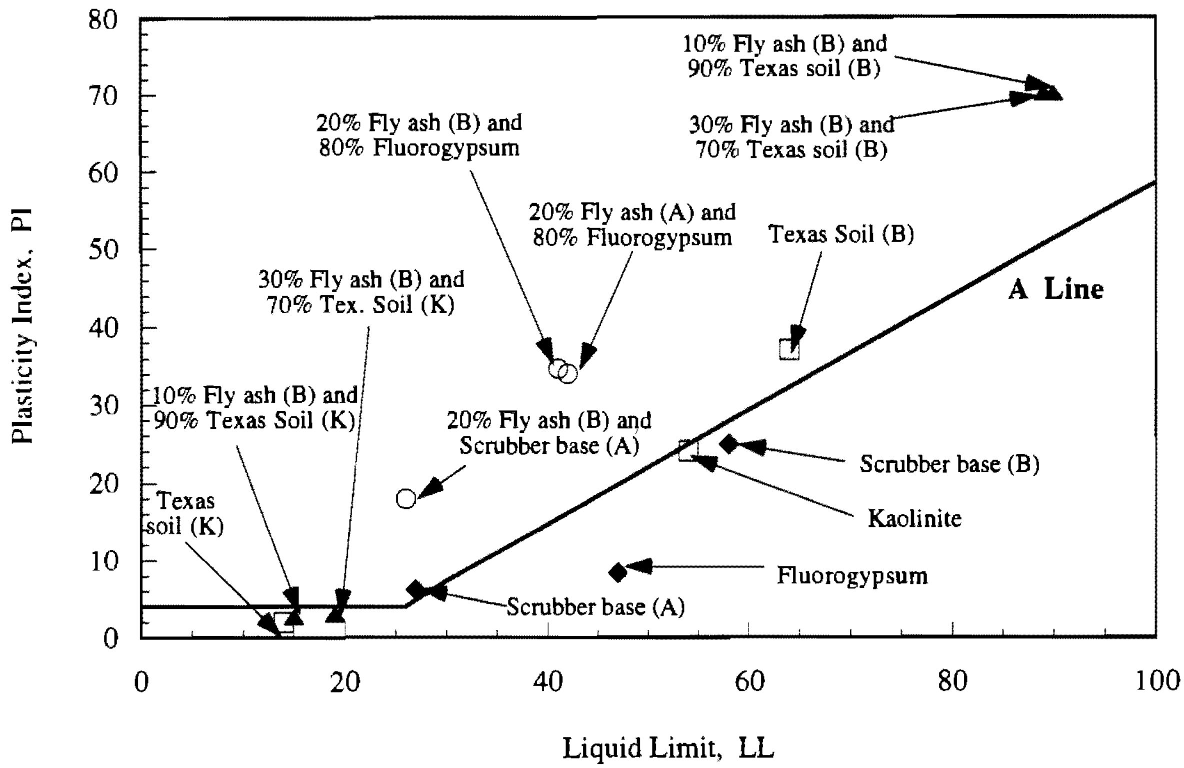


Figure. 3.2 Location of Various Materials on the Plasticity Chart

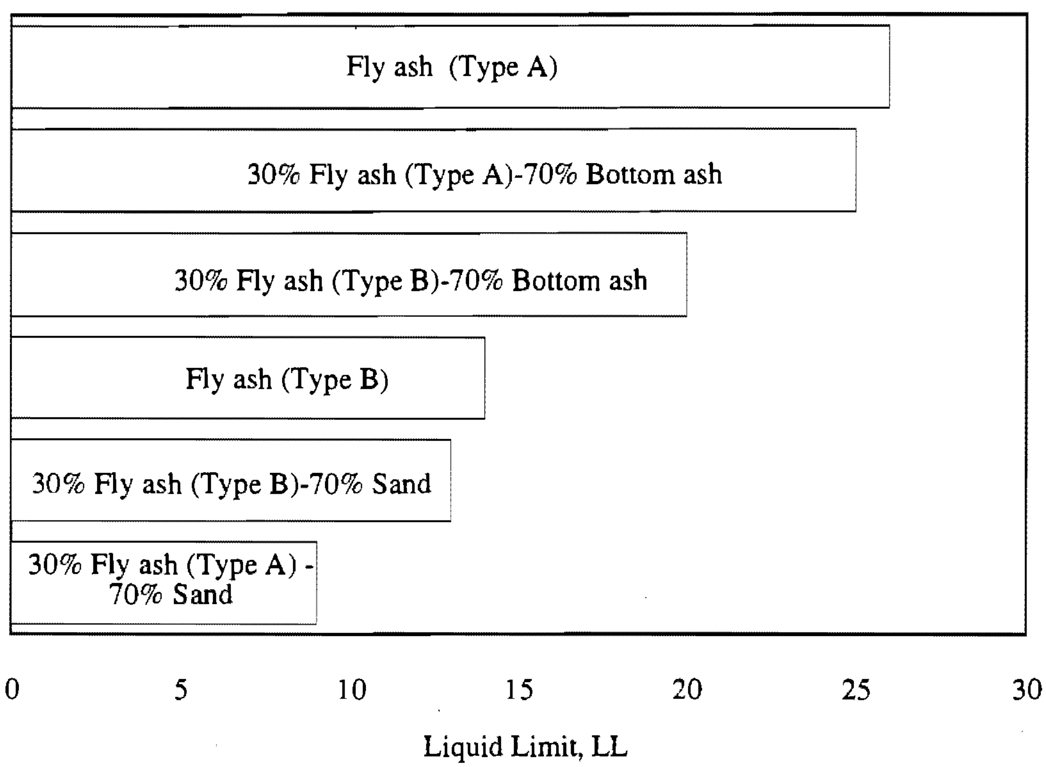


Figure. 3.3 Liquid Limit for Various Non-Plastic Materials

(1) Fly ash (Type B) and fly ash (Type A) are non-plastic materials. Atterberg limit tests are not applicable to bottom ash and tire chips.

(2) Addition of up to 30% fly ash (Type B) to the Texas soil (K) by weight did not affect the Atterberg limits of the soil. Fly ash (Type B) affected the Atterberg limits of Texas soil (B); it increased the liquid limit (LL), reduced the plastic limit (PL) and increased the plasticity index (PI).

(3) The bottom ash and fly ash (Type A and Type B) mixture is non-plastic. Fly ash reduced the PL of fluorogypsum, and scrubber base (B) and increased the PI.

Compaction: Dry densities were determined at four moisture contents to develop the moisture-density relationships for each material investigated in this study. The maximum dry density and optimum moisture content are summarized in Table 3.3 and Fig. 3.4. The effect of adding fly ash (Type B or Class-C) to the sand, Texas soils and other recycled materials are shown in Figs. 3.5 and 3.6. The effect of tire chips on the densities of sand, Texas soil (K) and fly ash is shown in Fig. 3.7. Mixing higher concentrations of the tire chips with Texas soils and fly ash is relatively difficult as compared to mixing tire chips with sand. Since 13 mm (1/2-inch) tire chips were used in this study, 6 in. x 8 in. size molds were used for compaction studies (**Tex-113-E**). Based on the test results the following observations can be advanced.

(1) Fly ash (Type B) had the highest dry density (2163 kg/m^3 or 135 pcf), and tire chips had the lowest (6.3 kN/m^3 or 40 pcf).

(2) Addition of 30% fly ash (Type B) increased the dry density of the sand by 10% but reduced the dry density of Texas soils by 10%. In all cases the maximum dry densities were higher than 17.3 kN/m^3 (110 pcf).

(3) Incorporating fly ash (Type B) increased the dry density of bottom ash and tire chips, had no effect on the scrubber base (B) but reduced the maximum dry density of fluorogypsum.

(4) With 30% of tire chips mixed with sand and Texas soils, maximum dry densities higher than 14.1 kN/m^3 (90 pcf) can be achieved.

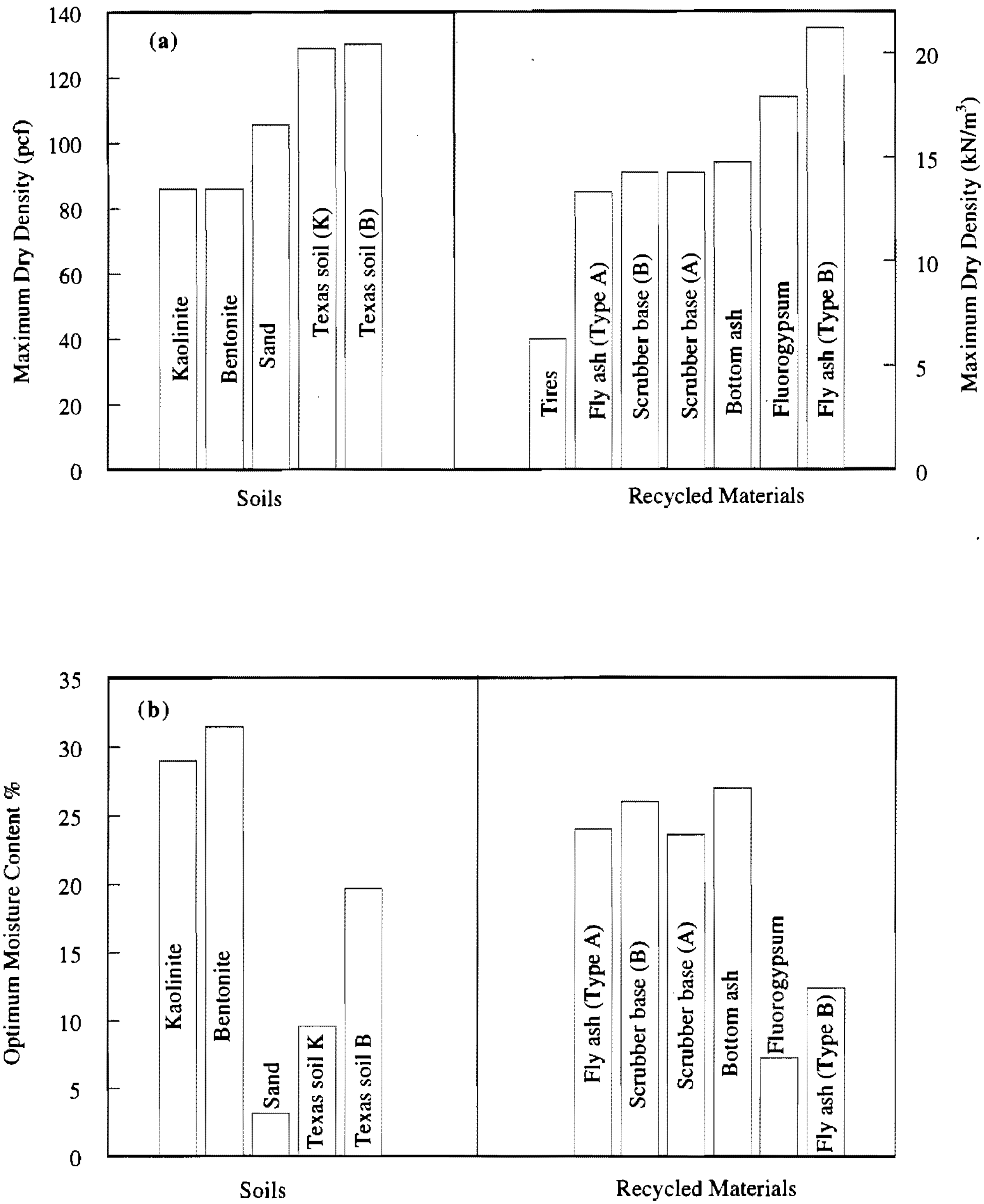


Figure. 3.4 Compaction Properties of Soils and Recycled Materials (a) Maximum Dry Density and (b) Optimum Moisture Content

Table 3.2. Atterberg Limits for Soils and Recycled Materials

Materials	LL (%)	PL (%)	PI (%)	USCS
1. Soils				
Kaolinite	54	30	24	MH
Bentonite	495	44	451	CH
Sand(80%)+Kaolinite(20%){Tx. soil (K)}	14	12	2	SC-ML
Sand(80%)+Bentonite(20%){Tx. soil (B)}	64	27	37	SC-CH
2. Recycled Materials				
Fly ash (Type B)	14	NP	-	NP
Fly ash (Type A)	26	NP	-	NP
Fluorogypsum	47	39	8	ML
Scrubber base (B)	27	21	6	SW-ML
Scrubber base (A)	58	33	25	SW-MH
3. Soils with Recycled Materials				
70% Sand + 30% Fly ash (Type A)	9	NP	-	NP
70% Sand + 30% Fly ash (Type B)	13	NP	-	NP
90% Tx.soil (K) + 10% Fly ash (Type B)	15	12	3	ML
90% Tx.soil (B) + 10% Fly ash (Type B)	90	20	70	CH
70% Tx.soil (B) + 30% Fly ash (Type B)	89	19	70	CH
70% Tx.soil (K) + 30% Fly ash (Type B)	19	16	3	ML
4. Recycled Material Mixtures				
30% Fly ash (Type A) - 70% Bottom ash	25	NP	-	NP
30% Fly ash (Type B) - 70% Bottom ash	20	NP	-	NP
20% Fly ash (Type A) - 80% Fluorogypsum	42	8	34	CL
20% Fly ash (Type B) - 80% Fluorogypsum	41	6	35	CL
20% Fly ash (Type B) - 80% Scrubber base (A)	26	8	18	CL

* Note: Fly ash Type A and Type B as specified by TxDOT material specifications: D-9 8900 represents closely Fly ash Class-F and Class-C (ASTM C 618) respectively.

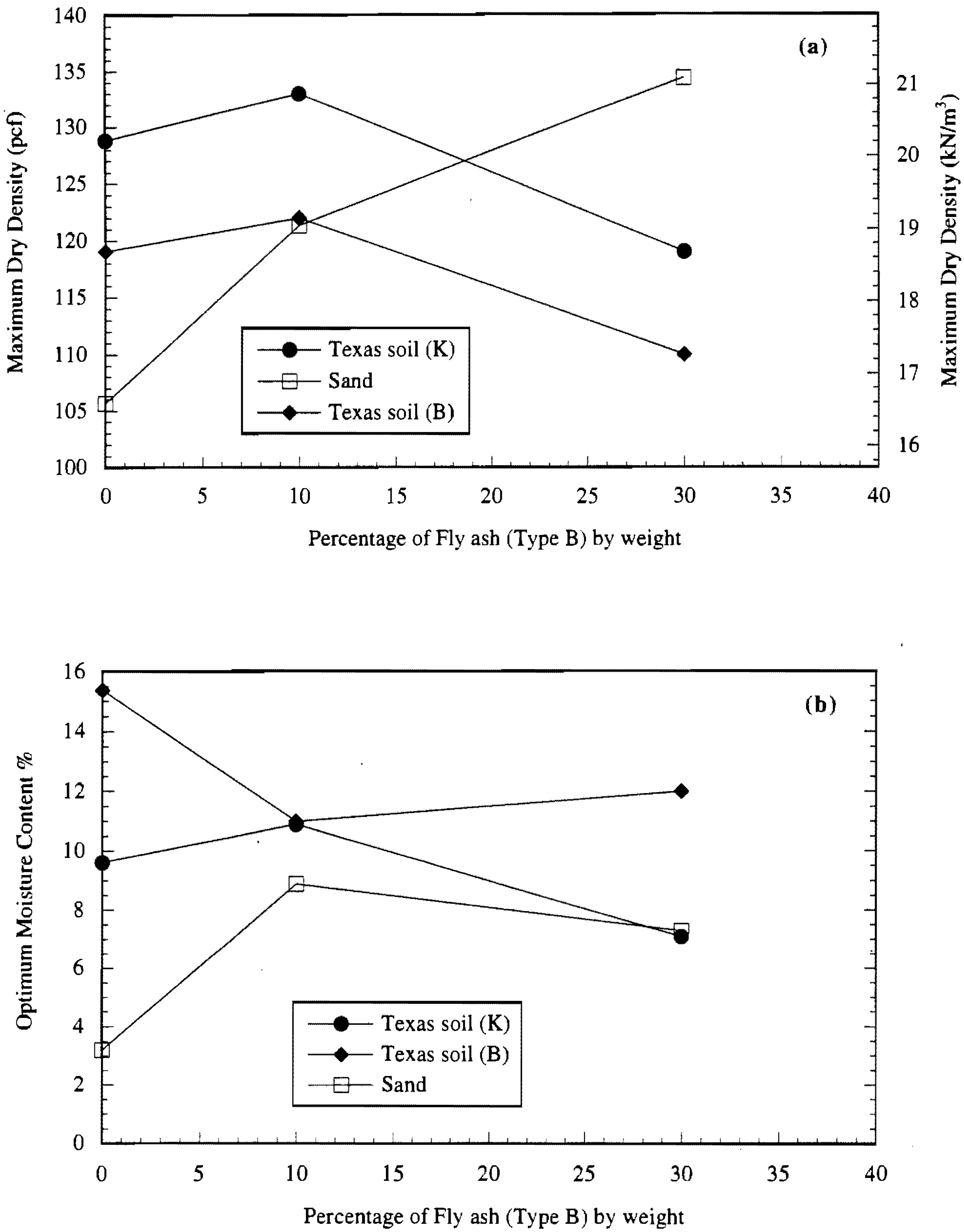


Figure. 3.5 Effect of Fly ash (Type B) on the Compaction Properties of Sand and Texas Soils (a) Maximum Dry Density and (b) Optimum Moisture Content

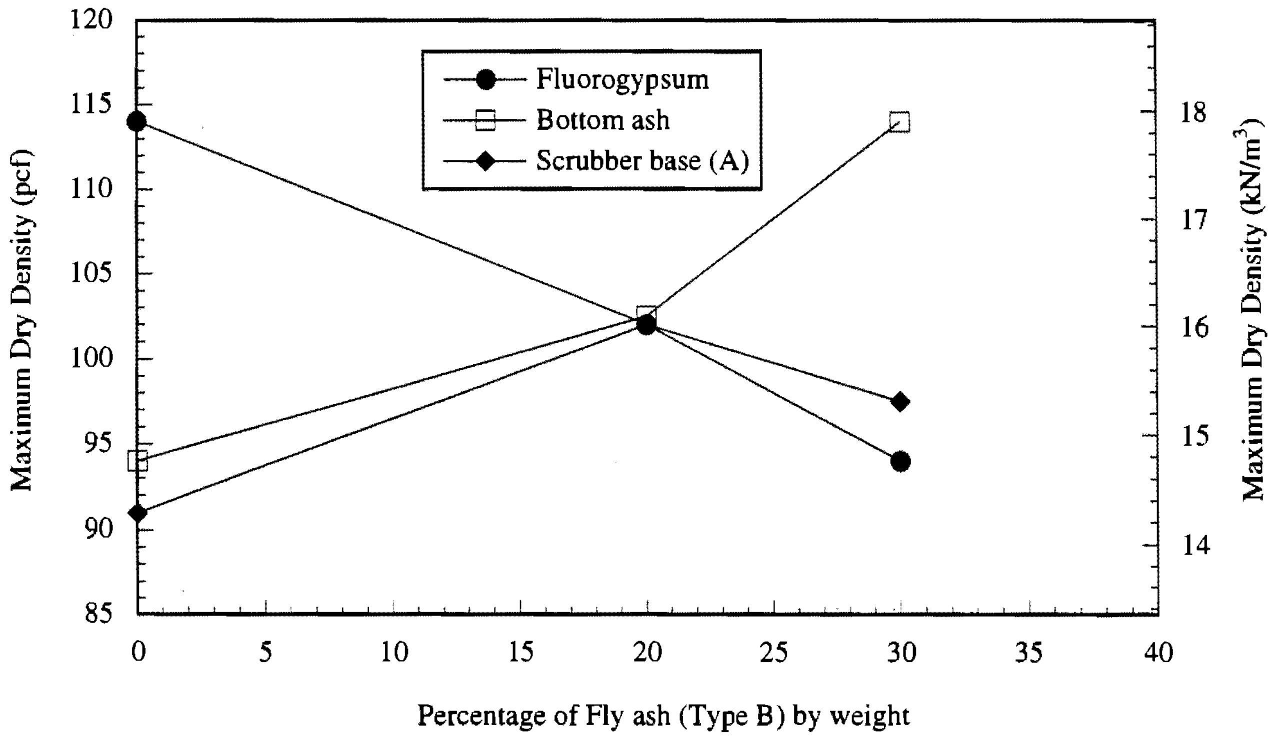


Figure. 3.6 Effect of Fly Ash (Type B) on the Maximum Dry Density of Fluorogypsum, Bottom Ash and Scrubber Base (A)

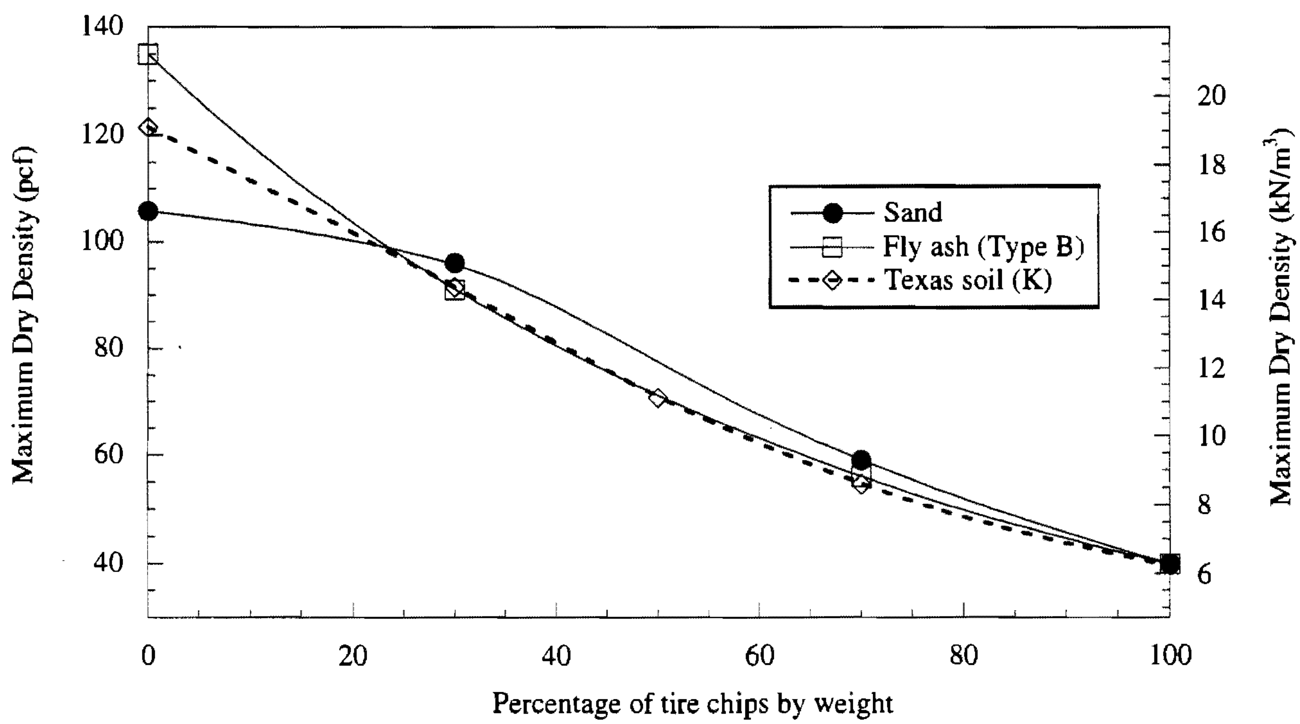


Figure. 3.7 Effect of Tire Chips (13mm) on the Maximum Dry Density of Sand, Texas Soil (K) and Fly Ash (Type B)

Table 3.3 Summary of Maximum Dry Density and Optimum Moisture Content

Materials	Maximum Dry Density kN/m^3 (pcf)	Optimum Moisture Content (%)
1. Soils		
Sand	18.9 (120)	5
Kaolinite	13.5 (86)	29
Bentonite	13.5 (86)	32
Sand(80%)+Kaolinite(20%){Tx. soil (K)}	20.2 (129)	24
Sand(80%)+Bentonite(20%){Tx. soil (B)}	18.6 (119)	15
2. Recycled Materials		
Fly ash (Type B)	21.2 (135)	12
Fly ash (Type A)	13.4 (85)	24
Fluorogypsum	17.9 (114)	7
Scrubber base (Type A)	14.3 (91)	24
Bottom ash	14.8 (94)	27
Scrubber base (Type B)	14.3 (91)	26
Tire Chips	6.3 (40)	dry
3. Soil with Recycled Materials		
50% Sand + 50% Tire chips	11.8 (75)	15
70% Sand + 30% Fly ash (Type A)	19.2 (122)	9
70% Sand + 30% Fly ash (Type B)	21.1 (134)	7
90% Tx. soil (K) + 10% Fly ash (Type B)	20.9 (133)	9
90% Tx. soil (B) + 10% Fly ash (Type B)	19.2 (122)	11
70% Tx. soil (B) + 30% Fly ash (Type B)	17.3 (110)	12
70% Tx. soil (K) + 30% Fly ash (Type B)	18.7 (119)	7
50% Tx. soil (K) + 50% Tire chips	11.0 (70)	24
4. Recycled Material Mixtures		
30% Fly ash (Type A) + 70% Bottom ash	16.8 (107)	16
30% Fly ash (Type B) + 70% Bottom ash	17.9 (114)	14
20% Fly ash (Type A)+ 80% Fluoroypsum	13.7 (87)	20
20% Fly ash (Type B)+ 80% Fluorogypsum	13.5 (86)	34
20% Fly ash (B) + 80% Scrubber base (A)	16.0 (102)	16
50% Fly ash (C) + 50% Tire chips	11.0 (70)	12

Permeability: Test results are summarized in Table 3.4. Figures 3.8 and 3.9 show the effect of fly ash (Type B) and fly ash (Type A) on the permeability of fluorogypsum, bottom ash and scrubber base (A). The changes in effluent pH are also shown in Figs. 3.8 (b) and 3.9 (b).

