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Coal Refuse and Fly Ash Compositions: Potential Highway Base-Course Materials

W.J. HEAD, P.V. McQUADE, AND R.B. ANDERSON

The necessity of using waste products in construction is becoming both evident and crucial as waste disposal continues to have a negative impact on the environment, disposal costs escalate, and traditional materials become scarce and expensive. Two by-products of the coal industry—coal refuse and fly ash—show promise for use in highway base-course applications. The already abundant supplies of these materials are expected to increase. Summarized in this paper are results of studies of the physical and engineering properties of both unstabilized and stabilized mixtures of coal refuse and fly ash. In addition, comparisons of performances of several hypothetical pavement systems are presented. The base courses of the pavements were either a crushed stone or coal refuse and fly ash mixtures. Findings indicate that stabilized coal refuse and fly ash mixtures are technically feasible base-course materials. In-service feasibility of the mixtures should be established by appropriate field testing. Unstabilized mixtures appear unsuitable for base-course applications because of questionable wet-dry and freeze-thaw durability. Both traditional substances and waste products should be considered as candidate construction materials. Technology for assessing competitive materials is available for many applications.

Waste use continues to concern engineers and others responsible for construction, environmental protection, and energy conservation. Waste products may be feasible alternatives to expensive or scarce conventional construction materials. Waste use obviates disposal problems. In addition, proper use of waste is an energy-conservation practice.

Two waste products that can be combined with appropriate stabilizing agents to yield potentially useful construction materials are coal refuse and fly ash. This paper deals with laboratory development and characterization of mixtures of these substances. Included are assessments of potential use of selected mixtures as highway base-course materials.

According to McQuade and others, (1, pp. 8-12):

> Coal mine refuse is usually comprised of clays, claystone, and/or shales which occur immediately above and below the coal or are interbedded in the coal seam itself. The exact nature of the refuse is a function of the geologic development of the coal seam....The automated [mining] equipment may extract portions of the mine floor and roof, in addition to interbedded impurities, with the coal. This results in the production of larger volumes of refuse material which are rejected in the [coal] cleaning process....Fly ash is a by-product of the coal combustion process. It is a very fine, light dust which is collected from stack gases....It is primarily comprised of rock detritus which collects in fissures of coal seams. The chemical composition of fly ash is highly variable....

Production of both coal refuse and fly ash exceeds use by huge margins. Refuse production is estimated to approach 200 000 000 tons annually (1, pp. 8-12). Most of the refuse is deposited in disposal sites. Annual production of fly ash approaches 50 000 000 tons. Approximately 8 400 000 tons were used in 1978 (2); excess ash remains in disposal sites.

The nature of both coal refuse and fly ash is complex; thus, general material characterization for design purposes is not possible. In addition, supply of these materials far exceeds demand. Consequently, significant use must at least accompany or indeed supplant disposal of the materials, given the finite extent of disposal sites and the general negative environmental impact associated with such sites. In light of these principles, the research reported here was undertaken for the following purposes: (a) to determine strength and durability characteristics of selected mixtures of coal refuse and fly ash, (b) to demonstrate that coal refuse and fly ash can be combined to yield potentially useful construction materials, and (c) to assess the feasibility of using mixtures of coal refuse and fly ash in pavement construction. The scope of the research effort was restricted to assessments of potential utility of selected mixtures as highway pavement base courses through the use of a computer-based pavement-performance-simulation program. Matters that deal with availability of refuse and ash and economic feasibility related to conventional construction materials were addressed in the research program and reported elsewhere (1, p. 8-12; 3); they are not considered here.

This paper is divided into four parts. A summary of the engineering characteristics of coal refuse and fly ash samples is presented followed by strength, durability, and environmental quality assessments of selected blends of coal refuse and fly ash. Next, the effects of various stabilizing agents on the strength and durability of the blends is presented. Finally, performances of four hypothetical highway pavements are compared with the aid of a pavement-performance-simulation program. The base courses of the pavements were a crushed stone aggregate, an unstabilized coal refuse and fly ash mixture, a lime-stabilized refuse and ash mixture, and a portland-cement-stabilized refuse and ash mixture. Base-course thicknesses, ambient temperatures, and subgrade support conditions were variables in the simulation program.