(1) Incorporating the fly ash into the soils and other recycled materials reduced the permeability. Fly ash (Type B) and fly ash (Type A) had a varying effects on the magnitude of permeability when mixed with other materials.

(2) Addition of 20% fly ash to sand, Texas soil (K), bottom ash and scrubber base (A) increased the pH of the effluent to over 12.

Table 3.4. Summary of Permeability Test Results

Materials	**Wet Density kN/m^3 (pcf)**	**Permeability (cm/s)**
1. Soils		
Sand(80%)+Kaolinite(20%) {Tx. soil (K)}	21.3 (137)	4×10^{-5}
2. Soils with Recycled Materials		
70% Sand+ 30% Fly ash (Type B)	23.1 (147)	$< 10^{-8}$
70% Sand+30% Fly ash (Type A)	20.3 (129)	3×10^{-6}
3. Recycled Material Mixtures		
30% Fly ash (Type B) + 70% Bottom ash	21.0 (134)	5×10^{-7}
30% Fly ash (Type A) + 70% Bottom ash	20.0 (127)	1×10^{-6}
20% Fly ash (Type B) + 80% Fluorogypsum	18.7 (119)	7×10^{-8}
20% Fly ash (Type A) + 80% Fluorogypsum	18.3 (116)	9×10^{-8}
20% Fly ash (Type A) + 80% Scrubber base (A)	17.7 (113)	9×10^{-7}
20% Fly ash (Type B) + 80% Scrubber base (A)	18.3 (116)	3×10^{-6}

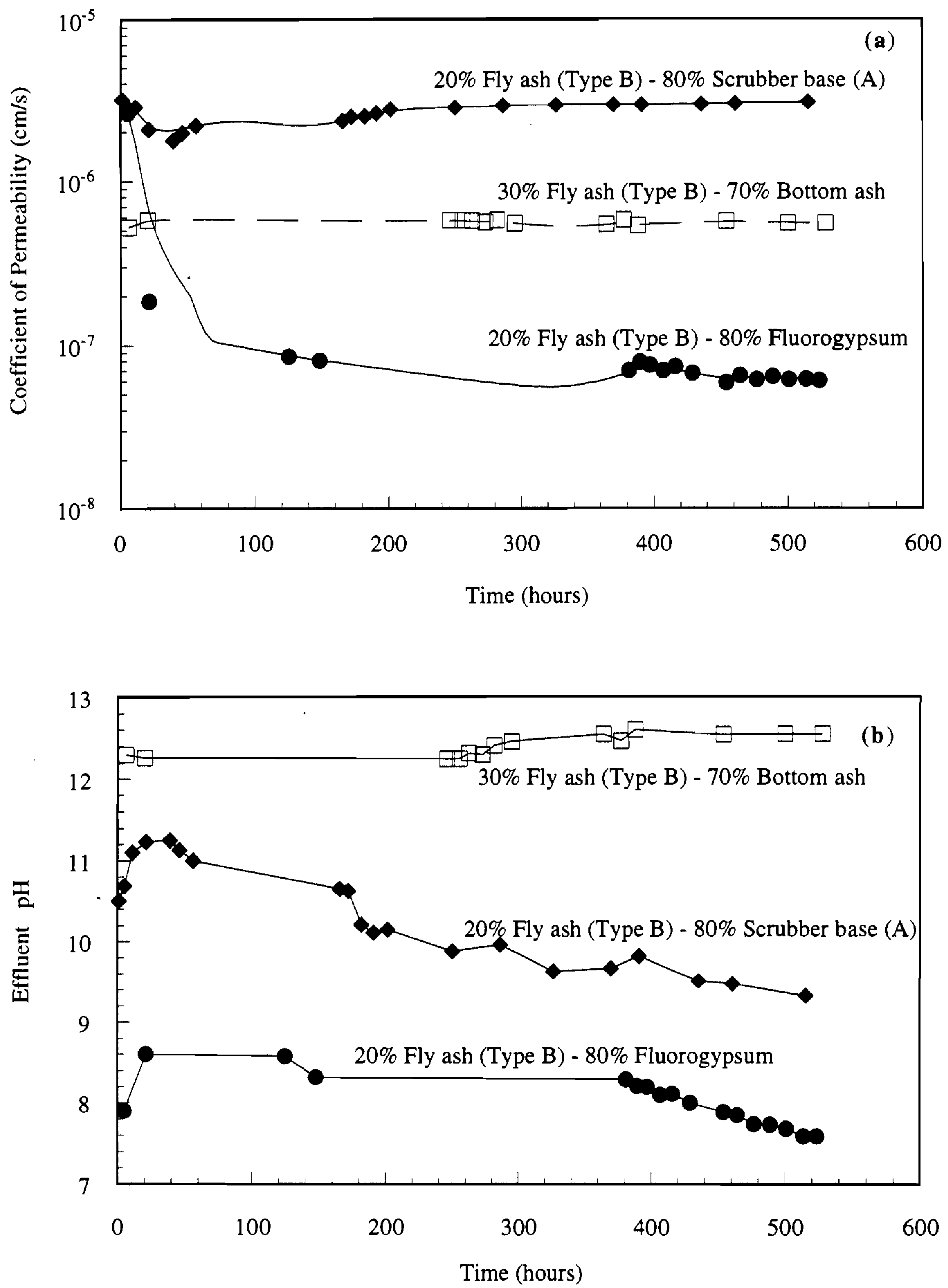


Figure 3.8 Effect of Fly Ash (Type B) on the Permeability of Fluorogypsum, Bottom Ash and Scrubber Base (A) (a) Permeabiltiy Time History (b) Effluent pH-Time History

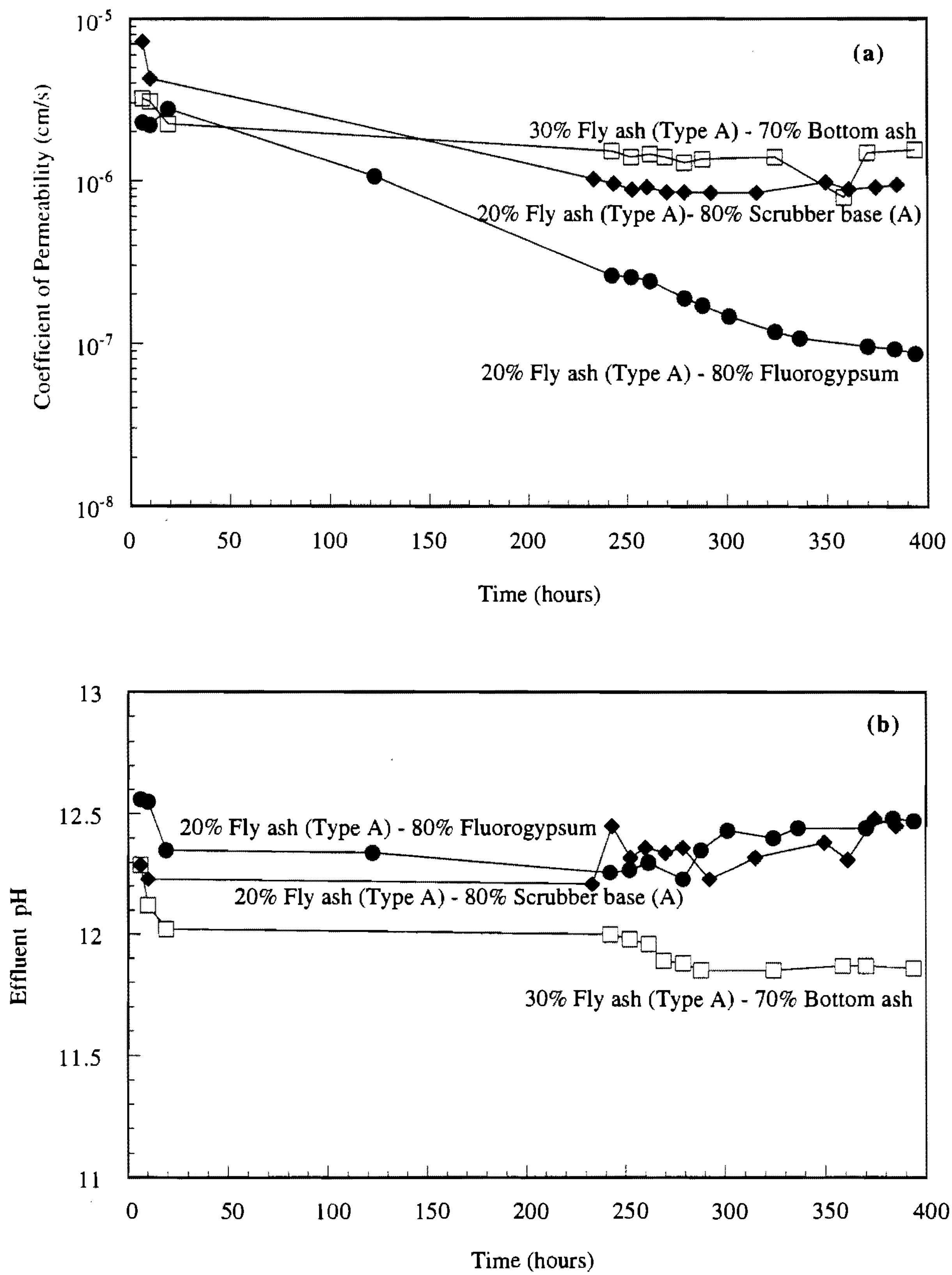


Figure. 3.9 Effect of Fly Ash (Type A) on the Permeability of Fluorogypsum, Bottom Ash and Scrubber Base (A) (a) Permeability-Time History (b) Effluent pH-Time History

Unconfined compressive strength: The samples were compacted in a Harvard miniature mold at optimum moisture content. Based on the test results the following observations are advanced:

Table 3.5 Summary of Unconfined Compression Strength of Various Materials

Materials	Wet Density kN/m^3 (pcf)	Strength kPa (psi)
1. Soils		
Kaolinite	18.4 (117)	434 (63)
Bentonite	16.7 (106)	317 (46)
Sand(80%)+Kaolinite(20%){Tx.soil (K)}	22.2 (141)	662 (96)
Sand(80%)+Bentonite(20%){Tx.soil (B)}	21.4 (136)	290 (42)
2. Recycled Materials		
Fly ash (Type B)	20.9 (133)	448 (65)
Fly ash (Type A)	17.0 (108)	179 (26)
Bottom ash	18.7 (119)	0
Fluorogypsum	18.4 (117)	441 (64)
Scrubber base (A)	18.2 (116)	214 (31)
Scrubber base (B)	17.1 (109)	359 (52)
Tire Chips	6.3 (40)	0
3. Soils with Recycled Materials		
70% Sand + 30% Fly ash (Type A)	19.5 (124)	207 (30)
70% Sand + 30% Fly ash (Type B)	22.2 (141)	538 (78)
90% Tx. soil (K) + 10% Fly ash (Type B)	22.3 (142)	503 (73)
90% Tx. soil (B) + 10% Fly ash (Type B)	21.4 (136)	352 (51)
70% Tx. soil (B) + 30% Fly ash (Type B)	21.3 (135)	593 (86)
70% Tx. soil (K) + 30% Fly ash (Type B)	21.9 (139)	1248(181)
4. Recycled Materials Mixtures		
30% Fly ash (Type A) + 70% Bottom ash	19.0 (121)	352 (51)
30% Fly ash (Type B) + 70% Bottom ash	21.5 (137)	428 (62)
20% Fly ash (Type A)+80% Fluorogypsum	14.9 (95)	786 (114)
20% Fly ash (Type B)+80% Fluorogypsum	18.9 (120)	779 (113)
20% Fly ash (Type B) + 80% Scrubber base (A)	18.2 (116)	241 (35)

(1) Bottom ash and tire chips are cohesionless materials (zero UCS). Fly ash (Type B) and fluorogypsum had UCS higher than 440 kPa (65 psi).

(2) Addition of up to 30% fly ash improved the UCS of sand and Texas soils. Fly ash (Type B) produced higher UCS than fly ash (Type A or Class-F).

(3) Addition of fly ash increased the UCS of bottom ash, scrubber base and fluorogypsum.

Shear strength parameters: Each sample was compacted in a harvard miniature mold at optimum moisture content, and tested under three confining pressures. The cohesion and internal friction angle were determined from the envelopes to the Mohr circles at failure. All the triaxial tests were drained tests. Peak stress in the stress-strain relationship for each material was used as the failure stress, and it should be noted that the corresponding failure strain varied substantially for the recycled materials. Based on the experimental results, the following conclusions can be advanced.

(1) Botttom ash and tire chips behave as cohesionless materials. Of the materials tested, tire chips had the lowest friction angle, 30 degrees, which was similar to the Texas soil (K). It should be noted that the corresponding failure strains were 4% and 10% for the Texas soil (K) and tire chips, respectively (Figs. 3.10 and 3.11).

(2) All the recycled materials (tested at the densities and within the confining pressures reported in Table 3.6) had friction angles in the range of 30 to 60 degrees.

(3) The mixture of 30% tire chips and sand (70%) or fly ash (70%) had good frictional properties (angle of friction > 40^o).

Table 3.6. **Triaxial Test Results for Various Materials and Their Mixtures.**

Materials	Cohesion, c (kPa)	Friction angle (ϕ)	Density (kN/m^3)	Confining pressure (kPa)
1. Soils				
Sand	0	39°	19.3	69-207
Sand (80%)+Kaolinite (20%) (Tx. soil (K))	14	31°	20.3	69-207
2. Recycled Materials				
Fly ash (Type B)	241	61°	20.9	35-138
Scrubber base (A)	55	29°	14.1	35-138
Scrubber base (B)	107	46°	14.3	35-138
Fluorogypsum	31	44°	17.9	35-138
Bottom ash	0	45°	14.8	35-138
Pure Tire chips	0	30°	6.3	35-138
3. Soils with Recycled Materials				
30% Tire chips + 70% Sand	0	41°	15.1	35-138
4. Recycled Material Mixtures				
30% Tire chips + 70% Fly ash (Type B)	45	45°	14.3	35-138

TNRCC Test: Leaching solutions were analyzed after 7 and 30 days of testing. The results are summarized in Tables 3.7 and 3.8. Ordinary portland cement was also evaluated under the same conditions. Organics in the leachate were measured using a TOC machine. Several metals selected based on the literature review were analyzed in the leaching solutions. Concentrations of Ba (II), Pb (II) and Cr (III & IV) were measured using the ICP. Ca (II) concentration in the leaching solution was measured using an ion selective electrode. The Maximum Contaminant Level (MCL) for Class 3 waste evaluation for barium (Ba(II)), chromium (Cr) and lead (Pb) are 1, 0.1 and 0.05 mg/L respectively. There is no MCL for Ca (II). Based on the test results, the following observations are advanced:

(1) Only tire chips had TOC higher than cement. TOC for tire chips increased with the leaching time.

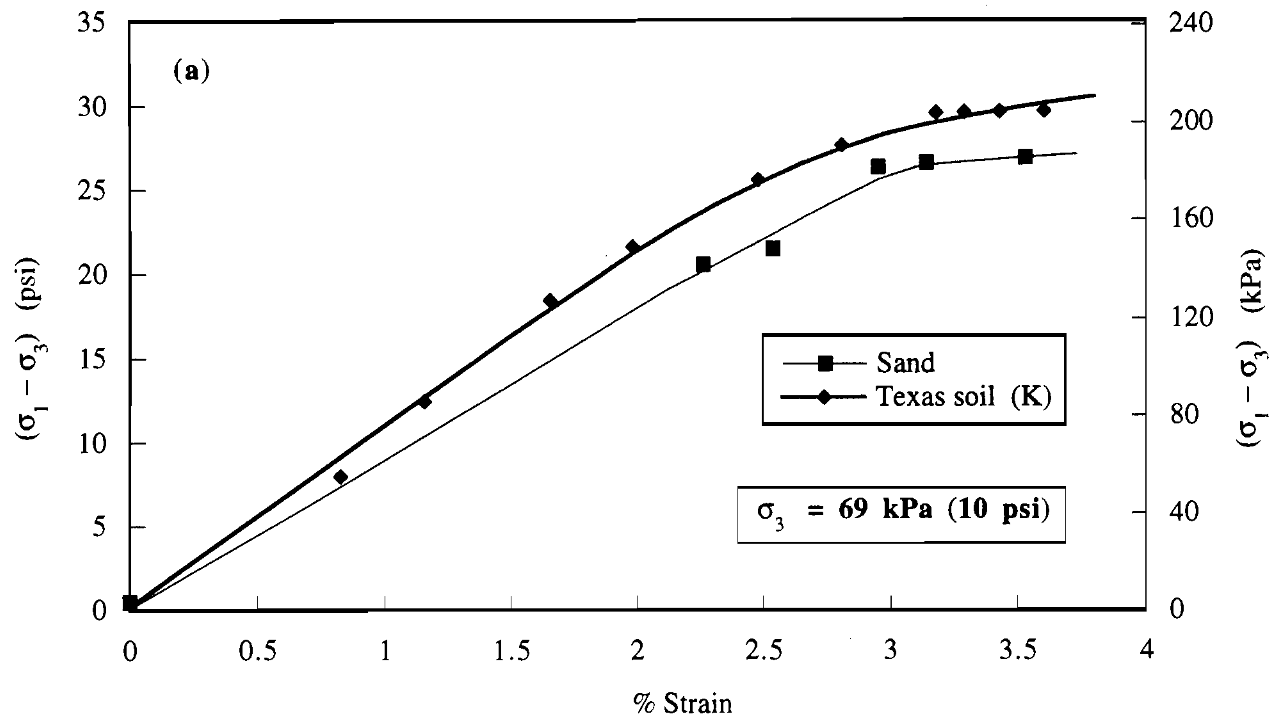
(2) Fly ash B, fly ash A, bottom ash, scrubber base and fluorogypsum had TOC far below that of cement. Only nominal changes in TOC was observed between 7 and 30 days of testing for these materials.

(3) Concentrations of Ba (II), Pb (II) and Cr (total) in the leachates were below the detection limit of the ICP, which is less than 0.1 mg/L.

(4) Ca (II) concentration in the leachate solutions from fly ash (Type B), bottom ash, gypsum and tire chip was less than that detected for cement. Fly ash (Type A), scrubber base (B) and (A) showed higher Ca (II) concentration than cement.

Table 3.7 TOC Results for TNRCC tests.

Material	TOC (mg/L) / pH	
	7 Days	30 Days
1. Recycled Materials		
Fluorogypsum	2.8 / 10.9	3.5 / 10.9
Fly ash (Type B)	0.87 / 11.5	1.2 / 11.4
Fly ash (Type A)	1.8 / 12.0	2.7 / 11.9
Bottom ash	1.1 / 9.6	0.90 / 9.0
Scrubber base(A)	4.3 / 10.3	5.8 / 10.4
Scrubber base(B)	1.7 / 9.2	2.0 / 9.2
Pure tire chips	23.0 / 8.9	33.3 / 8.6
Pure tire chips with protruding wires	13.4 / 12.2	23.2 / 12.1
2. Control Sample		
Cement	15.3 / 9.1	12.3 / 9.1



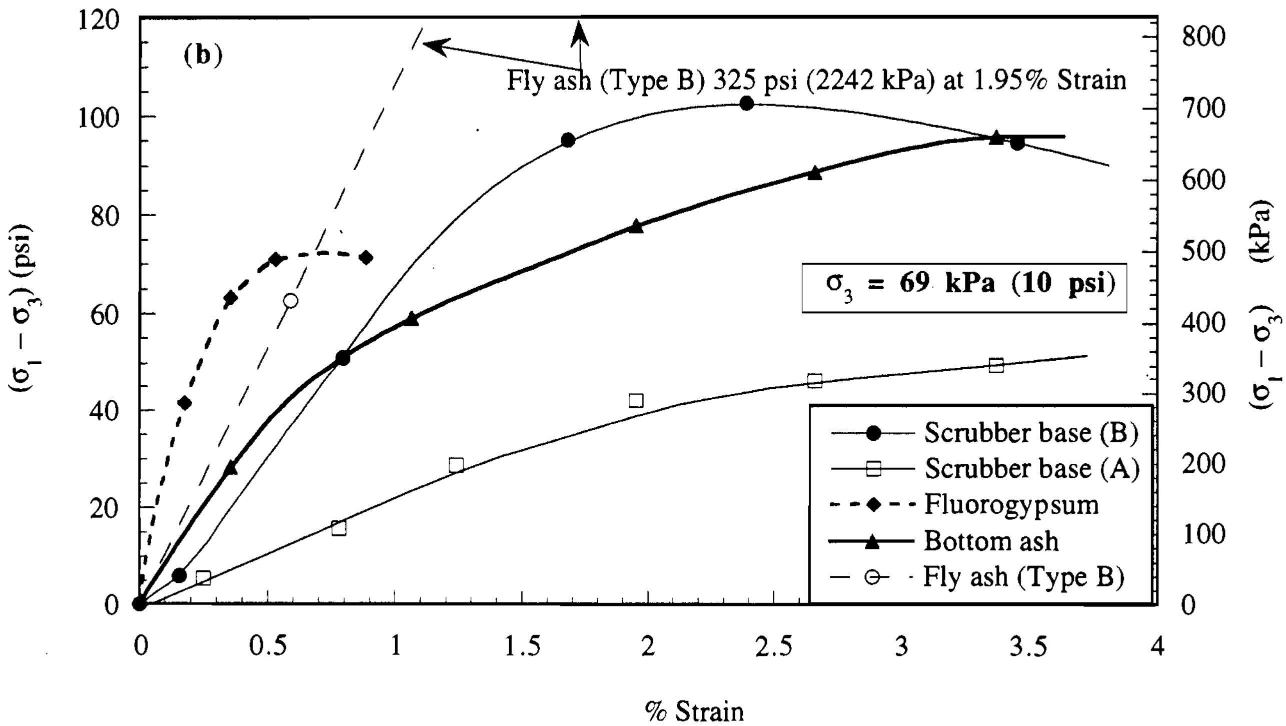


Figure. 3.10 Typical Stress-Strain Relationships (a) Sand and Texas Soil (b) Recycled Materials.