CHARACTERISTICS

Coal Refuse and Fly Ash Samples

Samples of coal refuse were obtained from 18 loca-

Table 1. Characteristics of coal refuse and fly ash samples.

Sample Identification	Classification	As-Received Moisture Content (%)	Atterberg Limits (%)			Specific Gravity	Max. Dry Unit Weight[a] (lb/ft^3)	Optimum Moisture Content (%)	Percentage Finer Than Sieve	
			w_l	w_p	PI				No. 4	No. 200
I-1a	GP	5.8	35.3	NP	NP	2.03	84.3	13.6	7	0
I-1b	GW	6.7	34.8	33.1	1.7	2.26	88.5	10.0	11	2
I-2	GP	8.1		NP	NP	2.27	97.0	15.0	49	3
II-1	GW	10.2		NP	NP	2.06	105.5	8.0	19	1
II-2	SC	8.5	34.9	24.7	10.2	2.58	112.1	12.0	52	27
II-3	GW	14.5	21.9	NP	NP	1.98	100.6	11.5	36	5
II-4	SP-SM	23.6	38.8	NP	NP	1.47	81.0	13.0	62	11
II-5	GW	2.8	25.5	NP	NP	1.73	99.3	7.6	14	3
II-6	GP-GM	7.7	25.2	20.9	4.3	2.34	120.0	8.8	32	8
II-7	GW	3.3	26.7	23.8	2.9	2.08	100.7	10.0	31	4
IV-1	GP-GM	8.8	20.8	NP	NP	2.15	114.6	8.8	33	7
V-1	SM	8.1	19.1	17.0	2.1	2.15	105.2	9.0	57	15
V-3	SM	13.4	27.5	21.6	5.9	2.07	97.8	13.4	88	19
VI-1	GW	2.5	26.8	21.5	5.3	2.46	112.4	10.3	25	3
VI-2	GW	7.7		NP	NP	1.72	86.5	8.2	32	2
VII-1	GP					2.47	100.9	4.3	6	0
IX-1	SM	14.5	49.2	33.1	16.1	2.60	108.2	14.7	52	32
IX-2	GC	7.6	32.3	22.7	9.6	2.51	113.4	13.0	37	12
FI-1	ML	0.2			NP	2.27	87	21.0	100	95
FII-1	ML	0.3			NP	2.34	85.0	23.5	100	85
FII-3	ML				NP	2.32	83.2	23.3	100	79
FII-6	ML	0.2			NP	2.23	69.3	29.0	100	60
FII-7	ML	22.6			NP	2.73	90.2	25.5	100	72
FIV-1	ML				NP	2.35	64.0	40.5	100	84
FV-1	ML	0.3			NP	2.25	87.0	20.0	100	84
FV-3	ML	4.3			NP	2.30	92.7	14.5	100	90
FVI-1	ML	0.3			NP	2.24	83.8	22.0	100	85
FVI-2	ML	0.1			NP	2.24	86.4	21.6	100	84
FVII-1	ML	0.1			NP	2.41	86.3	24.6	100	93
FIX-1	ML	4.9			NP	2.52	84.9	21.7	100	83
FIX-2	ML	0.6			NP	2.44	72.8	33.0	100	92

Note: NP = nonplastic.
[a]Standard Proctor compactive effort.

tions in the east, south, and midwestern portions of the United States. Both anthracite and bituminous coal refuse supplies were represented. Sample age ranged from several hours to approximately 80 years. Thirteen fly ash samples were obtained from power plants near the coal refuse sources. The bases on which the samples were selected and the sample identification scheme are presented elsewhere (1, pp. 8-12).