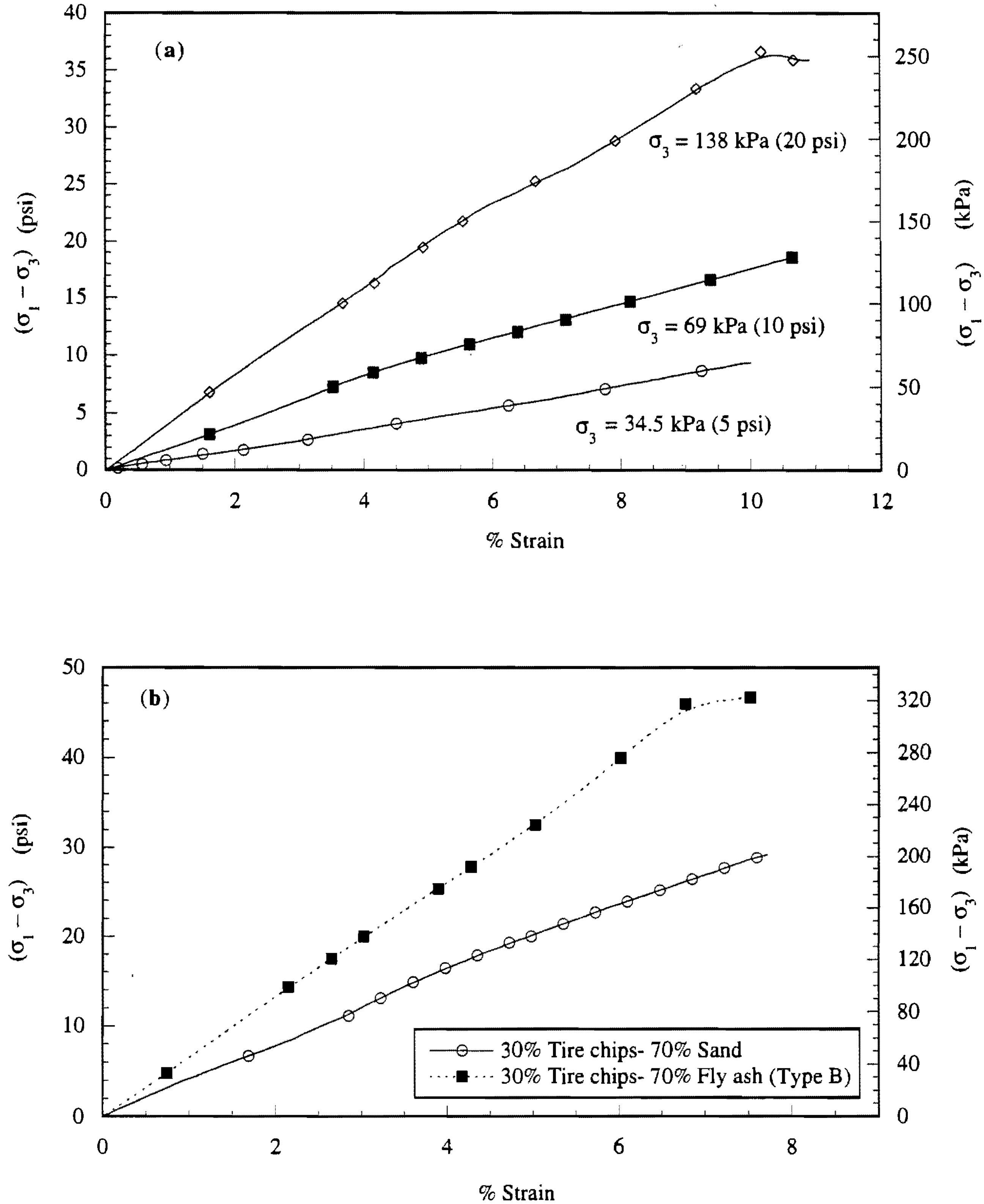


Figure. 3.11 Typical Stress-Strain Relationships
(a) Tire Chips (b) Tire Chips with Sand and Fly Ash (Type B)

Table 3.8. Metal Analysis Results from TNRCC Leachate Tests

Material	Ba (II) (mg/L)	Pb(II) (mg/L)	Cr (*) (mg/L)	Ca (II) (mg/L)
1. Recycled Materials				
Flourogypsum	ND	ND	ND	88
Fly ash (Type B)	ND	ND	ND	53
Fly ash (Type A)	ND	ND	ND	157
Bottom ash	ND	ND	ND	15
Scrubber base(A)	ND	ND	ND	186
Scrubber base(B)	ND	ND	ND	133
Pure tire chips	ND	ND	ND	12
Pure tire chips with protruding wires	ND	ND	ND	5
2. Control Samples				
Cement	ND	ND	ND	133
Distilled water	ND	ND	ND	< 1

* Includes Cr (III) and Cr (VI), ND = Not detected.

TCLP Test: Recycled materials were subjected to the TCLP test. Results of the metal analysis on leachate solutions are summarized in Table 3.9.

(1) There was detectable Ba (II) and Cr (total) in the leachate of the recycled materials investigated. All the metal concentrations are far below the TCLP limit for barium concentration of 100 mg/L and chromium concentration of 5 mg/L.

(2) Only fluorogypsum had a detectable amount of Pb in the leachate. Detected concentration of Pb (II) was below the TCLP limit of 5 mg/L.

Table 3.9. TCLP Results for Recycled Materials

Materials	Ba (II) (mg/L)	Cr (*) (mg/L)	Pb (II) (mg/L)	Ca (II) (mg/L)	pH**
1. Recycled Materials					
Fly ash (Type B or Class-C)	0.16	0.22	ND	515	7.7
Fly ash (Type A or Class-F)	1.41	0.16	ND	569	8.9
Bottom ash	0.22	ND	ND	16	4.7
Fluorogypsum	0.09	0.11	1.56	422	4.6
Pure Tire chips	0.18	ND	ND	13	4.8
Tire chips with wires	0.20	ND	ND	57	6.0
2. Control Sample					
Cement	1.0	ND	ND	1300	11.0

* Includes Cr (III) and Cr (VI). ** Starting pH for the leaching solution was 5.0.
ND = Not detected

CONCLUSIONS

Fly ash (Type A and Type B), bottom ash, scrubber base (Type A and Type B), fluorogypsum and tire chips were randomly obtained from various locations in Texas and tested. Behavior of recycled materials with and without sand and Texas soils were also studied. Based on the experimental results the following observations are advanced:

(1) Fly ash Type A and Type B are non-plastic. Fly ash could affect the Atterberg limits of clayey soils (CH) and other recycled materials.

(2) Fly ash (Type B) had the highest dry density, and tire chips had the lowest. Addition of 30% fly ash (Type B) to the sand increased the dry density by 10% but reduced the dry density of Texas soils by 10%. With 30% tire chips in the sand and

Texas soils, maximum dry densities higher than 14.1 kN/m^3 (90 pcf) can be achieved.

(3) Blending fly ash with the soils and other recycled materials reduced the permeability of these materials. Fly ash (Type B) and fly ash (Type A) had varying effect on the magnitude of permeability when mixed with other materials. Addition of 20% fly ash to sand, Texas soil (K), bottom ash and scrubber base (F) increased the pH of the effluent to over 12.

(4) Addition of up to 30% fly ash improved the unconfined compressive strength (UCS) of sand and Texas soils. Addition of fly ash increased the UCS of bottom ash, scrubber base and fluorogypsum.

(5) Bottom ash and tire chip behavior was similar to that of cohesionless soils. Fly ash, scrubber base and fluorogypsum exhibited cohesion and friction under drained loading.

(6) All the recycled materials passed the TNRCC (7-Day Distilled Water Leachate Test) and TCLP leaching tests and qualified as Class 3 waste materials, which are non-hazardous. Sulfate attack on concrete structures and buried pipes when using fluorogypsum, scrubber base and fly ash may become a concern.

(7) Dust must be controlled during placement of some recycled materials, such as fly ash and fluorogypsum. Recycled materials can be conditioned with water prior to placement.

CHAPTER FOUR. SPECIFICATION FOR EMBANKMENTS WITH RECYCLED MATERIALS

Based on the literature review and the limited tests performed in this study, a proposed specification has been developed for use by the Texas Department of Transportation. This specification follows:

ITEM X
EMBANKMENTS WITH RECYCLED MATERIALS

X.1. Description This item shall govern the placement and compaction of selected recycled materials, with and without mixing with soil, for the construction of roadway embankments where the use of recycled material is determined to be appropriate by the Engineer.

X.2. Materials Recycled materials obtained by the Contractor must meet the requirements of the Texas Department of Transportation (TxDOT) and the Texas Natural Resources Conservation Commission (TNRCC). The Contractor shall be responsible for securing all necessary permits that may be required for the transport and storage of recycled materials from the TNRCC and other federal, state, regional, county, or city agencies that may have jurisdiction over such transport and storage. All recycled materials used in embankments shall be suitable for forming a stable embankment and, when tested in accordance with the TxDOT test methods, will have suitable index, physical and mechanical properties. The contractor is responsible for furnishing the Engineer with documentation certifying that the proposed material complies with 30 Texas Administrative Code (TAC) Section 335.507. The source shall be approved by the Engineer prior to use. Recycled materials specifically covered under this specification are tire chips, fly ash, bottom ash, scrubber base and fluorogypsum.

(1) Tire Chips The material obtained from used tires that are shredded into various sizes as specified by TNRCC. The largest allowable chip shall be 9 square inches on any one side or as specified by TNRCC. The maximum length of any one chip will be limited to the compacted thickness of the layer being compacted, or not more than 12 inches, unless otherwise approved by the Engineer. It is required that all chips be free of any contaminants, such as oil or grease, which could leach into the ground water. No loose metal fibers are allowed in the shredded tires, and all metal fibers that remain after shredding must have more than half of their lengths embedded within the tire chips.

(2) **Fly Ash** (Tex-100-E) The finely divided residue from the combustion of ground or powdered coal or lignite used in the generation of electrical power that is transported from the firebox through the boiler by flue gases. It does not include incinerator ash produced by industrial and municipal garbage.

(3) **Bottom Ash** (Tex-100-E) Heavy residue from the combustion of ground or powdered coal or lignite used in the generation of electrical power.

(4) **Scrubber Base** A blend of flue gas desulfurization (FGD) gypsum and fly ash. Generally they are mixed in equal proportions.

(5) **Fluorogypsum** A by-product of wet-process acid production from finely ground rocks. It is a calcium sulfate hydrate.

X.3. Construction Methods

(1) **General** The ground surface beneath the embankment shall be compacted by sprinkling and rolling at the locations shown on the plans in accordance with Item 132.3(1), or as required by the Engineer. Recycled materials shall be placed in the embankment in one of the following configurations: (i) in the core with or without encapsulation in geosynthetics, (ii) in alternate layers with soil or (iii) completely mixed with soil. The configuration of the embankment cross-section must be approved by the Engineer. All recycled materials shall be placed at least 3 feet above the water table unless otherwise directed by the Engineer. A soil cap shall be placed on the top of the embankment and on the slopes, and geosynthetics shall be used to separate the soil cover from the recycled materials if shown on the plans. When recycled materials are mixed with the soil, recycled materials shall constitute not more than 20% by volume of that portion of embankment exclusive of the cap. The actual percentage shall be as directed by the Engineer. More than 20% of the volume of the embankment not including the cap may be constructed of recycled material provided the Contractor demonstrates the constructability and performance of such embankment to the Engineer.

The Engineer shall be notified sufficiently in advance of construction operations of the source of the recycled material to allow for any required testing by the TxDOT or its representative. Unless otherwise shown on the plans, or specified by the Engineer, the construction methods shall be in accordance with Item 132.3.

Embankments shall be constructed to the grade and sections shown on the plans or as established by the Engineer. Each section of the embankment shall correspond to the detailed section or slopes established by the Engineer. After completion of the roadway, the embankment shall be continuously maintained to its finished section and grade until the project is accepted.

(2) Constructing Earth Embankments. Earth embankments shall be defined as those embankments composed principally of material other than rock, and shall be constructed of acceptable material from approved sources. The construction method with the recycled materials can be selected by the contractor to best suit the type of materials used and meet the density requirement specified for the project. The method of construction shall be submitted to the Engineer for approval. The Contractor shall use granular earth materials conforming to Item 132.2, Type A, where feasible. Where not feasible, the Contractor may use earth materials conforming to Item 132.2, Type B, except that rock shall not be used, as approved by the Engineer, or Type D if borrow areas are explicitly shown on the plans.

The recycled material used in the construction should not cause undue change, as compared to the background levels in the surface waters or ground water in the immediate vicinity of the embankment, of the pH, salt, metal or organic contents of the runoff, groundwater or any other source of water in the surroundings. The Contractor shall be prepared to instrument the embankment to demonstrate the quality of runoff water from the embankment and water percolating through the embankment after construction over a period of time specified by the Engineer. In all embankment construction with recycled materials a cover of at least 6 inches of compacted soil shall be provided along the slopes and at least two feet of compacted soil shall be provided on the base and top of the embankment, unless otherwise approved by the Engineer.

When "Ordinary Compaction" is specified, each embankment layer shall be rolled and sprinkled when and to the extent directed by the Engineer. When "Density Control" is specified, each layer shall be compacted to the required density as outlined for "Earth

Embankments," Item 132.3(2)(a), or as shown on the plans. The Engineer may require the layer to be proof rolled to insure proper compaction. Compaction requirements for embankments shall be as specified in Item 132.3(3). When "Density Control" is specified, reference density tests shall be conducted upon specimens of the earth material, the recycled material and any mixtures of earth material and recycled material that the Contractor uses in the embankment, and density percentages will be based upon such tests.

After each layer of earth embankment is complete, tests as necessary may be made by the Engineer. When the material fails to meet the density requirements or should the material lose the required stability, density, moisture or finish before the next layer is placed or the project is accepted, the layer shall be reworked as necessary to obtain the specified compaction, and the compaction method shall be altered on subsequent work to obtain the specified density. Such procedures shall be subject to the approval of the Engineer.

(3) **Tolerances**

The tolerances shall be in accordance with Item 132.4.

X.4. Measurement Payment for embankment will be as specified in Item 132.5, except as shown on the plans. The quantity of recycled materials to be paid for will be the actual number of cubic yards of approved material measured in trucks, which have been delivered to the construction site and incorporated into the completed and accepted embankment. Each truck will be measured by the Engineer and shall bear a legible identification mark indicating its capacity in cubic yards. Other measurements will be according to Item 132.5.

X.5. Payment The work performed and materials furnished in accordance with this Item and measured as provided under "Measurement" will be paid for at the unit price bid for "Embankment with recycled materials," of the compaction method, type and class of material specified. This price shall be full compensation for furnishing embankment; for hauling; for placing, compacting, finishing and reworking; and for all labor, royalty, tools, equipment and incidentals necessary to complete the work.

X.6. Special Notes.

[1] It is difficult at this time to assess the long-term risk to the environment from utilizing recycled materials in this application.

[2] The quality of recycled materials changes from batch to batch. The Contractor must develop a quality control plan acceptable to the Engineer.

[3] This specification does not address safety problems or environmental concerns, if any, associated with the use of recycled materials. It is the responsibility of the Contractor to establish appropriate safety and health practices and determine the applicability of other local, state or federal regulatory limitations prior to the use of recycled materials in any embankment.

[4] Fly ash (fine-grained and non-cohesive) is susceptible to liquefaction and frost heave when saturated. Hence, it is recommended that embankments with fly ash be well drained. Fly ash with cementitious properties are not susceptible to liquefaction.

[5] Dust must be controlled during placement of some recycled materials, such as fly ash and fluorogypsum, in order to avoid nuisance complaints and to protect worker and public safety. Recycled materials can be conditioned with water prior to placement.

[6] Sulfate attack on concrete structures and buried pipes when using fluorogypsum, scrubber base and fly ash may become a concern. The Contractor must take necessary precautions to control this attack.

Summary and Comments

Based on this study a general specification for the use of recycled materials in earth embankments was developed. For more detailed specifications based on individual materials, additional studies are recommended, including construction and monitoring of test embankments

New laboratory compaction procedures must be developed to determine the compacted densities of masses of larger tire chips. The Engineer with the help of the TNRCC representative must decide on the level of changes in the water quality that can be tolerated in the vicinity of the embankment. This should be based on the location of the embankment with respect to the closest community. No specific numbers could be assigned to the tolerance level at this time.

CHAPTER FIVE. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Millions of tons of non-hazardous, non-toxic solid waste materials are produced each year in Texas. Recycling and usage of these waste materials for various applications, especially in highway construction, is increasing around the nation. Proper usage of these recycled materials may lead not only to considerable savings but also to the solution of environmental problems. Because highways require large volumes of construction materials, highway agencies have become frequent participants in efforts to recycle and reuse waste materials.

The use of recycled materials in embankments in Texas will become popular only if specifications and guidelines to use these materials are developed. This study was undertaken to develop a specification for the use of recycled materials in earth embankments based on a literature review and limited laboratory tests. The literature review indicates that recycled materials have been used in earth embankments for the past thirty years. While fly ash was popular in the 1970's and 1980's, tire chips have become increasingly popular recently. Thirty nine case studies have been documented. Three types of embankment configurations have been used with the recycled materials. Placing the recycled material in the core of the embankment was the most popular. Use of recycled materials can either increase or decrease the cost of earth embankment construction, and the transportation cost is an important factor influencing the project cost.

Availability of recycled materials and their locations in Texas have been documented. Large quantities are still not effectively utilized. In the laboratory study, properties of fly ash, bottom ash, scrubber base, tire chips and fluorogypsum were evaluated by obtaining random samples of the materials from various parts of Texas. All of the recycled materials showed very low levels of contaminant leaching during the TCLP and TNRCC tests and were characterized as Class 3 non-hazardous waste materials. Behavior of recycled materials with and without soils was also studied. Clay (20%)-sand (80%) mixtures were used to represent the Texas soils. Behavior of the recycled materials are comparable to sand and Texas soils and hence, could be effectively incorporated into earth embankments. Based on the literature review and laboratory tests, a specification was developed.

RECOMMENDATIONS

In order to develop specifications based on the type of recycled material, additional studies are needed. The specification developed in this study could be used for developing the field studies. Future studies should at least include the following:

(1) Perform field studies to evaluate the various embankment configurations with actual Texas soils and recycled materials. Instrument the embankments to quantify the short-term and long-term settlements of the embankments stability of side slopes and to evaluate the leachate quality.

(2) Evaluate the long-term risk to the environment from utilizing recycled materials in this application.

(3) Develop a new compaction test to evaluate the densities of long tire chips with and without soils.

(4) Develop an assurance program to minimize the effects of variability of recycled material properties.

(5) Establish appropriate safety and health practices for handling recycled materials in embankment construction.

BIBLIOGRAPHY

1) Ahmed, I., and Lovell, C. W., "Use of Rubber Tires in Highway Construction," Proceedings, Utilization of Waste Materials in Civil Engineering Construction, ASCE, 1992, pp. 166-181.

2) Ahmed, I., and Lovell, C. W., "Rubber Soils as Lightweight Geomaterials," Transportation Research Record No. 1422, 1993, pp. 61-70.

3) Ahmed, I., "Laboratory Study on Properties of Rubber Soils," Ph.D. Thesis, Purdue University, 1993, 450 p.

4) Ahmed, I., and Lovell, C. W., "Use of Waste Materials in Highway Construction: State of the Practice and Evaluation of the Selected Waste Products," Transportation Research Record No. 1345, 1992, pp. 1-9.

5) Allen, T. M., and Kilian, A. P., "Use of Wood Fiber and Geotextile Reinforcement to Build Embankment Across Soft Ground," Transportation Research Record No. 1422, 1993, pp. 46-54.

6) Bacon, L. D., "Fly Ash for Construction of Highway Embankments," Proceedings, Fourth International Ash Utilization Symposium, Energy Research and Development Administration, Report No. MERC/SP-76/4, Morgantown, WV, 1976, pp. 262-292.

7) Blumenthal, M., and Zelibor, J. L., "Scrap Tires in Rubber-Modified Asphalt Pavement and Civil Engineering Applications," Proceedings, Utilization of Waste Materials in Civil Engineering Construction, ASCE , 1992, pp. 182-192.

8) Bloomquist, D., Diamond, G., Oden, M., Ruth, B., and Tia, M., "Engineering and Environmental Aspects of Recycled Materials for Highway Construction," Report No. FHWA-RD-93-088, Environmental Protection Agency and US Department of Transportation, June 1993, 212 p.

9) Bosscher, P. J., Edil, T. B., and Eldin, N. N., "Construction and Performance of a Shredded Waste Tire Test Embankment," Transportation Research Record No. 1345, 1992, pp. 44-52.

10) Bowders, J. J., Jr., Gidley, J. S., and Usmen, M. A., "Permeability and Leachate Characteristics of Stabilized Class F Fly Ash," Transportation Research Record No. 1288, 1990, pp. 70-77.

11) Cauley, R. F., "Use of Tire Chips in a Highway Embankment," Report No. U91-5, Virginia Department of Transportation, Materials and Research, 1991, 7 p.

12) "Coal Ash Utilization, Fly Ash, Bottom Ash and Slag," Pollution Technology Review No. 48, Noyes Data Corporation, New Jersey, 1978.

13) Collins, R. J., and Ciesielski, S. K., "Highway Construction Use of Wastes and By-Products," Proceedings, Utilization of Waste Materials in Civil Engineering Construction, ASCE, 1992, pp. 140-152.

14) Collins, R. J., and Ciesielski, S. K., "Recycling and Use of Waste Materials and By-Products in Highway Construction," NCHRP Synthesis 199, Transportation Research Board, National Academy Press, Washington, DC, 1994, 84 p.

15) DiGioia, A. M., Jr., and McLaren, R. J., "Case History: Fly Ash Structural Fill, Culver Road Embankment," Presented at West Virginia University, Short Course on Technology and Utilization of Power Plant Ash in Structural Fills and Embankments, August 13 - 16, 1978.

16) Eaton, R. A., Roberts, R. J., and Humphrey, D., N., "Gravel Road Test Sections Insulated with Scrap Tire Chips," Special Report 94-21, CRREL, August 1994, 52 p.

17) Edil, T. B., Bosscher, P. J., and Eldin, N. N., "Development of Engineering Criteria for Shredded or Whole Tires in Highway Applications," Geotechnical Testing Journal, Vol. 17, No. 4, 1992, pp. 453-464.

18) El Ghoche, H., Coulet, C., and Daudon, D., "Plastic Waste for Low-Weight Embankments," Proceedings, ASCE Conference on Grouting, Soil Improvement, and Geosynthetics, New Orleans, LA, 1992, pp. 1368-1379.

19) Eldin, N. N., and Piekarski, J. A., "Scrap Tires: Management and Economics," Journal of Environmental Engineering, Vol. 119, No. 6, 1993, pp. 1217-1232.

20) Eleazer, W. E., and Barlaz, M. A., "Technologies for Utilization of Waste Tires in Asphalt Pavement," Proceedings, Utilization of Waste Materials in Civil Engineering Construction, ASCE, 1992, pp. 193-201.

21) Etsuo, S., and Makoto, S., "A Study on Utilization of Fly Ash as Embankment Materials In Railway," Quarterly Journal of Railway Transportation Research Institute, Vol. 32, No. 4, 1991, pp. 244-250.

22) Faber, J. H., and DiGioia, A. M., "Use of Fly Ash in Embankment Construction," Transportation Research Record No. 593, 1977, pp. 13-19.

23) Forysth, R. A., and Eagan, Jr., J. P., "Use of Waste Materials in Embankment Construction," Transportation Research Record No. 593, 1977, pp. 3-8.

24) GAI Consultants, Inc., "High-Volume Fly Ash Utilization Projects in United States and Canada," Electric Power Research Institute, Report No. CS-4446, Project No. 2422-2, Feb. 1986, 109 p.

25) GAI Consultants, Inc., "Fly Ash Design Manual for Road and Site Applications," Vol. 1, Dry or Conditioned Placement, Electric Power Research Institute, Report No. CS-4419, Project No. 2422-2, Feb. 1986, 355 p.

26) GAI Consultants, Inc., "Ash Utilization in Highways: Pennsylvania Demonstration Project," Electric Power Research Institute, Interim Report No. GS-6431, Project No. 2422-19, 1989, 80 p.

27) Hannon, J. B., and Forsyth, R. A., "Fill Stabilization Using Non-Biodegradable Waste Products - Phase 1," Department of Transportation, Division of Highways, California, Report No. CA-DOT-TL-2124-1-72-25, August 1973, 37 p.

28) Harbuck, I. D., "Lightweight Foamed Concrete Fill," Transportation Research Record No. 1422, 1993, pp. 21- 28.

29) Hardcastle, J. H. and Howard, T. R., "Wood Fiber Fill to Reduce Airport Pavement Settlement," Transportation Research Record No. 1310, 1992, pp. 81-86.

30) Hoppe, E. J., "Field Study of a Shredded Tire Embankment," Interim Report, Virginia Transportation Research Council, FHWA/VA-94-IR1, 1994, 46 p.

31) Humphrey, D. N., Sandford, T. C., Cribbs, M. M., and Manion, W. P., "Shear Strength and Compressibility of Tire Chips for Use as Retaining Wall Backfill," Transportation Research Record No. 1422, 1993, pp. 29-35.

32) Humphrey, D. N., and Manion, W. P., "Properties of Tire Chips for Lightweight Fill," Proceedings, ASCE Conference on Grouting, Soil Improvement, and Geosynthetics, New Orleans, LA, 1992, pp. 1344-1355.

33) Indraratna, B., "Problems Related to Disposal of Fly Ash and its Utilization as a Structural Fill," Proceedings, Utilization of Waste Materials in Civil Engineering Construction, ASCE, 1992, pp. 274-285.

34) Jackson, N. C., "A Summary of The Use of Saw Dust for Highway Fills," Report No. 153, Materials Office, Washington State Department of Transportation, 1979, 14 p.

35) Kilian A. P., and Ferry, C. D., "Long-Term Performance Evaluation of Wood Fiber Fills," Washington State Department of Transportation, Report Nos. WA 75-04 & 05 Olympia, Washington, September 1991, 68 p.

36) Kilian, A. P., and Ferry, C. D., "Long-Term Performance of Wood Fiber Fills," Transportation Research Record No. 1422, 1993, pp. 55-60.

37) Kumar Mehta, P., and Monteiro, P. J. M., Concrete Structure, Properties, and Materials, Prentice Hall, Englewood Cliffs, New Jersey, 1993.

38) Kyper, T. N., "Institutional Constraints to the Use of Coal Fly Ash in Civil Engineering Construction," Prooceedings, Utilization of Waste Materials in Civil Engineering Construction, ASCE, 1992, pp. 32-43.

39) Lamb, R., "Using Shredded Tires as Lightweight Fill Material for Road Subgrades," Draft Report, Materials and Research Laboratory, Minnesota Department of Transportation, Maplewood, 1992, 18 p.

40) Lewis, T. S., "Construction of Fly Ash Roadway Embankment in Illinois," Transportation Research Record No. 593, 1977, pp. 20-23.

41) Little, D. N., "GSM Calcium Sulfate as an Embankment Material: A Summary Report," Texas Transportation Institute, College Station, 1987, 15 p.

42) Little, D. N., and Crockford, W. W., "Stabilization of Calcium Sulfate," Report for Gulf State Materials, Texas Transportation Institute, 1987, 111 p.

43) "Markets for Scrap Tires," Report EPA/530-SW-90-047B, Environmental Protection Agency, 1991.

44) Minnesota DOT, "Mn/DOT's Experience with Scrap Tires," Report from Materials Research and Engineering Laboratory, Maplewood, MN, 1994, 2 p.

45) Nelson, D. S., and Allen, Jr., W. L., "Sawdust as Lightweight Fill Material," Report No. FHWA-RD-74-502, Federal Highway Administration, Washington, DC, May 1974.

46) Ormsby, W. C., and Fohs, D. G., "Use of Waste and By-Products in Highway Construction," Transportation Research Record No 1288, 1990, pp. 47-58.

47) Pierre, J. J., and Thompson, C. M., "User's Manual, Coal - Mine Refuse in Highway Embankment," Report No. FHWA-TS-80-213, 1979, 194 p.

48) Recycle Texas, Texas Water Commission, 1991, LP 91-09, 417 p.

49) Read, J., Dodson, T., and Thomas, J., "Experimental Project: Use of Shredded Tires for Lightweight Fill," Post-Construction Report, Oregon Department of Transportation, Salem, Feb. 1991.

50) Stinnett, B. C., "Construction of Fly ash Embankment in Kanawha County, West Virginia," Presented at the Ninth Annual Southeastern Transportation Geotechnical Engineering Conference, Hot Springs, Arkansas, October 25-28, 1977.

51) Taha, R., Seals, R. K., Tittlebaum, M. E., Thornsberry, W., Jr. and Houston, J. T., "Use of By-Product Phosphogypsum in Road Construction," Transportation Research Record No 1345, 1992, pp. 28-35.

52) Texas Recycles 2, Marketing Our Neglected Resources, Texas General Land Office, 1994, 106 p.

53) Upton, R. J., and Machan, G., "Use of Shredded Tires for Lightweight Fill," Transportation Research Record No. 1422, 1993, pp. 36-45.

54) "Uses of Recycled Rubber Tires in Highways," NCHRP Synthesis 198, Transportation Research Board, National Academy Press, Washington, DC 1994.

55) "Virginia Embankment: Where the Rubber Really Meets the Road," Engineering News Record, Sept. 20, 1993.

56) Waste Tires in Subgrade Road Beds, Minnesota Pollution Control Agency, St. Paul, 1990, 70 p.

57) Yee, W. S., "Fill Stabilization Using Non-Biodegradable Waste Products- Phase 2," Report No. FHWA/CA/TL-79/22, California Department of Transportation, Nov. 1979, 110 p

APPENDIX

(A1) CASE STUDIES

(A2) RECYCLED MATERIAL PROPERTIES

(A3) RECYCLED MATERIALS IN TEXAS

CASE STUDY [1]. 1/90
RAMSAY COUNTY, MINNESOTA

1. LOCATION: Local roadway in Ramsay County. Road No. 59, near St. Paul, Minnesota.

2. NATURE OF THE PROBLEM: The road passes over mucky low lying area with high water table. It experienced excessive settlements and in 1990 required reconstruction.

3. RECYCLED MATERIALS USED: Shredded waste tires and wood chips.

4. QUANTITY USED: 4,725 cubic yards of shredded tires

5. SPECIFICATION: Standard specifications were not reported.

Construction: **[1]** Shredded tires were to be placed at least 3 feet above the water table.
[2] The shredded tire embankment was required to be encapsulated in a geotextile cover.
[3] D8 dozer was required for the compaction of the fill.
Materials: **[1]** 3x3 inch tire shreds were to be used. **[2]** Majority of the steel wires were to be embedded in the chips.

6. PROPERTIES OF RECYCLED MATERIALS: Not reported. Shredded tire size as reported in the specifications.

7. CONSTRUCTION PROCEDURE: Existing material was excavated to a depth of 5 feet. A geotextile fabric was placed at the bottom and sides of the excavation. Next, the wood chips were placed to a depth of one foot above the water table. The shredded tires were then placed over the top of the wood chips and compacted to a depth of 3 feet below the original roadway elevation using a D8 dozer. Top layer of the geotextile fabric was then laid and sewn to the bottom layer in order to encapsulate the fill. A 3 foot layer of granular material, 6 inches of base and 5.5 inches of bituminous wearing course were placed on the shredded fill.

8. EMBANKMENT CONFIGURATION: Type B.

9. ENVIRONMENTAL NOTE: Details pertaining to the environmental monitoring were not reported.

10. COST:

Material: Details not available **Construction:** Details not available

11. PERFORMANCE HISTORY: Not available

12. REFERENCES :

(1) Ahmed, I., "Laboratory Study on Properties of Rubber Soils," Ph.D. Thesis Purdue University, 1991, 450 p.

(2) Lamb, R., "Using Shredded Tires as Light Weight Fill Material for Rubber Subgrades," Draft Report, Materials and Research Laboratory, Minnesota Department of Transportation, Maplewood, 1992, 18 p.

13. SPECIAL NOTE: This project was one of the 22 shredded tire embankments constructed in Minnesota from 1982 - 1994.

CASE STUDY [2]. 1/91
BENTON COUNTY, MINNESOTA

1. LOCATION: County State Aid Highway 21, North of Rice, which is in the Northwest corner of Benton County, Minnesota

2. NATURE OF THE PROBLEM: Roadway was across a swamp that is underlain with peat and muck. Original construction across the swamp was stable but an addition to raise the roadway level in order to save it from the rising water level in the swamp overloaded the embankment and subsequently failure occurred.

3. RECYCLED MATERIALS USED: After performing cost/benefit analysis, a recommendation for shredded tires was proposed.

4. QUANTITY USED: 52,000 tires or 1200 cubic yards of shredded tires were used.

5. SPECIFICATIONS: Standard specifications were not reported.

Construction: **[1]** Shredded tires were to be placed in 2-foot lifts. **[2]** A geotextile was needed both at the base and the top of the shredded tire fill. **[3]** A minimum of 3 feet of soil cap was required.

Materials: **[1]** Largest allowable piece was 8 inch square or round, and longest piece allowed was 12 inch long. **[2]** It was required that the chips be free of any contaminants such as oil or grease that could leach into the groundwater. [3] Metal fragments* were to be firmly attached and 98% embedded in the tire section. All pieces had to have at least one side wall severed from the face of the tire.

* refers to metal fragments that might be projecting out of the tire chips

6. PROPERTIES OF RECYCLED MATERIALS: No laboratory properties were reported. Details pertaining to the shredded tires are mentioned in the specifications.

7. CONSTRUCTION PROCEDURE: About a 250 foot portion of the roadway was distressed. This distressed portion was excavated and then a geofabric was installed directly over the swamp soil. Shredded tires were then placed in 2-foot lifts up to about 3.5 feet below the subgrade level.

After the tire shreds were compacted using a dozer, an additional layer of fabric was installed before placing a 3.5-foot clean granular soil cap.

8. EMBANKMENT CONFIGURATION: Type B.

9. ENVIRONMENTAL NOTE: No details available pertaining to the environmental monitoring except that the specifications required the tire chips to be clean and free of loose metal fiber.

10. COST: **Material:** Details not available **Construction:** Details not available

11. PERFORMANCE HISTORY: The embankment has been reported to be performing well to date.

12. REFERENCES:

(1) Lamb, R., "Using Shredded Tires as Light Weight Fill Material for Rubber Subgrades," Draft Report, Materials and Research Laboratory, Minnesota Department of Transportation, Maplewood, 1992, 18 p.

(2) Public Works, "Tire Fill Stabilizes Road Way Embankment," Vol. 120, No. 11, 1990, 68 p.

13. SPECIAL NOTE: This project was one of the 22 shredded tire embankments constructed in Minnesota between 1982 and 1994.

CASE STUDY [3]. 2/90
EDEN PRAIRIE, MINNESOTA

1. LOCATION: A local road embankment project in Eden Prairie near Minneapolis, Minnesota.

2. NATURE OF THE PROBLEM: The original fill placed over a swamp containing 40 ft. of soft organic soil failed during construction. Three years after the fill was corrected and reconstructed, the road bed was still settling at an average rate of 1 foot per year. Hence, it was required to replace this fill with a lightweight fill.

3. RECYCLED MATERIALS USED: It was decided to use shredded tire lightweight fill to correct the subsidence problem.

4. QUANTITY USED: 4,100 cu yards or 118,000 tires of shredded tires were used.

5. SPECIFICATIONS: Standard specifications were not reported.

Construction: **[1]** Shredded tires were required to be placed in 3 foot lifts. **[2]** A D8 dozer was required for compaction. **[3]** A soil cap at least 3 feet thick was required to be placed over the lightweight fill.
Materials: **[1]** The size of the shredded tires required was 6 - 8 inches wide and 12 - 24 inches long. **[2]** No loose metal fibers were allowed in the shredded tires.

6. PROPERTIES OF THE RECYCLED MATERIALS: No laboratory properties were reported. Size of the tire chips used were as per required in the specifications.

7. CONSTRUCTION PROCEDURE: The original fill was excavated to a depth of 10 - 14 ft and the shredded tires were placed in 2 - 3 ft lifts and compacted by a D8 dozer to a density of 40-45 pcf. A geotextile fabric was placed over the tire shreds and a 4 ft. layer of common borrow was then placed over the fabric. After 3 weeks, 12 inches of crushed limestone was graded over the fill material, followed by 3.5 inches of bituminous base course. The wearing course was laid in the ensuing spring.

8. EMBANKMENT CONFIGURATION: Type B.

9. ENVIRONMENTAL NOTE: No details of environmental monitoring were reported.

10. COST: **Material:** Details not available **Construction:** Details not available

11. PERFORMANCE HISTORY: Settlement plate data indicated that the fill was performing very well, and over a period of 19 months the roadway settled at a rate of 0.9 inches per year and the bottom of the fill settled about 0.4 inches per year. This shows that the settlement below the embankment has been arrested to a certain extent due to the lightweight fill.

12. REFERENCES:

(1) Lamb, R., "Using Shredded Tires as Light Weight Fill Material for Rubber Subgrades," Draft Report, Materials and Research Laboratory, Minnesota Department of Transportation, Maplewood, 1992, 18 p.

(2) Public Works (1990), "Tire Fill Stabilizes Road Way Embankment," Vol. 120, No. 11, 68 p.

13. SPECIAL NOTE: This was one of the 22 lightweight shredded tire embankments that were constructed in Minnesota between 1982 and 1994.

CASE STUDY [4]. 2/91
PRIOR LAKE, MINNESOTA

1. LOCATION: A new alignment of the intersection of Duluth and Tower Avenues in Prior Lake a suburb of Minneapolis.

2. NATURE OF THE PROBLEM: The intersection passed over a wetland area with 30 feet of organic deposits.

3. RECYCLED MATERIALS USED: After analyzing various options, it was found that shredded tires as a lightweight fill would be beneficial. The tire fill was laid over a foot of wood fiber fill.

4. QUANTITY USED: About 9,600 cubic yards of tire chips the equivalent of 432,000 tires were used.

5. SPECIFICATIONS: No standard specifications were available.

Construction: [1] The shredded tire fill was required to be laid at least 3 feet above the water table, and a geotextile was required to be used below the fill. [2] A D8 dozer was required to be used for compaction. [3] A soil cap at least 3 feet thick was required.
Materials: 4 inch tire shreds were required to be used.

6. PROPERTIES OF THE RECYCLED MATERIALS: No laboratory properties were reported.

7. CONSTRUCTION PROCEDURE: A geotextile fabric was placed over the wetland soil and then the wood chips were compacted to an elevation of 1 foot above the water table level. After this, the shredded tires were compacted using D8 dozers and loaders. The tire fill was then covered with 3 feet of granular fill and a base layer.

8. EMBANKMENT CONFIGURATION: Type B.

9. ENVIRONMENTAL NOTE: No details reported pertaining to environmental monitoring.

10. COST: **Material:** Details not available **Construction:** Details not available

11. PERFORMANCE HISTORY: A plate load test applied directly on top of the shredded tires indicated that the tire material was compressible and displayed a very low modulus.

12. REFERENCE: Lamb, R., "Using Shredded Tires as Light Weight Fill Material for Rubber Subgrades," Draft Report, Materials and Research Laboratory, Minnesota Department of Transportation, Maplewood, 1992, 18 p.

13. SPECIAL NOTE: This was one of the 22 lightweight shredded tire embankments constructed in Minnesota between 1982 and 1994.

CASE STUDY [5]. 3/91
LAKE COUNTY, MINNESOTA

1. LOCATION: Lake County State Highway No. 7, near Finland, Minnesota.

2. NATURE OF THE PROBLEM: Original embankment section built over peaty soil had experienced excessive settlements and needed reconstruction.

3. RECYCLED MATERIALS USED: After considering various options the County decided to construct the road using shredded tires.

4. QUANTITY USED: 3,900 cubic yards of shredded tires, the equivalent of 175,000 tires were used.

5. SPECIFICATIONS: No standard specifications reported.

Construction: [1] The road had to be constructed over the existing subgrade. [2] A soil cap was required, in addition to a geotextile, on the top of the fill.
Material: Large-sized tire shreds were used, ranging between 4x12 inches to 1/4th of the whole tire.

6. PROPERTIES OF THE RECYCLED MATERIALS: No laboratory properties were reported.

7. CONSTRUCTION PROCEDURE: The road was constructed over the existing subgrade. Shredded tires were laid and compacted to a height of 4 feet. After this, the fill was capped with a layer of geotextile fabric and above this 1.5 feet of gravel was compacted.

8. EMBANKMENT CONFIGURATION: Type B.

9. ENVIRONMENTAL NOTE: No details are available pertaining to environmental monitoring.

10. COST: **Material:** Details not available **Construction:** Details not available

11. PERFORMANCE HISTORY: After 2 years, the County reports no noticeable settlement of the road section containing tire chips.

12. REFERENCE: Lamb, R., "Using Shredded Tires as Light Weight Fill Material for Rubber Subgrades," Draft Report, Materials and Research Laboratory, Minnesota Department of Transportation, Maplewood, 1992, 18 p.

13. SPECIAL NOTE: Unlike the other cases, this fill was constructed over the original grade surface.

CASE STUDY [6]. 4/91
MILAKA, MINNESOTA

1. LOCATION: Distressed portion of the embankment is located on a road known as Esker Trail passing over wetlands in Milaka County.

2. NATURE OF THE PROBLEM: A 200-foot section of a gravel road passed over a section of wetland containing unsuitable peaty soil. Large settlements occurred in this section.

3. RECYCLED MATERIALS USED: Lightweight fill consisting of shredded tires was proposed.

4. QUANTITY USED: 3,000 cubic yards of shredded tires.

5. SPECIFICATIONS: Standard specifications were not available.

Construction: [1] A geotextile layer was required to be laid over the wetland soil before placement of the shredded tire fill. [2] A soil cap was required for the fill.
Material: No details available

6. PROPERTIES OF RECYCLED MATERIALS: None reported

7. CONSTRUCTION PROCEDURE: First, a layer of geotextile fabric was laid over the peaty wetland. Then, shredded tires were placed and compacted to a height of 3 feet. This was topped with a second layer of geotextile fabric followed with 1.5 feet of common borrow. Finally, the fill was capped with 6 inches of gravel.

8. EMBANKMENT CONFIGURATION: Type B

9. ENVIRONMENTAL NOTE: Details pertaining to environmental monitoring have not been reported.

10. COST: **Material:** Details not available **Construction:** Details not available

11. PERFORMANCE HISTORY: Post construction settlement was 40-50% less than that expected if a mineral fill would have been used.

12. REFERENCES: Lamb, R., "Using Shredded Tires as Light Weight Fill Material for Rubber Subgrades," Draft Report, Materials and Research Laboratory, Minnesota Department of Transportation, Maplewood, 1992, 18 p.

13. SPECIAL NOTE: This project was undertaken by the Minnesota Department of Natural Resources.

CASE STUDY [7]. 2/91
ORANGE COUNTY, NORTH CAROLINA

1. LOCATION: State Highway 54 in Orange County, North Carolina.

2. NATURE OF THE PROBLEM: This was an experimental project initiated by the North Carolina Department of Transportation with the assistance of the Federal Highway Administration to determine feasible usage of recycled materials in highway embankments. It consisted of widening 2.18 miles of a two-lane segment to a four-lane divided highway. The project received experimental status from the FHWA due to the use of special products.

3. RECYCLED MATERIALS USED: Shredded tires mixed with soil.

4. QUANTITY USED: About 65,000 tires were used (this quantity is equivalent to 1,250 cubic yards of shredded automobile tires or 5,000 cubic yards of whole tires).

5. SPECIFICATIONS: Standard specifications were not applicable to this work.

Construction: [1] Shredded tires shall not be placed within three 3 feet of the outside limits of embankment and within 4 feet of subgrade, or below the water level of the surrounding area. [2] Embankment shall be constructed by placing alternate layers of shredded tires and soil and mixing and blending them together during compaction. [3] The embankment shall be manipulated sufficiently to minimize voids. [4] The thickness of the uncompacted layers of shredded tires and soil shall be as directed by the Engineer. Shredded tires shall constitute between 10-40% by volume of that portion of embankment, achieving an average of 25%. The actual percentage shall be as directed by the Engineer. [5] The compaction shall be to the satisfaction of the Engineer.

Materials: [1] The material shall be from waste tires that shall be shredded to sizes ranging between 1 inch and 3 inch. [2] The Contractor shall be responsible for securing all necessary permits that may be required for the transport and storage of shredded tire material from the North Carolina Department of Environment, Health and Natural Resources, Solid Waste Section.

6. PROPERTIES OF RECYCLED MATERIALS: Not reported. Shredded tire size as mentioned in specification (1 to 3 inches).

7. CONSTRUCTION PROCEDURE: No additional details on construction procedures were available, but it is known that the first layer was a soil layer and then shredded tires were laid in alternate layers. Compaction, mixing and blending of both the layers was carried out by a dozer.

8. EMBANKMENT CONFIGURATION: Type A, Type B, Type C.

9. ENVIRONMENTAL NOTE: Necessary permits for the transportation and storage of the shredded tire material were obtained from the NC Department of Environment, Health and Natural Resources, Solid Waste Section.

10. COSTS:

Materials: **[1]** The quantity of shredded tires to be paid for will be the actual number of cubic yards of approved material measured in trucks, which has been delivered and incorporated into the completed and accepted work. **[2]** Each truck will be measured by the Engineer and shall bear a legible identification mark indicating its capacity. **[3]** Payment for the shredded tires for the embankment shall be full compensation for furnishing, placing, manipulating the soil and shredded tires to minimize voids, and compacting the material. [4] Shredded tire cost was $20/cubic yard.

Construction: When compared to the conventional items (borrow excavation at $3.29/cy) this project resulted in an additional cost of $29,000 to complete.

11. PERFORMANCE HISTORY: Not available

12. REFERENCE: Whitmill, M. E., "Recycling for Transportation", Project U-2003AA, State Project No. 8-1500605, North Carolina Department of Transportation, Raleigh, NC, 1991, 28 p.

13. SPECIAL NOTES: Statement from the Division of Environmental Management is summarized as follows:

[1] In applications where tires or tire-based products are used instead of stone aggregate, soil, or wood, the potential for increased environmental impact seems likely.

[2] It is difficult at this time to assess the risk to the environment from utilizing tires in these applications versus the benefit of reducing landfill space required for their disposal.

[3] Soil samples should be taken at a depth of 1 to 3 feet below the fill materials. Sampling should be conducted initially and at the end of one year. The need for stream and/or sediment sampling may be determined on a case-by-case basis, depending on the likelihood of direct runoff from the shredded tire fill area to a stream.

[4] Monitoring of the following metals and organics is recommended:
Metals: arsenic, cadmium, chromium, iron, lead, zinc, barium.
Organics: total petroleum hydrocarbons, poly aromatic hydrocarbons, benzthiazole, 2-(4-morpholinyl)-benzthiazole (Note: first determine whether these chemicals will be leached from the used tire).

CASE STUDY [8]. 3/90
ROSEBURG, OREGON

1. LOCATION: US Highway 42, Oregon State Route No. 35, Coos Bay - Roseburg, approximately 25 miles west of Roseburg, Oregon.

2. NATURE OF THE PROBLEM: As part of an improvement project on US Highway 42, an existing highway embankment 11 feet deep was widened 20 feet and raised 4 feet. The additional embankment load remobilized an old landslide that moved progressively downslope perpendicular to the highway to a small creek running parallel to the highway. Geotechnical analysis suggested reduction of embankment weight and construction of a counter-balance berm between the embankment toe and the creek. It was proposed to reduce the weight using light-weight recycled material.

3. RECYCLED MATERIALS USED: It was proposed to use shredded tires along with French drains at the bottom of the embankment.

4. QUANTITY USED: The design called for replacement of 12,800 cubic yards of existing soil with 5,800 tons of shredded tires (about 580,000 tires).

5. SPECIFICATIONS:

Construction: **[1]** The tire chips were required to be placed in 2 - 3 foot lifts and each lift was required to be compacted by at least 3 passes of a D8 dozer. **[2]** A soil cap was required on the top of the tire fill and slopes. **[3]** A Geotextile was needed to separate the soil cap from the tire chips. **[4]** An effective drainage system was required to be designed so that the groundwater would not rise into the tire fill.