Classification and compaction tests were performed on each coal refuse and fly ash sample. The results are summarized in Table 1. These results and results of other constituent identification and classification tests indicated and confirmed the following:

1. Characteristics of both by-products were highly variable, particularly those of the coal refuse samples where texture and plasticity ranged from coarse to fine-grained and from nonplastic to plastic, respectively; and
2. Characteristics of all samples were generally representative of those reported in the literature for both by-products.

Results of the initial characterization tests served as aids in developing blends of coal refuse and fly ash and in interpreting results of tests performed on the mixtures in latter stages of the laboratory testing program.

Coal Refuse and Fly Ash Mixtures

Three types of laboratory tests were employed in the characterization and evaluation of mixtures of coal refuse and fly ash; these were gradation-compaction-strength tests, durability tests, and environmental quality tests. Selected test results appear in Tables 2 and 3. Complete results appear elsewhere (3). The following observations appear warranted.

Gradation

The mixtures tested did not experience extensive particle degradation after compaction; consequently, preand post-compaction gradations were essentially identical. Only minor particle breakdown was observed as result of increased compactive effort. Weak, frangible particles do not necessarily constitute coal refuse.

Compaction

Changes in fly ash content affect both maximum dry unit weights and optimum water contents of the mixtures. Increasing the fly ash content generally tends to increase the maximum dry unit weight, and excessive amounts of fly ash tend to decrease unit weight. Exceptions to these trends were noted.

Strength

Mixture strength, as reflected by California bearing ratio (CBR) and Hveem stabiliometer values, varies as a function of fly ash content; an optimum ash content was apparent for most blends. Maximum 0.1-in (2.5-mm) penetration CBR values varied considerably from about 11 to about 68. Significant changes in CBR accompanied small changes in ash content for most of the mixtures.

Durability

Wet and dry durability was assessed by submerging compacted samples in water at room temperature for 24 h followed by oven drying at 225°F for 24 h. The wetting-drying cycle was repeated and the specimens

Table 2. Characteristics of coal refuse and fly ash mixtures.