Materials: **[1]** The tire chip size specification required 80 percent to be smaller than 8 inches and 50 percent to be larger than 4 inches. The maximum size was 24 inches. **[2]** A rock blanket capped with a geotextile was designed for drainage.

6. PROPERTIES OF RECYCLED MATERIALS: No laboratory properties were reported.

7. CONSTRUCTION PROCEDURE: The embankment construction was completed in two stages to allow traffic on one-half of the embankment when the other half was under construction. Shredded tires were brought to the construction site from four different vendors located 150-250 miles from the project site. Dump trucks were employed for this.

A D8 dozer was used for spreading and compacting the chips. The shredded tires were placed in 2-3 foot lifts and each lift was compacted with three coverages of the dozer. The in-place density achieved was about 45 pcf. After the desired height of the tire chip fill was reached, a layer of geotextile was laid over the top surface and then capped with 3 feet of soil, 23 inches of aggregate base and 6 inches of asphaltic concrete. After 3 months of traffic, the inplace density achieved was 52 pcf. The slopes of the embankment were cut to shape and then capped with a layer of geotextile and soil.

A drainage blanket consisting of free-draining rock between two layers of geotextile was placed beneath the shredded tire embankment and the berm in order to prevent the groundwater table from rising into the embankment. Three 10-foot-deep French drains were located beneath the blanket to enhance the subsurface drainage. The final pavement constructed over the embankment was heavily instrumented with slope inclinometers, settlement plates and survey monuments.

8. EMBANKMENT CONFIGURATION: Type A.

9. ENVIRONMENTAL NOTE: No environmental concerns were reported

10. COST: **Material:** $ 30/ton **Construction:** $ 8.33/ton
These are costs after considering the incentives offered by the Department of Environmental Quality.

11. PERFORMANCE HISTORY: It was observed that the thickest portion of the shredded tire fill compressed 13.4%. Deflection testing was conducted using a falling weight deflectometer. The average deflection of the pavement over the rubber tire fill was approximately 0.020 inch compared to a typical deflection of 0.010 inch normally measured for a similar asphaltic concrete and aggregate base pavement constructed over a conventional soil subgrade.

12. REFERENCES:

(1) Upton, R. J. and Machan, G., "Use Of Shredded Tires For Light Weight Fill," Transportation Research Record No. 1422, 1993, pp. 36-45

(2) Ahmed, I., "Laboratory Study on Properties of Rubber Soils," Ph.D. Thesis, Purdue University, 1991, 450 p.

13. SPECIAL NOTE: This project was funded by the FHWA as part of the Experimental Projects program. The cost of the project was comparatively small due to a rebate offered by the Department of Environmental Quality.

CASE STUDY [9]. 1/92
ADAMS COUNTY, COLORADO

1. LOCATION: The problem location is in between Huron Street and Broadway on Colorado's new Interstate I-76, which is a four-lane highway connecting Denver to Nebraska.

2. NATURE OF THE PROBLEM: A 200-foot strip of I-76 crosses an old sanitary landfill on which roads built several years ago sunk as much as six feet. In order to minimize settlements, a lightweight fill was necessary. Lightweight recycled materials were proposed to be used.

3. RECYCLED MATERIALS USED: Shredded tires were obtained from Denver-Arapahoe Disposal Site and Recycling center near Lowry Landfill, which has about 8 million tires stockpiled.

4. QUANTITY USED: About 500,000 tires shredded to 10,000 cubic yards were used, the equivalent of 700,000 cubic yards of soil fill.

5. SPECIFICATIONS :

Construction: [1] Shredded tires were required to be laid on top of a geofabric spread on the unsuitable soil. [2] Each lift of tire chips was required to be 2-feet thick or less, compacted and kneaded into place by 3 passes of a D8 dozer or equivalent type of tracked dozer.
Materials: 4-inch-size shredded chips were recommended.

6. PROPERTIES OF RECYCLED MATERIAL: Laboratory properties were not available.

7. CONSTRUCTION PROCEDURE: A layer of geofabric was first laid on the ground to serve as a blanket for the recycled material. Shredded tires were then placed as per the specifications on top of the geofabric to build a 5-foot-high and 300-foot-wide embankment. Each layer of tire fill was to be compacted and kneaded into place by 3 passes of a D8 or equivalent type tracked dozer. The shredded tire fill was deposited in layers of 2 feet or less in thickness before compaction. Once the embankment reached the required height of 8 feet, the fabric was folded to cover the entire mass to separate it from the overburden soil. Final pavement was placed after sufficient settlement of the fill. To speed up the settlement, additional soil layers were laid, which were later removed.

8. EMBANKMENT CONFIGURATION: Type A.

9. ENVIRONMENTAL NOTE: None reported.

10. COST: **Material:** Free **Construction:** Transportation: $ 60,000, actual construction cost not available at present.

11. PERFORMANCE HISTORY: The fill has been monitored using inclinometers to study the lateral movements. The project was completed in 1993 and is reported to be performing well.

12. REFERENCES: (1) Waste Watchers Newsletter (April/May 92)
(2) Rocky Mountain News (Thursday, Jan. 2, 1992)

13. SPECIAL NOTE: It was reported by Chief Geologist, J. B. Gilmore that, although projects utilizing shredded tires helped the environment, the total cost of the project was higher than those using ordinary fill material due to the transportation costs.

CASE STUDY [10]. 1/86
HOQUIAM, WASHINGTON

1. LOCATION: A portion of a new highway, State Route 109. The new 2.86 km segment of the two-lane highway begins just outside the western city limits of Hoquiam and extends north-easterly, connecting with SR101.

2. NATURE OF THE PROBLEM: The southern end of the highway begins near sea level and traverses undeveloped timber and swampland. Initially, the roadway made a 56 m cut through a bluff. Then for about 180 m it crosses a swampland, which is the subject site area , and continues through a cut across the Little Hoquiam River with side hill cuts and fills. Since much settlement was anticipated with conventional material on the swamp land, an alternative lightweight material was suggested.

3. RECYCLED MATERIALS USED: Wood fiber

4. QUANTITY USED: Not available

5. SPECIFICATIONS: Specifications developed by Washington DOT for wood fiber fills were used.

Construction: [1] For the installation of the geotextile, specifications mentioned in the FHWA Geotextile Engineering Manual were required to be used. [2] A minimum of 2 feet of soil cover was required on the slopes.[3] Gravel burrow was required to be compacted in 20 cm lifts to 90% of maximum relative density. [4] Lift thickness allowed for wood fiber fill was 1.0 m or 3 feet.
Materials: [1] The wood fibers to be used in the embankment were to be well graded, ranging in size between 1.3 cm and 5 cm. [2] The wood fiber to be used in the fill had to be fresh and showing no signs of decay.

6. PROPERTIES OF THE RECYCLED MATERIAL: .The gravel borrow used was a silty minus 3.2 cm gravely sand. The tensile strength of the geotextile was 23 kN/m. The compacted unit weight of the wood fibers ranged from 6.0 kN/m^3 - 6.3 kN/m^3.

7. CONSTRUCTION PROCEDURE: Six geotextile reinforcement layers were used. The minimum weight of the hauling equipment used to compact the fill was 15T. The wood fiber fill was compacted by routing the hauling equipment a minimum of two times with complete coverage over each lift. The slopes of the embankment were limited to 2H:1V. Embankment construction rate was decided by the pore pressure response of the foundation soils to embankment loading. The ratio of pore pressure increase to the maximum embankment vertical load was required to be 0.33 or less to ensure embankment stability during construction.
A working platform of 15 cm of granular soil with enough thickness to cover all stumps, logs and other protrusions was laid to preserve the root mat and minimize damage to the first geosynthetic layer. The bottom 1.5 m and the top 1.2 m of the 13.5 m-high embankment was constructed of silty gravely material. The gravel borrow was laid in 20 cm lifts and compacted to 90% of maximum relative density.

8. EMBANKMENT CONFIGURATION: Type A & B.

9. ENVIRONMENTAL NOTE: Details pertaining to environmental concerns were not reported, except that water samples taken upstream and downstream of the site indicated no difference in water quality from any leachates.

10. COST: The project cost was $972,221, which represented about $500,000 in savings compared with the next lowest cost alternative, i.e., ground improvement, and $700,000 less than a bridge.

11. PERFORMANCE HISTORY: The wood fiber fill was completed to subgrade level in September, 1987. Paving began more than 1 year later, in October 1988. Fill settlement, was 0.97 m when subgrade level was reached. Before paving, fill settlement had increased to 1.2 m. Total settlement is projected to reach 1.5 m. The performance of the wood fiber fill has been excellent. Samples of 5-year-old wood fiber were exhumed from below the 0.6 m top soil cover and found to be nearly fresh. The pavement to date has shown no signs of distress despite settlement and predominantly logging truck traffic.

12. REFERENCE: Allen, T. M., and Killian, A. P., "Use of Wood Fiber and Geotextile Reinforcement to Build Embankment Across Soft Ground", Transportation Research Record No. 1422, pp. 46-54.

13. SPECIAL NOTE: None

CASE STUDY [11]. 1/87
BENEWAH COUNTY, IDAHO

1. LOCATION: Benewah County airport, which is located in the flood plain inside a meander bend of the St. Joe River near St. Maries, Idaho.

2. NATURE OF THE PROBLEM: One of the runways and apron pavement, which were constructed in 1977 over an unknown thickness of peaty, silty and clayey flood plain deposits settled more than 2 ft and in 1987 required reconstruction.

3. RECYCLED MATERIALS USED: Wood fiber.

4. QUANTITY USED: Not available.

5. SPECIFICATIONS: Standard specifications were not reported.

Construction: [1] The uncompacted wood fiber material was required to be placed in lifts not more than 1 foot thick. [2] Each lift was required to be compacted by 2 passes of a crawler type tractor weighing equal to a D7 caterpillar . [3] The embankment was required to be encapsulated.
Material: No material requirements were reported.

6. PROPERTIES OF THE RECYCLED MATERIAL: In this project a comprehensive laboratory study was conducted at the University of Idaho. Wood chips used were of an average 1-in. size. The dry unit weights ranged from 13.0 to 14.0 pcf. Triaxial tests performed on a 4 in. x 8 in. sample showed that, at 5% and 20% strains, the shear strength was 4 psi and 8 psi, respectively and the corresponding angle of internal friction was 10° and 30°. Specific gravity obtained was 1.10.

7. CONSTRUCTION PROCEDURE: Because the AASHTO impact compaction methods do not produce unit weights as high as those obtained by static compaction, and because it is difficult to measure in-situ densities of the wood fiber material, compaction specifications were stated in terms of a method rather than an end result. Compaction requirements recommended that the uncompacted material be placed in lifts not more than 1 ft deep and should be compacted by rolling the surface of each lift by 2 passes of a crawler-type tractor or dozer of weight equal to or greater than a D7 caterpillar .

The average height of the wood fiber fill was 8 feet The average unit weight in the unsoaked condition was 55 pcf and in the soaked condition it was 5 pcf. About 5 ft of the wood fiber fill was confined in the excavation and above the fill; 3 ft of ballast was placed at an average density of 138 pcf before finally laying the pavement. All surfaces of the wood fiber fill were covered with at least 12" of compacted, well-graded crushed granular material to protect the fill from possible fire and also to protect it from the aerobic conditions, which will lead to decomposition.

8. EMBANKMENT CONFIGURATION: Type A.

9. ENVIRONMENTAL NOTE: Environmental concerns not reported.

10. COST: **Material:** $3 per cubic yard **Construction:** Details not available

11. PERFORMANCE HISTORY: Elevation measurements made on the runway surface 15 months after paving showed that the settlements of sections containing wood fill ranged between 0.03 ft to 0.4 ft. Settlements ranged between 0.07 ft to 0.5 ft after 32 months. It has been observed that the compacted wood fiber fill has substantial strength at large strains. Compressibility and creep susceptibility of the wood fibers were found to be comparable to levels usually observed for fine grained soils.

12. REFERENCE: Hardcastle, J. H., and Howard, T. R., "Wood Fiber Fill to Reduce Airport Pavement Settlement," Transportation Research Record No. 1310, 1991, pp. 81-86.

13. SPECIAL NOTE: None

CASE STUDY [12]. 4/90
DANE COUNTY, WISCONSIN

1. LOCATION: Embankment was constructed parallel to an access road by a sanitary landfill at Dane County Landfill No. 2 near Madison, Wisconsin. This site offered a sufficient supply of tire chips to be tested and an abundant soil source.

2. NATURE OF THE PROBLEM: This was a demonstration/research project.

3. RECYCLED MATERIAL USED: Rubber tire chips.

4. QUANTITY USED: Not available.

5. SPECIFICATIONS:

Construction: Not available.
Materials: Not available.

6. PROPERTIES OF THE RECYCLED MATERIALS: The density achieved during construction was monitored by computing unit weights from a record of the weights of the soils and chips used and the embankment dimensions. Sand used in inter-layering with the tire chips was not compacted as well as the top cap sand layer. Densities of the tire chips obtained varied between 20 pcf and 35 pcf. In the chip-sand mix the density obtained was 75 pcf. The inter-layering soil in the alternate chip-soil layers was about 60 pcf compared to the top cap sand layer compacted at a density ranging between 105 and 111 pcf.

7. CONSTRUCTION PROCEDURE: On the basis of site geometry and the number of variables, the test embankment was divided into 8 sections, each 20 foot long, 40 ft. wide at the base, 16 ft. wide at the top and having a height of 6 feet. The side slopes are 2H:1V. Three soil-chip compositions were adopted for study: pure tire chips, tire chips mixed with soil, and tire chips layered with soil. For the chip-soil mixture, a ratio of 50% tire chips and 50% sand was chosen. The layered tire chip and soil section was built by placing alternate 1-ft lifts of tire chips and sand.

After scraping of the surface of the organic soil, an elevation survey was made of the foundation base. A geotextile was placed to separate the foundation soil from the embankment materials. The geotextile also covered (encapsulated) the whole embankment before placing the gravel wearing course and the organic soils on the slopes. The embankment was constructed in 1-ft lifts. A backhoe was used for spreading the tire chips. The compactor used was a Case 1102 PD 12 ton sheeps foot roller with vibratory capabilities.

Construction observations: 1) The backhoe seemed more capable of spreading the material evenly for each section than the front end loader or grader.
2) Tracked equipment had no problem maneuvering over the shredded tire fill, but trucks occasionally got stuck and had to be pulled out when the lift of pure tire chips exceeded 2 ft.
3) Vibratory equipment did not have an advantage over non-vibratory compaction because of the low inertial mass of the tire chips.
4) The tire chips compressed permanently with the first pass of the equipment. With the subsequent passes rebound of the tire chips was visible.

8. EMBANKMENT CONFIGURATION: Type A, Type B & Type C.

9. ENVIRONMENTAL NOTE: Duplicate EPA toxicity tests and AFS leaching tests were performed on the tire chip samples. The test results indicated that the tire chip samples showed no likelihood of being a hazardous waste. Water quality analysis of leachates was done, which indicated the values to be within limits. The pH value of leachates was 7.5.

10. COST: Materials: Not available. **Construction:** Not available.

11. PERFORMANCE HISTORY: The embankment was instrumented with settlement plates, surface markers, target markers and lysimeters to collect the leachates. The compressibility behavior of the embankment was monitored by regular surveys of surface markers and settlement plates. For surface surveys, target markers were located at seven locations in the center of each section. These markers provided the x, y, z coordinates of these points and any changes that occurred. Settlement plates were placed at the midheight of the embankment and, in one of the sections, another plate was placed below the embankment in order to assess foundation settlements.

The embankment was opened to the heavy incoming traffic of trucks that were pre-weighed. Due to this, immediate rutting took place, and 32 tons of crushed ballast was placed over the whole embankment. Subsequently the embankment went through several cycles of reopening and regrading. At the time the reference document was published, recommendations of constructing a concrete pavement over the embankment were being considered after a fairly long period of satisfactory performance of the embankment.

Surveys conducted on ground surface elevation, surface markers and settlement plates indicated that there was no noticeable lateral or longitudinal movement of the embankment. The settlement was remarkably high when the embankment first opened to traffic and then the rate reduced when the ballast was laid. Examination of the various sections of the embankment indicated that the section having soil-chip mix without any layering performed best, followed by the sections that had a layer of at least 3-ft of soil layer over the tire chip fill.

12. REFERENCE: Bosscher, P. J., Edil, T. B., and Eldin, N. N., "Construction and Performance of A Shredded Waste Tire Test Embankment," Transportation Research Record, No. 1345, 1992, pp. 44-52

13. SPECIAL NOTE: The following important conclusions were made by the authors:

[1] Normal construction machinery can be used for the construction of tire chip embankments.

[2] Tire chips, when used for constructing a fill to support a roadway, perform better when covered by 3-ft soil cap.

[3] Based on the tire leachate data and environmental monitoring, it was inferred that the tire chips do not show any likelihood of being a hazardous solid waste.

[4] Finally, the authors infer that the tire chips can be used as a lightweight fill in highway applications.

CASE STUDY [13]. 1/65
WAUKEGAN, ILLINOIS

1. LOCATION: The embankment is a trial embankment on a site adjacent to an electrical-generating plant at Waukegan, IL.

2. NATURE OF THE PROBLEM: The project was an experimental project.

3. RECYCLED MATERIALS USED: Fly ash generated from the electrical-generating plant.

4. QUANTITY USED: About 5,555 cubic yards. of Class F (Type A) fly ash.

5. SPECIFICATIONS:

Construction: **[1]** Required lift thickness was 6 inches. **[2]** 85% of AASHTO T-99 relative compaction was required to be obtained. **[3]** The total height, width and length of the embankment was 6 feet, 40 feet and 200 feet respectively. **[4]** Stockpiled fly ash was required to be used in the lower 4 ft of the embankment, and the younger silo-stored fly ash for the upper 2-foot portion of the embankment. **[5]** The fly ash was required to be compacted at 4 to 8 percent above the optimum moisture content.
Materials: Not available.

6. RECYCLED MATERIAL PROPERTIES: (1) The fly ash has particles that are spherical in shape and silty in texture. (2) It has an undrained angle of internal friction of 25°. (3) It is non -plastic and has a dry density of 85-92 pcf at an optimum moisture content varying between 20 and 26%. (4) Fly ash used in this project consisted of 45% oxides of silica, 19% oxides of iron, and lesser percentages of aluminum, sodium, calcium, magnesium, and potassium oxides. (5) It had a pH of 10 and a high pozzolanic activity.

7. CONSTRUCTION PROCEDURE: Fly ash was dumped in 6-inch loose lifts using tandem dump trucks. Compaction was carried out using a 10-ton, self-propelled pneumatic roller. Because of the formation of a crust and the presence of large lumps of hardened fly ash rotary tilling, scarification and compaction with six to eight passes of the pneumatic tired roller was carried out. With this, a relative compaction of 85% of AASHTO T-99 was obtained. It was observed that the most effective range of compaction moisture contents varied from optimum + 8% to optimum + 4%.

8. EMBANKMENT CONFIGURATION: Type A.

9. ENVIRONMENTAL NOTE: According to the information available from the reference, recommendations were made for the environmental study of leachates from the embankment.

10. COST: **Material:** Details not available **Construction:** Details not available

11. PERFORMANCE HISTORY: Because of the apparent high permeability and high demand for water when fly ash is compacted, contractor operations were not impeded due to rainfall. Freezing occurred to a depth of 18 inches below the grade line. This was less than half the 42 inches normally expected in this area.

12. REFERENCE: Thomas, S. L., "Construction of Fly Ash Roadway Embankment in Illinois," Transportation Research Record, No. 529, 1972, pp. 20-23.

13. SPECIAL NOTE: This project was a demonstration project planned and supervised by the Chicago Fly Ash Company.

CASES STUDY [14]. 1/71
WAUKEGAN, ILLINOIS

1. LOCATION: This embankment was constructed between Grand and Greenwood avenues in Waukegan, 40 miles north of Chicago. This is now known as Melvin E. Amstutz Expressway.

2. NATURE OF THE PROBLEM: This was a major highway improvement project. Alternative material was used because a nearby power plant offered an available source of material at a cost savings. The site conditions consisted of approximately 6,500 feet of swampy vegetation underlain by clean sand. The mean water table is controlled by the adjacent Lake Michigan.

3. RECYCLED MATERIALS USED: Fly ash.

4. QUANTITY USED: 246,000 cubic yards of fly ash was used.

5. SPECIFICATIONS:

Construction: [1] Each lift of fly ash was required to be 6 in. thick. [2] 85% of relative compaction (AASHTO T-99) was required for each lift. [3] An envelope of cohesive soil was required to be placed as a cover on the slopes of the embankment. [4] Side slopes of 2H:1V were required.
Materials: Not available

6. PROPERTIES OF RECYCLED MATERIAL: (1) Fly ash particles were spherical in shape and silty in texture. (2) Fly ash had an undrained angle of internal friction of 25°. (3) It is non plastic and has a density of 85-92 pcf at an optimum moisture content varying between 20 and 26%. (4) Fly ash used in this project consisted of 45% oxides of silica, 19% oxides of iron, and lesser percentages of aluminum, sodium, calcium, magnesium, and potassium oxides. (5) It had a pH of 10 and a high pozzolanic activity.

7. CONSTRUCTION PROCEDURE: The project consisted of 1.45 miles of 4-lane concrete pavement with a concrete median. The height of the embankment was 3.3 ft nominally, but in the ramp areas near Grand and Greenwood avenues the height was 28 ft. Fly ash was spread in lifts of 6 inches. Disking and tilling into the surface of the preceding compacted lift was done to obtain a uniform moisture content. Relative compaction of 85% (AASHTO T-99) was obtained on each lift. The contractor chose a vibratory, single-steel-drum 10-ton roller. The compaction moisture content was 8% to 4% in excess of the optimum (25%). An 8-in. envelope of cohesive soil was placed on the slopes of the embankment to serve as an erosion protection device and also for vegetation.

8. EMBANKMENT CONFIGURATION: Type A.

9. ENVIRONMENTAL NOTE: According to the information available from the reference, recommendations were made for the environmental study of the leachates from the embankment.

10. COST: **Material:** Details not available **Construction:** Details not available

11. PERFORMANCE HISTORY: Freezing occurred to a depth of 18 in. below the grade line. This was less than half the 42 in. normally expected in this area.

11. REFERENCE: Thomas, S. L., "Construction of Fly Ash Roadway Embankment in Illinois," Transportation Research Record No. 529, 1972, pp. 20-23.

12. SPECIAL NOTE: This project was let by the Illinois Division of Highways. Certain conclusions were made on the use of fly ash as an alternative embankment material:

(1) Electrically precipitated fly ash is an acceptable alternative to naturally occurring soils in both subgrade and fills.

(2) Compaction characteristics of fly ash are similar to some naturally occurring cohesive soils.

(3) Provisions need to be made in the contract for the use of large quantities of water, in order to control dust and for obtaining required compaction.

(4) Variation in the standard density of fly ash should be expected and provided for in the control procedures.

CASE STUDY [15]. 4/90
MIDDLESEX, VERMONT

1. LOCATION: Town of Middlesex and hamlet of Putnamville.

2. NATURE OF THE PROBLEM: The objective of the project was to eliminate the need for guardrails, removing an existing two-cable guardrail and flattening the side slope from 1:1.5 to 1:3.

3. RECYCLED MATERIALS USED: Scrap tire chips as side slope fill

4. QUANTITY USED: 2,738 cu. yards.

5. SPECIFICATIONS: No standard specifications are available.

Construction: [1] The tire chips were required to be laid in 18-inch lifts. [2] A geotextile was required to separate the tire fill from the overlying soil cap.
Materials: Not available.

6. PROPERTIES OF RECYCLED MATERIALS: The tire chips had a laboratory specific gravity of 1.21, and an in-situ density of 47-56 pcf and an average compacted void ratio of 0.45 was attained. It was observed that compacted chips had a steep unsupported angle of repose. Packed chips remained in the truck at vertical angles when the rear doors were opened, causing a problem in unloading.

7. CONSTRUCTION PROCEDURE: Site preparation was initially accomplished. Then the tire chips were brought in trucks from North Ferrisburg, Vermont, and from a source in New Hampshire. The tire chips were spread and compacted using a 5-ton dozer. The material was spread in 18-in. lifts. It was observed that a freshly placed pile of chips depressed 6 in.-12 in. under the first pass of the dozer. On the second pass, the pile depressed about 3- 4 in. but then rebounded. Following placement and shaping of the embankment, a geotextile fabric was placed on the slope and covered with approximately 2 ft of earth borrow. The site was then fine graded, seeded and mulched.

8. EMBANKMENT CONFIGURATION: Type A.

9. ENVIRONMENTAL NOTE: Samples of flowing water at the culvert inlet and outlet were tested for pH. The pH value at the inlet was 8.8 and at the outlet was 8.3. The results of this testing indicate that although surface water may flow through the chips, it probably will not get contaminated by leaching of metals in the tire chips.

10. COST: **Material:** $ 12,206 **Construction:** $ 29,067

11. PERFORMANCE HISTORY: When the height of the embankment reached 18 ft a plate load test was performed. The test loading progressed to a total of 20, 828 pounds in 200 pound increments. Deflection readings were taken with survey equipment during each load increment. At 600 pounds, a linear stress - strain relationship was established with a modulus of 313 psf. A non-linear stress-strain curve was developed during the unloading sequence. A permanent deflection of about 0.028 in./foot of fill depth resulted. The embankment will be monitored for 3 years for signs of sloughing, depression, wetting of the toe or cracking of the shoulder or road surface.

12. REFERENCE: Cauley, R. F. "Use of Tire Chips in a Highway Embankment," Report No. U91-51991, Vermont Department of Transportation, Materials and Research, 1991, 7 p.

13. SPECIAL NOTE: None

CASE STUDY [16]. 1/93
YORK COUNTY, VIRGINIA

1. LOCATION: Located at the intersection of the future Route 199 and Route 646 connector in York County, approximately 3 km North of Williamsburg, Virginia. The site is bordered to the north by Route 646 and to the east by Interstate 64.

2. NATURE OF THE PROBLEM: Experimental project.

3. RECYCLED MATERIAL USED: Tire chips.

4. QUANTITY USED: 56, 059 cubic yards, which is the equivalent of 1.7 million tires.

5. SPECIFICATIONS: Standard specifications developed by VDOT were used.

Construction: [1] The shredded scrap tires shall be blended with soil within 2 feet above the high water table at the bottom, within 4 feet inside the side slopes and 5 feet on the top of the embankment. [2] The embankment shall be constructed by placing alternate layers of shredded tires and soil and mixing and blending during compaction. [3] For those areas where the shredded tires are to be incorporated into the embankment, shredded tires shall constitute approximately 50% by volume of that portion of the embankment. [4] Thickness of each lift was required to be not more than 2 feet.

Materials: [1] The average size of the shredded scrap rubber shall not exceed 40 sq. inches. [2] The maximum length of any piece shall not be more than 10 in. [3] All pieces shall have at least one side wall severed from the face of the tire.[4] No metal particles shall be placed in the fill that are not firmly attached to a rubber segment. [5] Stockpiling of shredded tires was not permitted at the site, and tire chips had to be placed directly in the embankment.

6. PROPERTIES OF RECYCLED MATERIAL: The borrow material used was mostly silty sand with about 20% of the particles passing the No. 200 sieve. The typical compacted unit weight of the soil fill used on the project was 17.3 kN/m^3 and the resulting 50/50 soil/tire mixture had a compacted unit weight of 11.2 kN/m^3. Laboratory properties pertaining to the tire chips were not reported.

7. CONSTRUCTION PROCEDURE: The construction involved two embankments. One embankment was about 530 feet long, and the other was 264 feet long. The embankments have varying thickness. They form portions of an approach to a proposed bridge that is to be constructed over the Route 646 connector.

Spreading, mixing and compacting of soil and shredded tires was performed with bulldozers, scarifiers and sheepsfoot rollers. Compaction was controlled by monitoring the number of passes of a compactor. A minimum of 3 passes was recommended for each lift. Tire chips were spread and mixed with soil by a D8 bulldozer and a motor grader equipped with a scarifying teeth attachment. The resulting mix had a substantially layered structure. The thickness of each lift was 2 feet prior to compaction.

Construction monitoring: The instrumentation was installed only in one of the embankments and consisted of two earth pressure cells and four settlement sensors interfaced with an electronic data logger. Earth pressure cells were installed at the base, and settlement sensors were placed at the base and the top. The earth pressure cells and settlement sensors were equipped with temperature probes. This kind of instrumentation facilitated remote collection of a large volume of settlement, pressure, and temperature data. During construction, data were collected at half-hour interval but currently they are being collected every 2 hours.

8. EMBANKMENT CONFIGURATION: Types B and C

9. ENVIRONMENTAL NOTE: The study was expanded to include groundwater monitoring for contaminants that might be leached from the tire core. One monitoring well was installed hydraulically upstream of the shredded tire section, and one well was installed at the toe of the section. Groundwater monitoring was conducted in accordance with the Virginia Department of Environmental Quality Solid Waste Management Regulations (VR 672-20-10) pertaining to the landfill site. It was also proposed to address potential generation of hazardous leachates.

10. COST: The total cost of the project was $1,129,688, and the cost over-run was $425,509. All these costs were inclusive of material, construction, and monitoring.

11. PERFORMANCE HISTORY: Final average settlement recorded at the base of the embankment at the end of construction 132 mm. Post-construction settlements differed considerably. After 6 days, the settlement of the top of the tire core had stabilized at about 150 mm. After 68 days, the tire core underwent a vertical expansion of about 80 mm, with a resulting net settlement of 70 mm. A load test was performed at the end of construction by positioning a D9G dozer having a mass of 30 tons on the embankment. The bottom sensors did not detect any settlement. However, the top sensor detected a settlement of 2 mm, which was recoverable. The latest records indicate a vertical pressure of 32 kPa and 85 kPa under the shredded tire and soil sections.

12. REFERENCE: Hoppe, E. J., "Field Study of a Shredded Tire Embankment," Interim Report FHWA/VA-94-IR1, Virginia Transportation Research Council, 1994, p. 46.

13. SPECIAL NOTE: None.

CASE STUDY [17]. 1/67
SOUTH HEIGHTS, PENNSYLVANIA

1. LOCATION: The embankment supports a choked-aggregate access road from Culver Road to a fly ash disposal area for the Phillips Electric generating station, South Heights, Pennsylvania.

2. NATURE OF THE PROBLEM: The access road supported by this embankment passes through an area having compressible soils. In addition, fly ash available at the disposal site provided a source of an alternate borrow material.

3. RECYCLED MATERIAL USED: Class F fly ash.

4. QUANTITY USED: 190,000 cubic yards of fly ash was used.

5. SPECIFICATIONS: Standard specifications are not available.

Construction: [1] The fly ash had to be laid in 12 in lifts. [2] A minimum of 90% of modified Proctor compaction density was required. [3] A minimum, 1-foot thick soil cap was required to prevent erosion and to support vegetation. [4] An effective drainage system was required for the embankment.
Materials : Not available.

6. PROPERTIES OF RECYCLED MATERIAL USED: The Class F fly ash used showed a large variability because of the different kind of boilers and precipitators in the Phillips Power station from which the fly ash was supplied.

(1) Maximum dry relative densities varied from 30.9 to 81.5 pcf and minimum dry relative densities from 22.5 to 62.3 pcf. Modified Proctor tests (ASTM D1557-64T) were also conducted on the fly ash. The maximum dry density varied from 89.3 to 45.2 pcf and corresponding moisture contents were 19.3 and 69 percent. (2) The specific gravity of fly ash at this site varied from 2.30 to 2.48. (3) Strength parameters, based on previous studies of Phillips fly ash, were estimated as 0 cohesion with an effective friction angle of 30°. (4) The chemical composition of fly ash was SiO_2, 51.1%; Fe_2O_3, 10.9%; Al_2O_3, 29.2%; CaO, 1.6% and small quantities of oxides of magnesium and sulfur.

7. CONSTRUCTION PROCEDURE: The embankment was 800 feet long and 75 feet high at its deepest point. The construction included a 72-inch corrugated metal drainage conduit to route the existing stream through the base of the embankment and a 100-ft by 100-ft bottom ash drainage blanket at the downstream toe. The embankment area was cleared and stripped, and surface drainage was provided along the toe of the final embankment.

Unstable foundation material was excavated and replaced with sandy shale. Prior to placement, silo fly ash was mixed with water at the pugmill and trucked to the site. Fly ash was placed in 12- inch lifts and compacted with 8 passes of a Buffalo Springfield compactor, which weighs about 6.5 tons. When the fly ash was significantly drier than optimum, the compactor was operated at 2,000 cpm (cycles per minute) vibration. When the water content of fly ash was wetter than optimum, the compactor was operated at 1,250 cpm. This procedure was designed to achieve a density of 90% of maximum modified Proctor compaction density. A 1-foot thick layer of top soil was placed over the compacted ash to support vegetation and prevent erosion.

The haul road was constructed of slag aggregates choked with fines. The fly ash used had sufficient shear strength to be constructed on a 2H:1V slope assuming that the embankment was well drained by a subsurface drainage system. The haul road embankment was designed and constructed with 3H:1V side slopes and was not subjected to any slope stability analysis.

Construction monitoring: A study was performed to evaluate the effectiveness of the compaction program. The study included 24 surface density tests, 3 borings, 16 Shelby tube samples with water content and natural density determinations on each Shelby tube sample. A reference density of 67 pcf was established for 90% of maximum modified proctor density of fly ash. The in-place fly ash densities were measured using a Washington Dens-O-Meter. The in-place densities ranged from 91% to 118% of the reference density. Borings showed that the majority of the fill was in a medium-dense condition, suitable as a structural fill to support an access road. The average unit weight of the fill ranged from 67-71 pcf.

8. EMBANKMENT CONFIGURATION: Type A.

8. ENVIRONMENTAL NOTE: Details pertaining to environmental concerns have not been reported.

10. COST: **Material:** Details not available **Construction:** Details not available

11. PERFORMANCE HISTORY: This embankment has performed well under heavy loads since 1968. It has demonstrated the ability of a fly ash structural fill to produce an embankment with a long, trouble-free life.

12. REFERENCE: DiGioia, A. M., Jr., and McLaren, R. J., "Case History: Fly Ash Structural Fill, Culver Road Embankment," Presented at West Virginia University, Short Course On Technology and Utilization of Power Plant Ash in Structural Fills and Embankments, August 13-16, 1978.

13. SPECIAL NOTE: No special permits were needed for this project. The equipment used and the number of passes per lift were decided by studying test sections at the site.

CASE STUDY [18]. 2/76
MILWAUKEE, WISCONSIN

1. LOCATION: This embankment is called the Airport Spur Highway embankment, between 13th and 16th Streets on Layton Avenue, near Lake Michigan.

2. NATURE OF THE PROBLEM: The embankment was constructed as an alternative to disposal and to demonstrate the use of fly ash as a fill material. The subsurface investigation performed at this site indicated that the foundation soil was stiff, silty clay loam (glacial till) to depths of over 100 ft.

3. RECYCLED MATERIAL USED: Class F fly ash supplied by Valley power plant in downtown Milwaukee and Port Washington power plant in Port Washington.

4. QUANTITY USED: 120,000 tons of fly ash, which amounted to 100,000 cubic yards of in-place fly ash fill.

5. SPECIFICATIONS: No standard specifications were available.

Construction: [1] Fly ash was required to be laid in 6 inch lifts, each lift being compacted to at least 90% of T-180 AASHTO maximum dry density. [2] Soil cover was required for the top and slopes of the embankment, respectively. [3] An effective drainage system was required to be designed for the embankment.
Materials: No specific material requirements were reported.

6. PROPERTIES OF RECYCLED MATERIALS: Engineering properties of fly ash were not reported. However, chemical composition was reported. The fly ash contains 44.4% of SiO_2, 19.7% of Al_2O_3, 19% of Fe_2O_3, and 1.3% of CaO.

7. CONSTRUCTION PROCEDURE: The highway embankment was 900 ft long and had a maximum depth of 25 feet. The width of the embankment was about 100 ft and side slopes were 4H:1V. A 2-foot thick soil cover was designed for the side slopes, and 1 foot of soil was designed to cover the top. The 4-lane highway was provided with a drainage system to intercept pavement runoff. A 15-inch-thick pavement layer was provided at the top of the embankment.

An envelope of cohesive material and a pavement drainage system was provided to prevent the infiltration of the moisture and subsequent leachates from fly ash.

Prior to construction of the fill, the site was prepared by removing trees and available top soil. The embankment was constructed in 3 stages, and each stage added to the width of the embankment. Each stage was constructed to its fullest height before the next stage was started. Water was added by sprinkling and was mixed using a road grader. Fly ash was placed in 6-inch lifts and compacted with a rubber-tired roller. The final layer of fly ash was covered with earth to prevent erosion.

Fly ash was placed at 90 percent of AASHTO T-180 maximum dry density, with the exception of the top 4 feet, which was placed at 95 percent. The whole procedure used 1 D6 dozer, 1 road grader, 1 large water truck. Dusting was a serious problem when winds exceeded 25 mph. Additional water was sprayed to control the dust, which formed a protective crust over the fly ash surface.

Construction monitoring: The effectiveness of the placement procedure was controlled by periodic density tests. Nuclear density gages gave erratic results; hence, the sand cone test was used. While digging holes, it was observed that moisture was not evenly distributed throughout the ash, which explained why the nuclear density gage gave erratic results. The construction procedure was modified to use more water, and a road grader was used to achieve a uniform mix.

8. EMBANKMENT CONFIGURATION: Type A.

9. ENVIRONMENTAL NOTE: A detailed environmental study was not done.

10. COST: **Material:** Not available. **Construction:** Not available.

11. PERFORMANCE HISTORY: Settlement of the embankment was monitored weekly. Four plates were installed at each shoulder to monitor the settlement at various levels. The 25-foot-deep fill at the north shoulder had a maximum settlement of 0.13 feet . Only 0.05 feet of additional settlement was measured in the first year after the fill completion. The 21-foot-deep fill at the south shoulder had a maximum settlement of 0.26 feet. Following completion, an additional 0.02 feet of settlement was measured in the next year. Standard penetration tests produced blow counts ranging from 60 to 150 blows per foot, which greatly exceed normal values for earth work.

12. REFERENCES: (1) Petersdorf, R. J., "Coal Ash Used as a Fill Material for Highway Embankments, Airport Spur Demonstration Project," Report, Wisconsin Electric Power Company,
December, 1977.

(2) Wisconsin Department of Transportation, "Plans and Specifications for the Proposed Use of Power Plant Fuel Ash in a Roadway Embankment, Airport Spur Freeway, C. M. St. P. & P. Railroad to South 6th Street," Report 2015-01-00, February, 1977.

13. SPECIAL NOTE: The site was licensed as a solid waste disposal area under DNR Section NR151 of the Wisconsin Administrative Code. The embankment construction was a cooperative effort between the Wisconsin Electric Power Company and the Wisconsin Department of Transportation.

CASE STUDY [19]. 2/81
ONTARIO, CANADA

1. LOCATION: This project is located on the Highway 402 overpass at Front Street in Sarnia, Ontario.

2. NATURE OF THE PROBLEM: Lightweight fill was required instead of traditional construction material to avoid differential settlement and expensive stage construction of the bridge approach and interchange ramps.

3. RECYCLED MATERIAL USED: Class F fly ash supplied by Ontario Hydro's Lambton generating station.

4. QUANTITY USED: A total of 181,000 tons of fly ash was used.

5. SPECIFICATIONS: Standard specifications were not available.

Construction: **[1]** An effective drainage system was required for the embankment. **[2]** The embankment was required to have a soil cover on the slopes and a comparatively granular cap.
Materials: No specific material requirements were reported.

6. PROPERTIES OF RECYCLED MATERIALS : The ash used in the embankment was produced by burning a bituminous coal. Laboratory tests performed on the samples yielded a standard Proctor density equal to 77.6 pcf at an optimum moisture content of 30.5 percent.

7. CONSTRUCTION PROCEDURE: The embankment was 26 ft high and had a base layer of bottom ash, a fly ash core and a bottom ash cap. The base layer consisted of a 3-foot thick bottom ash drainage blanket to prevent the upward movement of ground water into the fly ash core. The fly ash was capped with approximately 4 feet of bottom ash to minimize the effects of frost action on the fine-grained fly ash. A 2-inch layer of top soil was placed on the embankment slopes to control erosion and to support vegetation.

The initial phase of construction consisted of clearing and grubbing the area on which the embankment would be located. A 3-foot drainage blanket of bottom ash was then placed on the cleared area. The average haul distance was about 10 miles. The fly ash was spread by bulldozers and compacted by a self-propelled, smooth-drum vibratory compactor. The compactor achieved the required fill densities with moderate effort.

Construction monitoring: Monitoring consisted of field density tests and moisture content tests. These tests were performed periodically to assure that proper compaction was being obtained by the construction equipment.

8. EMBANKMENT CONFIGURATION: Type A.

9. ENVIRONMENTAL NOTE: The effects of the fly ash embankment on the groundwater quality were proposed to be studied but had to be canceled because of the absence of preconstruction data.

10. COST: Material: Fly ash was provided free of charge. Bottom ash was supplied for a fee of $18,000 i.e. about $0.20 per ton.
Construction: $ 8,282,000 excluding the property acquisition cost.
Note: Costs are in Canadian dollars.

11. PERFORMANCE HISTORY: Instrumentation was placed in the embankment to monitor settlements, frost penetration, and frost heave. Consolidation of the natural soil below the embankment was monitored by 14 water manometer-type settlement cells. The settlement cells were placed in trenches below the embankment and connected to a remote gage housing. The consolidation of the natural soil due to the weight of the embankment averaged 0.97 feet after 10 months. Approximately two-thirds of this consolidation occurred within 1 month after placement of the fill was completed. Consolidation of the embankment was monitored by 4 settlement rods installed in the fill. Results showed a maximum consolidation of 0.1 inch within the embankment.

Frost penetration was measured by 8 frost depth sensors. From January '82 through April '82, frost depths from 2 to 3.3 feet were recorded. Frost heave was measured by 8 sensors that were similar to settlement rods. The frost heave sensors indicated that up to 0.2 inches of settlement occurred on the north side of the embankment, while up to 0.3 inches of heave occurred on the south side of the embankment.

12. REFERENCE: Cragg, C. B. H., "Instrumentation of Highway 402 Fly Ash Embankment in Sarnia, Ontario, Toronto, Canada,", Ontario Hydro, Research Division, Report No. 83-372-K December 19, 1983.

13. SPECIAL NOTE: The use of fly ash as a construction material did not require any special permits or approvals. The permitting procedure was identical to that when standard construction materials were used.

CASE STUDY [20]. 2/74
LUZERNE COUNTY, PENNSYLVANIA

1. LOCATION: This embankment is designated as section 2G of the Cross Valley Expressway and is located between the borough of Forty Fort and Kingston, across the Susquehanna River from Wilkes-Barre, Luzerne County.

2. NATURE OF THE PROBLEM: Foundation soil was weak, and it was decided to use a lightweight fill material. This was considered as an experimental project.

3. RECYCLED MATERIAL USED: Coal mine refuse was used. Both burned and unburned refuse was utilized. The unburned refuse came from Swoyersville, about 2 miles west of the project site, and burned refuse was obtained from anthracite fields located farther to the north.

4. QUANTITY USED: 1.5 million cubic yards of both burned and unburned refuse.

5. SPECIFICATIONS: No standard specifications were reported.

Construction: [1] The coal refuse was required to be compacted to 97% of the maximum standard Proctor density. [2] Lift thickness was required to be less than 8 inches. [3] The embankment was required to be sufficiently contained in soil so as to prevent exposure to the atmosphere. [4] Slope stability analysis was required.
Materials: The coal refuse was required to be free from brush and scrap metal.

6. PROPERTIES OF THE RECYCLED MATERIALS: The grain-size distribution of the coal refuse indicated that the material had a coarse texture and fairly uniform grading. This material had fewer fines than the bituminous refuse tested at another site (Revloc). It was assumed from the grain-size distribution that, to achieve the desired densities during construction it would require a greater compactive effort in order to break down the particles and provide sufficient fines. Fifteen repetitive compaction tests on the anthracite refuse samples indicated an improvement in the compaction characteristics. The average specific gravity of the samples was 2.15. CU tests on the anthracite refuse samples gave a mean internal friction angle of 28° and a mean cohesion value of 5 psi. The range for friction angle and cohesion intercept varied between 25° and 33° and 1 to 10 psi, respectively.

7. CONSTRUCTION PROCEDURE: The embankment was 2,344 feet in length with a maximum width of an outer berm of about 475 feet and a maximum height of 57 feet. Special consideration was given to the slope stability of the embankment . The embankment slopes were designed and constructed on a 2H:1V with counter berms that were 3H:1V. A safety factor of 1.35 was obtained when considering foundation shear failure.

The refuse was spread and tracked with D8 and D9 bulldozers and compacted with a steel drum vibratory compactor and steel-drum rollers. The coal refuse was compacted to 97% of maximum standard Proctor density. Each lift thickness was 8 inches as required by Penn DOT. A 4-foot thick soil cover was placed over the embankment and counter berm slopes. The top of the embankment was covered with 2 feet of soil upon which 2 feet of burnt refuse was placed to provide an access road for the construction of a bridge. The soil cover was mulched and seeded with Crown Vetch (Cornilla Varia) legume, which exhibited excellent erosion control and winter hardiness.

Construction monitoring: Moisture-density data was obtained from 12 samples collected from the embankment after completion of compaction. The mean value of the dry unit weight was 112 pcf with a moisture content of 12%. The dry unit weight and moisture content varied from 102 to 118 pcf and 10 to 15% respectively. For in-place densities, nuclear moisture density gages were used. It was believed that the carbon content of the refuse would make the results invalid, but proper air gap adjustments gave acceptable results.

Thermocouples were placed in the embankment to monitor temperature changes and determine the possibility of spontaneous combustion of the refuse material. The near-surface thermocouples showed temperature variations coinciding with the ambient temperatures. Thermocouples monitoring the interior of the embankment showed no rise in temperature and were independent of the ambient temperature.

8. EMBANKMENT CONFIGURATION: Type A.

9. ENVIRONMENTAL NOTE: Sulfate and pH levels of anthracite were determined in accordance with British Standards (BS 1377:1967). Results of 38 tests gave a mean of 0.03% of sulfate and a mean pH of 5.2. The sulfate levels were low and needed no special considerations for their effect on concrete structures. The pH values indicated some concern with the water quality. Therefore, water samples were obtained from the Cross Valley Expressway embankment for over 7 months to check the water quality. The mean value of the pH was found to be 6.7, with a range of 6.2 to 7.4 during this monitoring period.

10. COST: Not reported.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCE: Pierre, J. J., and Thompson, C. M., "User's Manual, Coal - Mine Refuse in Highway Embankment," FHWA-TS-80-213, 1979, 194 p.

13. SPECIAL NOTE: The following conclusions were made after the completion of this project:

[1] Steel drum rollers produce a better compactive effort than the vibratory compactors.

[2] Improvements in compaction of the refuse could be realized with the addition of fines. Slurry refuse or pulverized fly ash could be used to provide these fines.

CASE STUDY [21]. 1/74
CAMBRIA COUNTY, PENNSYLVANIA

1. LOCATION: This embankment was located on US 219 and had the identification of L. R. 1022 - Section J06, in Cambria County, Pennsylvania.

2. NATURE OF THE PROBLEM: The project was an experimental project.

3. RECYCLED MATERIAL USED: Bituminous coal mine refuse was used. This was acquired from the Revloc dump site located near the proposed highway site and owned by Bethlehem Mines Corp.

4. QUANTITY USED: 200,000 cubic yards of coal mine refuse.

5. SPECIFICATIONS: Standard specifications not available.

Construction: [1] A minimum of 2 feet of natural soil barrier was required around all pipes and inlets that were laid through the embankment. [2] No coal refuse was allowed to be placed within 5 feet of the subgrade in order to protect it from frost. [3] Natural soil wherever placed in the embankment, was required to be compacted to achieve 95% of maximum standard Proctor density.

Materials: The coal mine refuse used in the embankment was required to be free of any tree stumps and scrap metals.

6. PROPERTIES OF RECYCLED MATERIAL: The coal mine refuse used in the embankment was well graded with sufficient fines to facilitate compaction. The specific gravity ranged from 1.61-1.84. Moisture-density tests were performed on 3 samples. The optimum moisture content ranged from 9-12%, and the corresponding densities ranged between 84 and 95 pcf. CU tests on 15 samples gave an angle of internal friction ranging between 33° and 42° and a cohesion value between 0 and 14 psi.

7. CONSTRUCTION PROCEDURE: The haul road to the designated borrow site was constructed according to the design plan. Initial clearing of some debris on top of the refuse area was required. Scrap metal and mine timbers were removed and the top of the pile was regraded to facilitate the traversing of construction equipment. The coal mine refuse formed the core of the 1000-foot-long embankment, which was about 18 feet high. A 12-foot-wide embankment of natural soil was provided on each side of the embankment. This width was selected for ease of construction and to facilitate use of compaction equipment. All pipes and inlets were protected with a minimum 2-foot barrier of natural soil material, and no coal refuse was placed within 5 feet of the subgrade. This was done to keep the refuse material below the frost line.

The refuse material was excavated using a D9 dozer to push Cat 631-13 scrapers. The 12 foot width of natural soil placed on each side of the embankment was constructed using 18 inch lifts forming a box like earthen containment structure. This material was compacted to 95% of maximum dry density, determined by standard Proctor method. The perimeter soil placement preceded the refuse placement. When the designed height of the embankment was reached, the refuse was covered with natural material. Compaction was achieved by a vibratory roller. Two passes by the roller with 50% overlay were required to reach maximum density. Approximately 200,000 cubic yards of refuse material was placed in a period of 8 weeks using Cat 631-13 scrapers. The average load per scraper was approximately 25 cubic yards.

8. EMBANKMENT CONFIGURATION: Type A.

9. ENVIRONMENTAL NOTE: Sulfate levels were determined by water extraction of 21 samples. The test method followed was BS 1377. Results showed a mean of 0.02% sulfate and a mean pH of 4.5. The sulfate levels were low and did not call for special considerations for the protection of concrete structures. The pH levels were within a range requiring a special underdrain pipe to be used or requiring a buffer zone around the pipe. The use of coal mine refuse needed approval from the Pennsylvania Department of Environmental Resources (DER) and for this a letter was sent including a sketch of the proposed borrow area. After typical sections of the embankment and a detailed design of the project were furnished, the project was approved.

10. COST: The bid price for special borrow excavation was $1.00 per cubic yard. The common borrow excavation estimated at that time was $1.25/cu. yard.

11. PERFORMANCE HISTORY: No specific details available.

12. REFERENCE: Pierre, J. J., and Thompson, C. M., "User's Manual, Coal - Mine Refuse in Highway Embankment," FHWA-TS-80-213, 1979, 194 p.

13. SPECIAL NOTE: Bethlehem Mines Corporation granted approval for using the refuse material under 3 conditions:

[1] The designated borrow area should be selected in areas of the dump where the material had a low coal content.

[2] The surface areas disturbed by construction and all work involving the removal of the coal mine refuse would be conducted in accordance with all state and federal rules.

[3] Any future intended use of the material when the highway is extended north be coordinated with other parties interested in developing the refuse disposal area

CASE STUDY [22]. 4/76
RAYMOND, WASHINGTON

1. LOCATION: This embankment is constructed as part of a grading and surfacing project on SR101 between South Bend and Raymond.

2. NATURE OF THE PROBLEM: The alignment crosses a 600-foot long section of tidal flats before tying back into the existing alignment. The soils in this tidal flat consisted of 20-70 feet of very soft peat together with organic silts and clays overlying steeply dipping sandstone. Standard penetrometer blow counts of less than one were encountered to a depth of 25-30 feet.

3. RECYCLED MATERIAL USED: Sawdust stockpiled next to the site by an adjacent saw mill.

4. QUANTITY USED: About 100,000 cubic yards.

5. SPECIFICATIONS: Specifications developed by Washington DOT for wood fiber fills were used.

6. PROPERTIES OF THE RECYCLED MATERIALS: Specific material properties are not available, except that certain triaxial and direct shear tests performed on saw dust samples indicated an angle of internal friction of 31° to 50°.

7. CONSTRUCTION PROCEDURE: To construct a stable embankment, 20-25 feet of foundation soil was initially planned to be excavated and replaced with quarry rock, but a subsidence of 3 feet or more was anticipated. An alternate design requiring use of lightweight material (sawdust) was proposed. The sawdust embankment is about 20 ft in height and was constructed during the summer of 1976. This was topped off with ballast and was used as a detour throughout the winter. It was finally paved in 1977. Normal embankment construction techniques were used.

Construction monitoring: The embankment was instrumented to monitor surface elevations, settlements and in-situ temperatures. In-place density of 59-60 pcf was achieved. This was greater than expected. Dutch cone penetrometer tests indicated a maximum angle of internal friction ranging from 36°-39° which increases with depth. A value of 35° was used in design. Data from the plate bearing, rebound deflection and facsimile seismograph indicated that the embankment has a modulus of subgrade reaction of 1400 psi in the top 1-2 feet. This equates to a CBR of 1.0. This requires a minimum of 2 feet of surfacing over sawdust, more if the traffic warrants. Settlement data indicated that the settlement was more than expected. The post-construction consolidation was 6 in. - 8 in. The sawdust stockpile was at a temperature of +85° F and had started to decay when placed in the embankment. The temperature rose to 100° F before ultimately declining to ambient temperatures.

8. EMBANKMENT CONFIGURATION: Type A.

9. ENVIRONMENTAL NOTE: A potential water quality problem was anticipated with the construction of all sawdust fills due to an aqueous solution of wood extractions (leachate), which has a dark color, oily sheen and a septic smell. The leachate had a high metal ion content, high TOC and BOD, low pH and may be toxic in sufficient concentrations. It was observed that the water draining from the fill was normal after 6 months to 1 year. But the quantity of leachate is very small and is usually in very high dilution if water samples were recovered from a nearby flowing stream.

10. COST: Approximately $250,000 in cost savings were achieved, which according to today's cost would be about $1,000,000.

11. PERFORMANCE HISTORY: The settlement data indicated that there was more settlement than predicted. More details about the performance history were not available.

12. REFERENCE: Jackson, N. C., "A Summary of the Use of Sawdust for Highway Fills," Report No. 153, Materials Office, Washington State Department of Transportation, 1979, 14 p.

13. SPECIAL NOTE: An average life of 15 years is predicted for most sawdust fills. There is also an anticipation of progressive deterioration in the geometry of the roadway prism, increasing with time until some reconstruction is warranted. Hence, it has been recommended that reconstruction should be done every 15 years.

CASE STUDY [23]. 3/74
DURHAM COUNTY, ENGLAND

1. LOCATION: This embankment was built on the principal road A182 in Durham County by the British Transport and Road Research Laboratory (TRRL).

2. NATURE OF THE PROBLEM: This was a demonstration project.

3. RECYCLED MATERIAL USED: Unburned colliery shale.

4. QUANTITY USED: Exact quantity not available.

5. SPECIFICATIONS:

Construction: The British Ministry of Transport requires compaction to a maximum of 5% air voids for the material within 2 feet of the formation level.
Material: The material was required to be free of any stumps or pit props.

6. PROPERTIES OF THE RECYCLED MATERIAL: The refuse material selected was well graded and had a loss of weight on ignition up to 29.3%. The material was generally free of post stone and pit props and was conveniently situated near the proposed embankment. The maximum dry density achieved was 115 pcf at an optimum moisture content of 8%. The material was not frost susceptible.

7. CONSTRUCTION PROCEDURE: The embankment is about 1,150 feet in length and has a maximum height of 14 feet. The refuse material was spread in 15 in. thick lifts and compacted using a Bomag 7.8 Mg double vibrating roller. This achieved a very high state of compaction. Trials were carried out with a Bomag roller to determine the degree to compaction versus number of passes using 8 in. lifts with not less than 4 passes by the vibrating roller. Six passes of the Bomag roller gave a dry density of 115 pcf. Field tests gave an average specific gravity of 2.19. The average air voids were determined to be close to 9%. The British Ministry of Transport requires that a compaction to a maximum of 5% air void be achieved for the material within 2 feet of formation level, this was found difficult to achieve.

8. EMBANKMENT CONFIGURATION: Type A.

9. ENVIRONMENTAL NOTE: Not available.

10. COST: Not available.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCE: Pierre, J. J., and Thompson, C. M., "User's Manual, Coal - Mine Refuse in Highway Embankment," FHWA-TS-80-213, 1979, 194 p.

13. SPECIAL NOTE: None

CASE STUDY [24]. 3/76
BRISTOL AND SOMERSET, ENGLAND

1. LOCATION: The embankment at Bristol forms a 2-mile-long section of the M5 between Bristol and Avonmouth in England, and the embankment at Somerset forms another section of M5 between Clevden Hills and Brent Knoll.

2. NATURE OF THE PROBLEM: The section at Bristol crossed a highly compressible layer of alluvium as much as 40 feet thick. In the other section in Somerset the motorway crosses an alluvium layer as much as 90 feet thick; this posed serious settlement problems at the site of 14 bridges and 2 interchanges.

3. RECYCLED MATERIAL USED: Fly ash was used in both cases.

4. QUANTITY USED: The quantities in the Bristol case are not available. The embankment in Somerset used about 1,025,000 tons of fly ash.

5. SPECIFICATIONS: None available.

6. PROPERTIES OF THE RECYCLED MATERIAL: Not available.

7. CONSTRUCTION PROCEDURE: The embankment in Bristol was 7 feet high and was required along the trunk road with side road and interchange embankments up to 20 feet in height. Detailed construction descriptions are not available.

8. EMBANKMENT CONFIGURATION: Details available are not sufficient to categorize the embankment.

9. ENVIRONMENTAL NOTE: Not available.

10. COST: Not available.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCE: Faber, J. H., and DiGioia, A. M. "Use of Fly Ash in Embankment Construction," Transportation Research Record No. 593, 1977, pp 13-19.

13. SPECIAL NOTE: None

CASE STUDY [25]. 1/85.
FLYING V, WYOMING

1. LOCATION: The name of the project was the Flying V project, it was located on US 85 Highway in Wyoming.

2. NATURE OF THE PROBLEM: Not known.

3. RECYCLED MATERIAL USED: Wood chips.

4. QUANTITY USED: 40,000 cubic yards.

5. SPECIFICATIONS: Not available.

Construction: Not available.
Materials: Not available.

6. PROPERTIES OF RECYCLED MATERIALS: Not available.

7. CONSTRUCTION PROCEDURE: Not available.

8. EMBANKMENT CONFIGURATION: Not available.

9. ENVIRONMENTAL NOTE: Not available.

10. COST:
Material: $ 3 per cubic yard. **Construction:** Not available.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCE: Wyoming DOT, "Lightweight fill projects".

13. SPECIAL NOTE: None

CASE STUDY [26]. 1/94.
SHERIDAN - BECKTON, WYOMING

1. LOCATION: The name of the project was the Sheridan-Beckton project, it was located on Highway SH 331 in Wyoming.

2. NATURE OF THE PROBLEM: Not known.

3. RECYCLED MATERIAL USED: Wood chips.

4. QUANTITY USED: 6300 cubic yards.

5. SPECIFICATIONS: Not available.

Construction: Not available.

Materials: Not available.

6. PROPERTIES OF RECYCLED MATERIALS: Not available.

7. CONSTRUCTION PROCEDURE: Not available.

8. EMBANKMENT CONFIGURATION: Not available.

9. ENVIRONMENTAL NOTE: Not available.

10. COST:
Material: $ 6.19 per cubic yard. **Construction:** Not available.

11. PERFORMANCE HISTORY: Not available

12. REFERENCE: Wyoming DOT, "Lightweight fill projects".

13. SPECIAL NOTE: None

CASE STUDY [27]. 2/94.
DOUBLE NICKEL, WYOMING

1. LOCATION: The name of the project was the Double Nickel project. It was located on Highway SH 28, in Wyoming.

2. NATURE OF THE PROBLEM: Not known.

3. RECYCLED MATERIAL USED: Shredded tires.

4. QUANTITY USED: 13,000 cubic yards.

5. SPECIFICATIONS: Not available.

Construction: Not available.
Materials: Not available.

6. PROPERTIES OF RECYCLED MATERIALS: Not available.

7. CONSTRUCTION PROCEDURE: Not available.

8. EMBANKMENT CONFIGURATION: Not available.

9. ENVIRONMENTAL NOTE: Not available.

10. COST:
Material: $26.1 per cubic yard. **Construction:** Not available.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCE: Wyoming DOT, "Lightweight fill projects"

13. SPECIAL NOTE: None

CASE STUDY [28]. 1/78.
CARBO, VIRGINIA

1. LOCATION: This is located in Carbo, Virginia, on SR 665.

2. NATURE OF THE PROBLEM: Not known.

3. RECYCLED MATERIAL USED: Fly ash (Class F).

4. QUANTITY USED: 300 tons.

5. SPECIFICATIONS: Not available.

Construction: Not available.
Materials: Not available.

6. PROPERTIES OF RECYCLED MATERIALS: Not available.

7. CONSTRUCTION PROCEDURE: Not available.

8. EMBANKMENT CONFIGURATION: Not available.

9. ENVIRONMENTAL NOTE: Not available.

10. COST:
Material: Not available. **Construction:** Not available.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCE: GAI Consultants, Inc., "High-Volume Fly Ash Utilization Projects in United States and Canada," Electric Power Research Institute, Report No. CS-4446, Feb. 1986.

13. SPECIAL NOTE: The fly ash was supplied by the American Electric Power Co. and this project was completed by the DOT.

CASE STUDY [29]. 1/83.
GALLIA COUNTY, OHIO

1. LOCATION: This project is located in Gallia County on US 35 in Ohio.

2. NATURE OF THE PROBLEM: Not known.

3. RECYCLED MATERIAL USED: Fly Ash (class F).

4. QUANTITY USED: 27,000 tons.

5. SPECIFICATIONS: Not available.

Construction: Not available.
Materials: Not available.

6. PROPERTIES OF RECYCLED MATERIALS: Not available.

7. CONSTRUCTION PROCEDURE: Not available.

8. EMBANKMENT CONFIGURATION: Not available.

9. ENVIRONMENTAL NOTE: Not available.

10. COST:
Material: Not available. **Construction:** Not available.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCE: GAI Consultants, Inc., "High-Volume Fly Ash Utilization Projects in United States and Canada," Electric Power Research Institute, Report No. CS-4446, Feb., 1986.

13. SPECIAL NOTE: The fly ash was supplied by the American Electric Power Co., and this project was completed by the DOT.

CASE STUDY [30]. 1/76
MALDEN, WEST VIRGINIA

1. LOCATION: This embankment is built on a 1100 foot realignment of County Route 60/12 near Malden, West Virginia.

2. NATURE OF THE PROBLEM: The new alignment eliminated hazardous curves and provided two 11 feet lanes with 5 feet shoulders. This was an experimental project.

3. RECYCLED MATERIAL USED: Fly ash was supplied from the Kanawha River Electric Generating Station of the American Electric Power (AEP) Co.

4. QUANTITY USED: 20,000 cubic yards of fly ash was used instead of soil.

5. SPECIFICATIONS:

Construction: [1] Fly ash was required to be laid in 12 inch lifts and each lift was required to be compacted to 95% of maximum standard proctor compaction density. [2] Soil cover was required both on the top and side slopes of the embankment. [3] Prior to the placement of any drainage layer or fly ash, unsuitable material was required to be excavated. [4] An effective drainage system was required to be designed.
Materials: No specific material requirements were reported, except that the fly ash had to be acquired dry from the silos.

6. PROPERTIES OF RECYCLED MATERIAL: The Class-F fly ash used on this project had the following constituent percentages by weight, SiO_2-53.6%, Al_2O_3-28.3%, Fe_2O_3-5.8%, CaO-0.4%. The specific gravity of the fly ash used varied between 2.3 and 2.5 and the maximum dry density was 94.7 pcf at an optimum moisture content of 15.5%. The coefficient of permeability of the bottom ash used in this project was 5.0×10^{-3} cm/sec.

7. CONSTRUCTION PROCEDURE: The length of the embankment was 1100 feet and the width was about 30 feet. Principal features of the design include 2:1 side slope, a 4 foot layer of bottom ash beneath the embankment, and a 2 feet thick soil cover on the side slopes for erosion protection. The bottom ash layer was provided to permit free flowing drainage of any water that seeps into the fly ash.

Construction began in the summer of 1976. The area was cleared and grubbed, and a 2 foot layer of wet organic material was removed from the foundation. Next, bottom ash was placed in 12-inch lifts compacted to 95% of the standard Proctor maximum dry density (AASHTO T-99). The maximum dry density for the bottom ash was 72.6 pcf at an optimum moisture content of 26.2%. This process was continued until the entire 4 foot layer of bottom ash was placed.

The fly ash was then delivered to the site in tandem trucks covered with tarpaulins. It was removed dry from the silos at the station and conditioned to within -3 to +5 percent of optimum moisture content in a drum mixer at a plant. The fly ash was spread in 12 inch loose lifts with a D7 dozer and compacted by 6 passes of a 20-ton self-propelled smooth drum vibrating roller. After compaction, each lift was compacted to a thickness of approximately 9 inches. The average field compaction achieved was 101 percent of the maximum standard Proctor density. The fly ash portion of the embankment was completed in October of 1976 along with the soil cover on the side slopes and installation of the culvert.

The pavement over this embankment was constructed by West Virginia Paving Inc. First a limestone-aggregate base course was placed in a thickness of 4 to 6 inches and compacted prior to the placement of remaining aggregate that formed the entire 12 inch base course. No appreciable loss into the fly ash was noted without using geotextile. A 3 inch hot mix bituminous base course was then placed over the aggregate in December, 1976. The final wearing course was not placed until June, 1977.

Construction monitoring: Compaction testing was performed with a Troxler Model 2401 nuclear moisture-density gauge. Monitoring was conducted on top of the frozen subgrade prior to placing the aggregate base course.

8. EMBANKMENT CONFIGURATION: Type A.

9. ENVIRONMENTAL NOTE: There was no significant change in the groundwater quality in the two observation wells that were placed immediately beyond the embankment.

10. COST: The embankment was constructed by AEP at no charge to the West Virginia Department of Highways.

11. PERFORMANCE HISTORY: The pavement and the subgrade were strong, and split spoon samples taken in February, 1977, and September, 1977, showed no noticeable difference in the blows per foot or moisture content of the embankment. During the split spoon (standard penetration) testing, a Shelby tube sample of the embankment was taken. The field moisture content was 19.7%, the dry density was 87.3 pcf and the internal friction angle was 28.9°. The pavement in the area of the fly ash embankment was in as good or better condition than the rest of the highway.

12. REFERENCE: Stinnett, B. C., "Construction of Fly Ash Embankment in Kanawha County, West Virginia," Presented at the Ninth Annual Southeastern Transportation Geotechnical Engineering Conference, Hot Springs, Arkansas, October 25-28, 1977.

13. SPECIAL NOTE: No special permits or approvals were required.

CASE STUDY [31]. 1/80
JOSEPH CITY, ARIZONA

1. LOCATION: This project is located in Joseph City on I-40 in Arizona.

2. NATURE OF THE PROBLEM: Not known.

3. RECYCLED MATERIAL USED: Fly Ash (Class-F).

4. QUANTITY USED: 60,660 tons.

5. SPECIFICATIONS: Not available.

Construction: Not available.
Materials: Not available.

6. PROPERTIES OF RECYCLED MATERIALS: Not available.

7. CONSTRUCTION PROCEDURE: Not available.

8. EMBANKMENT CONFIGURATION: Not available.

9. ENVIRONMENTAL NOTE: Not available.

10. COST:
Material: Not available. **Construction:** Not available.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCE: GAI Consultants, Inc., "High-Volume Fly Ash Utilization Projects in United States and Canada," Electric Power Research Institute, Report No. CS-4446, Feb., 1986.

13. SPECIAL NOTE: The fly ash was supplied by the Arizona Public Service Co. and this project was completed by the ADOT.

CASE STUDY [32]. 1/81
AVON, OHIO

1. LOCATION: This project is located in Avon, Ohio, on I-480.

2. NATURE OF THE PROBLEM: Not known.

3. RECYCLED MATERIAL USED: Fly Ash (Class-F).

4. QUANTITY USED: 30,000 tons.

5. SPECIFICATIONS: Not available.

Construction: Not available.
Materials: Not available.

6. PROPERTIES OF RECYCLED MATERIALS: Not available.

7. CONSTRUCTION PROCEDURE: Not available.

8. EMBANKMENT CONFIGURATION: Not available.

9. ENVIRONMENTAL NOTE: Not available.

10. COST:
Material: Not available. **Construction:** Not available.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCE: GAI Consultants, Inc., "High-Volume Fly Ash Utilization Projects in United States and Canada," Electric Power Research Institute, Report No. CS-4446, Feb., 1986.

13. SPECIAL NOTE: The fly ash was supplied by Cleveland Electric Illuminating Co., and this project was completed by the ODOT.

CASE STUDY [33]. 1/78
NORTON, MASSACHUSETTS

1. LOCATION: This project is located in Norton, Massachusetts, on John Scott Blvd.

2. NATURE OF THE PROBLEM: Not known.

3. RECYCLED MATERIAL USED: Fly Ash (Class F).

4. QUANTITY USED: 5000 cubic yards.

5. SPECIFICATIONS: Not available.

Construction: Not available.
Materials: Not available.

6. PROPERTIES OF RECYCLED MATERIALS: Not available.

7. CONSTRUCTION PROCEDURE: Not available.

8. EMBANKMENT CONFIGURATION: Not available.

9. ENVIRONMENTAL NOTE: Not available.

10. COST:
Material: Not available. **Construction:** Not available.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCE: GAI Consultants, Inc., "High-Volume Fly Ash Utilization Projects in United States and Canada," Electric Power Research Institute, Report No. CS-4446, Feb. 1986.

13. SPECIAL NOTE: The fly ash was supplied by the New England Electric Co. and this project was completed by the MaDOT.

CASE STUDY [34]. 3/79
EAGAN, MINNESOTA

1. LOCATION: This project is located in Eagan, Minnesota, on SR 13.

2. NATURE OF THE PROBLEM: Not known.

3. RECYCLED MATERIAL USED: 80% Fly Ash (Class C).

4. QUANTITY USED: 350,000 cubic yards.

5. SPECIFICATIONS: Not available.

Construction: Not available.
Materials: Not available.

6. PROPERTIES OF RECYCLED MATERIALS: Not available.

7. CONSTRUCTION PROCEDURE: Not available.

8. EMBANKMENT CONFIGURATION: Not available.

9. ENVIRONMENTAL NOTE: Not available.

10. COST:
Material: Not available. **Construction:** Not available.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCE: GAI Consultants, Inc., "High-Volume Fly Ash Utilization Projects in United States and Canada," Electric Power Research Institute, Report No. CS-4446, Feb., 1986.

13. SPECIAL NOTE: The fly ash was supplied by the Northern States Power Co. and this project was completed by the Mn DOT.

CASE STUDY [35]. 1/84
ONTARIO, CANADA

1. LOCATION: This project is located in Sarnia, Ontario on Highway 402.

2. NATURE OF THE PROBLEM: Not known.

3. RECYCLED MATERIAL USED: Fly Ash (Class F).

4. QUANTITY USED: 80,000 tons.

5. SPECIFICATIONS: Not available.

Construction: Not available.
Materials: Not available.

6. PROPERTIES OF RECYCLED MATERIALS: Not available.

7. CONSTRUCTION PROCEDURE: Not available.

8. EMBANKMENT CONFIGURATION: Not available.

9. ENVIRONMENTAL NOTE: Not available.

10. COST:
Material: Not available. **Construction:** Not available.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCES: GAI Consultants, Inc., "High-Volume Fly Ash Utilization Projects in United States and Canada," Electric Power Research Institute, Report No. CS-4446, Feb., 1986.

13. SPECIAL NOTE: The fly ash was supplied by Ontario Hydro and this project was completed by the Ontario MTC.

CASE STUDY [36]. 4/79
ONTARIO, CANADA

1. LOCATION: This project is located in Windsor, Ontario on E.C. Row Expressway.

2. NATURE OF THE PROBLEM: Not known.

3. RECYCLED MATERIAL USED: Fly Ash (Class F).

4. QUANTITY USED: 113,000 tons.

5. SPECIFICATIONS: Not available.

Construction: Not available.
Materials: Not available.

6. PROPERTIES OF RECYCLED MATERIALS: Not available.

7. CONSTRUCTION PROCEDURE: Not available.

8. EMBANKMENT CONFIGURATION: Not available.

9. ENVIRONMENTAL NOTE: Not available.

10. COST:
Material: Not available. **Construction:** Not available.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCES: GAI Consultants, Inc., "High-Volume Fly Ash Utilization Projects in United States and Canada," Electric Power Research Institute, Report No. CS-4446, Feb., 1986.

13. SPECIAL NOTE: The fly ash was supplied by Ontario Hydro, and this project was completed by the Ontario MTC.

CASE STUDY [37]. 2/93
PINE CITY, MINNESOTA

1. LOCATION: This project is located in Pine City, Minnesota on I-35.

2. NATURE OF THE PROBLEM: Not known.

3. RECYCLED MATERIAL USED: Tire chips.

4. QUANTITY USED: 1 million tires.

5. SPECIFICATIONS: Not available.

Construction: Not available.
Materials: Not available.

6. PROPERTIES OF RECYCLED MATERIALS: Not available.

7. CONSTRUCTION PROCEDURE: Not available.

8. EMBANKMENT CONFIGURATION: Not available.

9. ENVIRONMENTAL NOTE: Not available.

10. COST:
Material: Not available. **Construction:** Not available.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCE: Minnesota DOT, "Mn/DOT's Experience with Scrap Tires," Report from Materials Research and Engineering Laboratory, Maplewood, Minnesota, 1994, 2 p.

13. SPECIAL NOTE: None

CASE STUDY [38]. 3/93
E. FOSSTON, MINNESOTA

1. LOCATION: This project is located in E. Fosston, Minnesota on TH-2.

2. NATURE OF THE PROBLEM: Not known.

3. RECYCLED MATERIAL USED: Tire chips.

4. QUANTITY USED: 80,000 tires.

5. SPECIFICATIONS: Not available.

Construction: Not available.

Materials: Not available.

6. PROPERTIES OF RECYCLED MATERIALS: Not available.

7. CONSTRUCTION PROCEDURE: Not available.

8. EMBANKMENT CONFIGURATION: Not available.

9. ENVIRONMENTAL NOTE: Not available.

10. COST:
Material: Not available. **Construction:** Not available.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCE: Minnesota DOT, "Mn/DOT's Experience with Scrap Tires," Report, Materials Research and Engineering Laboratory, Maplewood, Minnesota, 1994, 2 p.

13. SPECIAL NOTE: None

CASE STUDY [39]. 3/94
TAYLOR FALLS, MINNESOTA

1. LOCATION: This project is located in Taylor Falls, Minnesota on TH-95.

2. NATURE OF THE PROBLEM: Not known.

3. RECYCLED MATERIAL USED: Tire chips.

4. QUANTITY USED: 100,000 tires.

5. SPECIFICATIONS: Not available.

Construction: Not available.

Materials: Not available.

6. PROPERTIES OF RECYCLED MATERIALS: Not available.

7. CONSTRUCTION PROCEDURE: Not available.

8. EMBANKMENT CONFIGURATION: Not available.

9. ENVIRONMENTAL NOTE: Not available.

10. COST:
Material: Not available. **Construction:** Not available.

11. PERFORMANCE HISTORY: Not available.

12. REFERENCES: Minnesota DOT, "Mn/DOT's Experience with Scrap Tires," Report, Materials Research and Engineering Laboratory, Maplewood, Minnesota, 1994, 2 p.

13. SPECIAL NOTE: None

A 2.1. MATERIAL PROPERTIES #1.

1. RECYCLED MATERIAL: Tire chips.

2. SOURCE: Land fills and tire disposal agencies.

3. MIXTURE: Pure tire chips.

4. TYPE OF TESTS: Compaction (10 in. x 10 in. mold), Direct shear (12 in. x 12 in. x 9 in. shear box), Compressibility (12 in. x 12.5 in. mold, custom made), Triaxial test (6 in. x 12 in. specimen)

5. PROPERTIES:

SIZE / GRADATION: 1/4 in., 1/2 in., 1 in., 2 in., 3 in., commercial tire chips are available in a uniform gradation.

SPECIFIC GRAVITY: 0.88-1.36

FRICTION ANGLE: 19°- 25° (Triaxial test), 21°-26° (Direct shear)

COHESION: 1-2 psi (Triaxial), 4-11 psi (Direct shear)

DRY DENSITY: 38-43 pcf (standard compaction)
29-33 pcf (vibration)

COMPRESSION INDEX: 0.175-0.259
(slope of e-log p curve)

6. COST: Cost of the tire chips is not mentioned in the references cited. Costs found from local sources are: 1/4 in. chips ---- $80-$100/ton, and 2-3 in. chips -- $25-$30 /ton.

7. REMARKS: For use in embankments, chip sizes larger than 3" are needed. Leachate from the tire chips in a fill should be monitored.

8. REFERENCES: (1) Dana, N. H., "Shear Strength and Compressibility of Tire Chips for Use as Retaining Wall Backfill," Transportation Research Record No. 1422, 1993, pp. 29-35.

(2) Ahmed, I., and Lovell, C. W., "Rubber Soils As Light Weight Geomaterials," Transportation Research Record No. 1422, 1993, pp. 61-70.

A 2.2. MATERIAL PROPERTIES # 2

1. RECYCLED MATERIAL: Tire chips.

2. SOURCE: Tire chips obtained from recyclers.

3. MIXTURE: Tire/sand mix.

4. TYPE OF TESTS: Compaction (6 in. standard ASTM mold), Triaxial (6 in. x 12 in. specimen), Compressibility test (12 in. x 12.5 in. mold)

5. PROPERTIES: **SIZE / GRADATION:** Tire chips range from 0.25 in., 0.5 in., 1 in. and sand used is either Ottawa sand or normal blasting sand

DRY UNIT WEIGHT: Pure sand = 118 pcf. With 40% chips = 70 pcf

FRICTION ANGLE: Pure sand = 40°, With 40% chips = 36°

COHESION INTERCEPT : Pure sand = 0. With 40% chips = 6 psi at a confining pressure of 15 psi

COMPRESSION INDEX: 0.055-0.079 for 40% chips (slope of e - log p curve)

6. COST: Not available

7. REMARKS: Tire chips mixed with sand can form a very good embankment material due to the light weight, low compressibility and high angle of internal friction.

8. REFERENCES: (1) Ahmed, I., and Lovell, C. W., "Rubber Soils as Light Weight Geomaterials," Transportation Research Record No. 1422, 1993, pp 61-70.

(2) Ahmed, I., "Laboratory Study on Properties of Rubber Soils," Ph.D. Thesis, Purdue University, 1993, 450 p.

A 2.3. MATERIAL PROPERTIES # 3

1. RECYCLED MATERIAL: Tire chips.

2. SOURCE: Tire recyclers and landfills.

3. MIXTURE: Tire chips and natural fine grained soil (Crosby till).

4. TYPE OF TESTS: Compaction (6 in. standard ASTM mold), Triaxial (6 in. x 12 in. specimen) and Compressibility (12 in. x 12.5 in. mold)

5. PROPERTIES:

SIZE / GRADATION: Tire chips tested were 0.25 in., 0.5 in. and 1 in. The soil used was minus No. 4 sieve and classified as CL- ML

DRY UNIT WEIGHT: Pure crosby till = 130 pcf With 50% chips =75 pcf

FRICTION ANGLE: Pure crosby till = 25.4°, With 50% chips = 32°

COHESION INTERCEPT: Pure crosby till = 7-11 psi, With 50% chips 5 - 9 psi at a confining pressure varying between 4.5 and 28.8 psi

COMPRESSION INDEX: 0.101 - 0.109 for 50% chips (slope of e-log p curve)

6. COST: Not available.

7. REMARKS: This mixture of tire chips and locally available borrow material has the potential to form a very good lightweight fill due to the low compacted density. However, the compressibility values are greater than for chip - sand mix.

8. REFERENCE: Ahmed, I., and Lovell, C. W., "Rubber Soils as Light Weight Geomaterials," Transportation Research Record No. 1422, 1993, pp. 61-70.

(2) Ahmed, I., "Laboratory Study on Properties of Rubber Soils," Ph.D. Thesis, Purdue University, 1993, 450 p.

A 2.4. MATERIAL PROPERTIES # 4

1. RECYCLED MATERIAL: Fly ash

2. SOURCE: Electric power utility plants.

3. MIXTURE: Pure

4. TYPE OF TESTS: Compaction, Permeability, and Triaxial Test.

5. PROPERTIES: **SIZE / GRADATION:** 65% of the fly ash particles are less than # 200. They lie between silty sand and silty clay particle size and are predominantly spherical in shape. Commercially available fly ash is uniformly graded

SPECIFIC GRAVITY: 2.1 to 2.6

FRICTION ANGLE: 30° to 42° at a confining pressure varying between 54 and 83 psi

COHESION : 10 to 15 psi

DRY DENSITY: 77 pcf at 29% moisture and 89 pcf at 19% moisture.

COMPRESSION INDEX: Not available

COEFFICIENT OF PERMEABILITY: $1x10^{-4}$ - $5x10^{-4}$ cm/s

6. COST: Cost is not available; however, costs obtained from local sources are $17 - $23 per ton (FOB).

7. REMARKS: Fly ash has a very good potential to be used as a construction material for embankments due to self hardening properties, lightweight and high shear strength.

8. REFERENCE: Faber, J. H., and DiGioia, A. M., "Use of Fly Ash in Embankment Construction," Transportation Research Record No. 593, 1976, pp. 13-19.

A 2.5. MATERIAL PROPERTIES # 5

1. RECYCLED MATERIAL: Bottom ash.

2. SOURCE: This is the ash that is collected at the furnace bottom in coal combustion electric utility plants.

3. MIXTURE: Pure bottom ash.

4. TYPE OF TESTS: Compaction, Permeability, Compressibility, Direct Shear.

5. PROPERTIES: **SIZE / GRADATION:** The bottom ash available commercially exhibits well-graded size distribution ranging from fine gravel to fine sand. The fines passing the #200 sieve range from 0-14 %

SPECIFIC GRAVITY: 1.9-3.4

SHEAR STRENGTH: 7 psi-36 psi at normal pressures varying between 5 and 34 psi

FRICTION ANGLE: 46°-50°

COHESION: 1.49-3.0 psi

CBR VALUE: 40-70

DRY DENSITY: 69-116 pcf.(maximum relative densities)
50-91 pcf. (minimum relative densities)

COMPRESSION INDEX: 0.01
(slope of e - log p curve).

COEFFICIENT OF PERMEABILITY: 3 X 10^{-2} cm/s

6. COST: $5 per ton (FOB).

7. REMARKS: If bottom ash is used in embankments or subgrades, the resulting bearing capacity and stability will be higher than the naturally available granular soils. CBR values indicate that bottom ash serves as a good subgrade material.

8. REFERENCE: Lovell, C. W., and Huang, W. H., "Bottom Ash as Highway Material," Transportation Research Record No. 1310, 1991, pp. 106-117.

A 2.6. MATERIAL PROPERTIES # 6

1. RECYCLED MATERIAL: Coal mining waste.

2. SOURCE: Coal mine waste land fill site.

3. MIXTURE: Coarse coal refuse is a mixture of associated mining wastes and coal itself.

4. TYPE OF TESTS: Compaction, Triaxial.

5. PROPERTIES: **SIZE / GRADATION:** This is well graded ranging from 3 inches to less than 0.004 inches (0.01 mm) and has less than 25 % fines (passing #200 sieve)

SPECIFIC GRAVITY: 1.8-2.4

DRY DENSITY: 84-95 pcf

FRICTION ANGLE: 29°-38° (drained)

COHESION: 0-14 psi (much variability)

6. COST: Can be negotiated with the coal processing industry to whom the landfill site belongs. It is known that the cost is less than that of common borrow material.

7. REMARKS : Coal mine refuse forms a very good embankment material, but it should be placed in such a way that it does not get into contact with water. In addition, potential sulfate leachates may occur; hence, it should be placed with at least 2 feet of a buffer material from any abutting concrete structure.

8. REFERENCE: Pierre, J. J., and Thompson, C. M., "User's Manual, Coal - Mine Refuse in Highway Embankment," Report No. FHWA-TS-80-213, 1979, 194 p.

A 2.7. MATERIAL PROPERTIES # 7

1. RECYCLED MATERIAL: Wood waste .

2. SOURCE: Lumber industry, saw mills, wood recycling

3. MIXTURE: Pure wood chips ,

4. TYPE OF TESTS: Compaction, Triaxial test

5. PROPERTIES: **SIZE / GRADATION:** The wood chip size mentioned in the reference varies from 0.25-0.75 inches

SPECIFIC GRAVITY: 1.0-1.2

DRY DENSITY: 30-39 pcf

FRICTION ANGLE: 10°-30°

COHESION INTERCEPT: 4-8 psi

COMPRESSIBILITY: Anticipated settlement was about 11% during the first 4 months of construction of an embankment and an additional 1% during the next 20 years

6. COST: Not available.

7. REMARKS : Wood waste forms a good lightweight material where it is abundantly available and at sites where highly organic compressible soils are encountered in the right-of-way, but care should be taken to make the wood waste embankment anaerobic so that the wood does not get exposed to the atmosphere and decays.

8. REFERENCE: Allen, T. M., and Killian, A. P., "Use of Wood Fiber and Geotextile Reinforcement to Build Embankment Across Soft Ground," Transportation Research Record No. 1420 1993, pp. 46-54.

A 2.8. MATERIAL PROPERTIES # 8

1. RECYCLED MATERIAL: Fluorogypsum calcium sulfate (anhydrite gypsum).

2. SOURCE: Gulf State Materials at La Porte, Texas.

3. MIXTURE: Pure calcium sulfate.

4. TYPE OF TESTS: Compaction, Triaxial, Compressibility, Hydraulic conductivity.
Above tests were performed according to the Texas standards.

5. PROPERTIES:

SIZE / GRADATION: Similar in gradation to silty fine sand and sandy silt. Has more than 65% fines (i.e., passing #200 sieve)

DRY DENSITY: 96 pcf at optimum moisture content of 18%

FRICTION ANGLE: 65° (uu-test), 36° (cu-test), 40° (effective)

COHESION: 10 psi (uu-test), 78 psi (cu-test), 14 psi (effective)

COMPRESSION INDEX: 0.120 (standard compaction)
(slope of e-logp curve) 0.090 (modified compaction)

PERMEABILITY: $2x10^{-6}$ - $9x10^{-6}$ cm/sec(standard compaction)
$2x10^{-10}$- $3x10^{-10}$ cm/sec (modified)

6. COST: $2 per cubic yards.

7. REMARKS: Gypsum forms a good embankment material due to its lightweight, low compressibility, and high shear strength. There might be some concerns for sulfate attack in wet environment; however, this can be taken care, by the use of at least 3 ft. of soil cap both on the top and side slopes of the embankment.

8. REFERENCE: Little, D. N., "GSM Calcium Sulfate as an Embankment Material: <u>A Summary Report</u>," Texas Transportation Institute, College Station, 1987, 15 p.

A3.1. SCRAP TIRES IN TEXAS

1. SOURCES:

Total of 22 tire recycling plants in Texas. Each recycling plant is inspected by the TNRCC a regular basis for funding.

2. QUANTITY:

(1) Tires comprise an estimated 1.2% of the total waste stream in Texas.
(2) 65 million tires have been shredded in Texas over the past two years; 15% of those shreds being marketed.
(3) 16 million of the shredded tires came from the more than 427 priority enforcement list (PEL) sites remediated; 20-25 million additional tires remaining in PEL sites.
(4) 18 million waste tires are generated each year in Texas (one tire per person per year)

3. LOCATIONS (Recycling plants):

(1) Lubbock (1); Abilene (1); Duncanville (3); Tyler (1); El Paso (1); Odessa (1); Waco (1); Beaumont (1); Houston (6); San Antonio (5); Corpus Christi (1).

4. PROPERTIES:

Size/Gradation: 1/4 inch to 100 sieve size rubber pieces are used for rubber-modified asphalt paving and tire-derived fuel (TDF) [1] The size of shredded tire chips can be several inches long with steel reinforcements. TNRCC limits the shredded tire size to 9 sq. inches.

TCLP: Needs to be evaluated for metals and polynuclear aromatic hydrocarbons in leachate. Results show compounds to be 10 to 100 times less than TCLP limits and EPA's Drinking Water Standard MCL values.

5. COST:

(1) \$5- \$25/CY (Waste Recovery, Baytown; Environmental Recovery, Stamford; Tire Shredder Services, Beaumont); Particle size from 0.5 - 2 in.

(2) Cost of rubber-modified asphalt (RMA) can be up to twice as much as traditional asphalt. Life-cycle cost associated with RMA has been shown to be economical.

6. DISPOSAL PRACTICE:

Landfills

7. REMARKS:

(1) The tire recycling program was created by Senate Bill 1340 and amended by Senate Bill 1051, addressing the environmental concerns associated with illegal tire dumping.

(2) Piles of tires can catch fire, especially in monofills.

(3) A typical tire weighs about 18.7 lbs. and contains about 60% rubber, 20% steel and 20% fiber-all materials that can potentially be recycled.

(4) Discarded tires: 85% automobile, 15% truck, <1% construction equipment, military or aircraft vehicles.

(5) Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) mandates the use of ground tire rubber in asphalt paving from 5% in 1994 (17 million tires), increasing by 5% every year until 1997 when maximum required usage rate is 20%.

(6) As of December 1992, TxDOT has paved over 2,500 miles of roadway and airstrips with hot mix rubber-modified asphalt (RMA) with mixed results. In order to meet ISTEA requirements, just over 5% of all Texas roads were paved with RMA last year.

(7) Market Value: (a) Cement kilns use tires as fuel (b) rubber modified asphalt (RMA) (6 million tires)

(8) There are approximately 200 tire retreading plants in Texas retreading about 1 million tires per year.

(9) Rubber used in tire manufacturing is a thermoset or vulcanized material comprised of rubber and sulfur.

(10) Maine, North Carolina, Vermont, Colorado, Minnesota, Wyoming, California, and Virginia have tested the use of scrap tires in Civil Engineering applications.

8. DEFINITIONS:

Ground Rubber: Scrap tire rubber that is ground into particles ranging in size from 1/4 inch to 100 mesh or smaller.

Crumb rubber modifier (CRM): Crumb rubber derived from scrap tire rubber that has been reduced to particle size less than 6.3 mm and is used in asphalt paving.

Tire-Derived Fuel (TDF): This refers to the tire chips smaller than 1/4" size (100% free of any metal fragments) used as a fuel in boilers.

9. REFERENCE:

TNRCC, Scrap Tire Market Study, Recycling Market Development and Recycling Research Program, Office of Pollution Prevention and Recycling, Texas Natural Resource Conservation Commission, Austin, Texas, 1994.

A3.2. COAL COMBUSTION BYPRODUCTS (CCBP) IN TEXAS

1. FLY ASH

1. SOURCES:

Coal-fired electricity generating power plants.

2. QUANTITY:

(1) Texas leads the nation in producing CCBP's with more than 13 million tons or 15% of the national production. Almost 89 million tons of CCBP are generated from electric utilities in the U.S.

(2) Coal ash ranks similar to municipal solid waste on the national and state level.

(3) 6.5 million tons of fly ash was produced in Texas. 51.3 million tons of fly ash was produced nationwide in 1991.

(4) Fly ash comprises almost half of all CCBPs produced in Texas.

(5) 11.9 million tons of coal ash are currently disposed in Texas.

3. LOCATIONS: (Production Plants)

(1) 16 locations in Texas.

(2) Amarillo (1); College Station (1); Austin (3); Dallas (3); Tyler (2); Longview Marshall (2); Lubbock (1); San Antonio (2); Corpus Christi (1).

4. PROPERTIES:

Characterization: According to the definition of ASTM C618, Texas fly ash is categorized as Class-F and Class-C.

TCLP: Leaching of metal may be of concern. Results not available.

Others: Carbon content in fly ash may become a concern.

5. COST:

(1) Average market price for fly ash is $22 to $24 per ton delivered. Average freight costs represent about one-half the value of the material.
(2) CCBP qualifies for Tariff 20, which sets maximum rates at which recyclable commodities may be hauled as opposed to minimum rates as set in Tariffs 2 and 12 (Railroad Commission of Texas (RCT)); therefore, lower rates can be negotiated between the truckers and shippers.
(3) Nationally, $800 million per year is spent on CCBP disposal.

6. DISPOSAL PRACTICE:

(1) Settling ponds and landfills.

7. REMARKS:

(1) Fly ash is a finely divided residue from combustion of ground and powdered coal.
(2) It is a pozzolan, meaning that when mixed with water, it will chemically combine with lime (calcium oxide) to produce a cement-like material with excellent performance-enhancing properties. Some fly ashes are self hardening because they contain sufficient calcium compounds.
(3) Market Value: (a) cement concrete mixture (b) road bases, grouts and mortar (c) soil amendments.

8. DEFINITIONS:

CCBP: This refers to the byproduct remaining after the combustion of coal in the electric power plants.
Fly ash: Finely divided residue from the combustion of ground or powdered coal.

9. REFERENCES:

(1) Texas Recycles 2. Marketing Our Neglected Resources, Texas General Land Office, Austin, Texas, 1994, 106 p.

(2) ASTM Standards. (1992).

A3.3.COAL COMBUSTION BYPRODUCTS (CCBP) IN TEXAS

2. BOTTOM ASH

1. SOURCES:

Coal-fired electricity generating plants.

2. QUANTITY:

(1) 4 million tons of bottom ash was produced in Texas in 1991. 13 million tons of bottom ash was produced nationwide in 1991.

(2) Bottom ash comprises almost 28% of all CCBPs produced in Texas.

3. LOCATIONS:

(1) 17 locations in Texas. Same as fly ash but includes Limestone, Texas.

4. PROPERTIES:

SIZE/GRADATION: Much more coarser than fly ash.

EPA: Some are classified as inert materials (class III solid waste) while others are classified as class II solid waste and are subject to more stringent regulations for use.

5. COST:

(1) $5 per ton (FOB).

6. DISPOSAL PRACTICE:

(1) Settling ponds and landfills

7. REMARKS:

Much coarser than fly ash and falls to the bottom of the boiler.

8. DEFINITIONS:

Bottom ash: Resulting from burning of coal and falls to the bottom of boiler.

9. REFERENCE:

Texas Recycles 2. Marketing Our Neglected Resources. Texas General Land Office, Austin, 1994, 106 p.

3. FLUE GAS DESULFURIZATION MATERIAL (FGD)

1. SOURCES:

Coal-fired electricity generating plants. From the pollution control system in the electric utility boiler, commonly called a scrubber system (Flue gases such as sulfur dioxide are passed through a limestone system to be removed).

2. QUANTITY:

(1) Almost 3 million tons of FGD was produced in Texas in 1991.
(2) FGD comprises almost 22% of all CCBP's produced in Texas.

3. LOCATIONS: (Production plants)

(1) 10 locations in Texas.
(2) Facility: Limestone, Houston, Fayette, San Miguel, Pirkey, Gibbons Creek, Martin Lake, Monticello, Sandow, Oklaunion.

4. PROPERTIES:

CHEMICAL COMPOSITION: A combination of calcium sulfite and/or calcium sulfate and calcium carbonate. Fly ash is normally blended in dry to stabilize the FGD material.

EPA: Some are classified as inert materials (class III solid waste) while others are classified as class II solid waste and are subject to more stringent regulations for use.

5. COST:

(1) $7 per ton (FOB).

6. DISPOSAL PRACTICE:

Landfills

7. REMARKS:

None

8. DEFINITIONS:

Flue gas desulfurization (FGD): Obtained from the scrubber system. A combination of calcium sulfite and/or calcium sulfate and calcium carbonate.

9. REFERENCE:

Texas Recycles 2, Marketing Our Neglected Resources, Texas General Land Office, Austin, Texas, 1994, 106 p.