Sample Identification	Mixture Composition (% of dry weight)		Maximum Dry Unit Weight[a] (lb/ft^3)	Optimum Water Content[a] (%)	CBR, 4-day soak[a]			Fineness Modulus[b]		Permeability[c] (cm/s)	Hveem Stability Resistance Value[d]
	Coal Refuse	Fly Ash			0.1-in Penetration	0.2-in Penetration	Swell (%)	Before Compaction	After Compaction		
I-2	100	0	97.0	15.0							
	90	10	108.8	9.7	2	3	2.8	4.3	4.1	3.8×10^{-6}	
	80	20	112.4	9.8	17	26	0.2	4.0	3.6	1.5×10^{-6}	
	70	30	113.2	11.1	7	9	1.1	3.0	3.1	2.5×10^{-6}	
	60	40	112.6	10.6	10	13	1.6	2.7	2.3		
	0	100	87.0	21.0							
II-1	100	0	105.5	8.0							
	90	10	103.2	9.2	42	48	0.5	4.8	4.0		63
	80	20	106.0	9.2	29	28	1.0	4.2	3.7		
	70	30	108.0	9.2	24	26	1.4	2.7	3.5		
	60	40	107.8	10.0	17	18	1.8	2.9	3.1		
	0	100	85.0	23.5							
II-5	100	0	99.3	7.6							
	90	10	110.3	8.5	50	63	0.5	5.4	5.1		
	80	20	109.0	10.0	49	61	0.4	4.7	4.8		
	70	30	108.1	9.4	51	60	0.7	4.5	4.4		
	60	40	104.5	10.5	29	37	0.3	3.6	4.0		
	0	100	83.2	23.3							
II-6	100	0	120.0	8.8							
	90	10	115.4	9.1	10	14	1.2	5.1	4.3		
	80	20	111.6	9.8	40	44	1.7	4.4	3.6		
	80	20	111.6	9.8	11[e]	14[e]	0.7[e]				
	80	20	118.6[f]	8.0[f]	60	52	0.5	3.8	3.8		
	80	20	118.6[f]	8.0[f]	37[e]	42[e]	0.5[e]				
	70	30	106.4	10.7	43	42	1.8	3.7	3.5		
	60	40	103.0	12.0	31	27	3.5	3.4	2.9		
	0	100	69.3	29.0							
II-7	100	0	100.7	10.9							
	90	10	100.0	10.8	31	35	1.5	4.9	4.7		
	80	20	100.7	12.5	18	39	0.6	4.3	4.0		
	70	30	101.2	12.0	31	36	1.3	4.2	4.4		
	60	40	100.4	13.2	40	40	0.7	3.6	3.6		
	0	100	90.2	25.5							
IV-1	100	0	114.6	8.8							
	90	10	110.1	9.2	40	53	0.4	5.1	4.2		
	80	20	105.3	11.9	54	56	0.3	4.2	3.8		78
	70	30	100.6	15.0	29	29	0.5	3.4	3.1		
	60	40	93.5	18.1	26	32	0.6	3.2	2.8		
	0	100	64.0	40.5							
V-1	100	0	105.2	9.0							
	90	10	110.4	8.5	13	18	0.05	4.4	3.8		
	80	20	110.2	8.6	10	15	0.04	3.9	3.7		
	70	30	108.5	8.5	15	21	0.06	3.5	3.1		
	60	40	105.8	9.9	25	26	0.7	2.8	2.9		65
	0	100									
V-3	100	0	87.8	13.4							
	90	10	110.0	9.3	5	7	1.3	4.7	4.1		
	80	20	110.4	9.4	7	11	1.7	4.2	3.7		
	70	30	109.8	9.7	11	12	1.5	4.0	3.2		
	60	40	109.6	9.4	6	8	1.4	3.2	2.5		
	0	100	92.7	14.5							
VI-1	100	0	112.4	10.3							
	90	10	101.1	8.1	22	27	0.3	5.1	4.7		
	80	20	106.8	7.9	46	41	0.2	4.6	4.4		
	70	30	105.9	9.1	29	34	0.5	3.8	4.1		
	60	40	102.0	10.1	24	28	0.7	3.3	3.7		
	0	100	83.8	22.0							
VII-1	100	0	100.9	4.3							
	90	10	117.4	6.1	18	24	0.1	5.8	5.4		
	80	20	115.6	9.3	43	52	0.2	5.4	4.8		
	70	30	119.9	10.6	42	53	0.1	4.8	4.5		
	60	40	126.4	7.5	68	62	0.5	3.9	3.8		
	0	100	86.3	24.6							
IX-1	100	0	108.2	14.7							
	90	10	105.0	17.5	6	5	2.5	4.8	4.9		
	80	20	107.8	13.2	9	10	4.3	4.5	4.7		
	70	30	107.0	12.8	12	15	4.7	4.0	4.2	1.4×10^{-6}	
	60	40	106.4	12.5	21	20	4.7	3.8	4.2		66
	60	40	118.6[f]	11.0[f]	40	32	2.2	3.8	3.8		
	60	40	118.6[f]	11.0[f]	16[e]	12[e]					
	0	100	84.9	21.7							

[a]Standard Proctor compactive effort.
[b]Cumulative percentage retained on standard sieve series.
[c]Falling head test.
[d]Exudation basis.
[e]Two wet-dry cycles followed by 4-day soak.
[f]Modified Proctor compactive effort.

Table 3. Results of leachate quality tests.

Sample Identification	Mixture Composition (% of dry weight) Coal Refuse	Fly Ash	pH Initial[a]	Final[b]	Permissible Range[c]	Element	Measured Concentration (ppm)	Max. Permissible Concentration[d] (ppm)
II-6	70	30	9.2	3.9	12.5-2.0	Al	0.352	
						As	0.007	5
						Ba	0.078	100
						Cd	<0.001	1
						Cr	0.042	5
						Cu	0.084	
						Fe	4.223	
						Mn	0.389	
						Mo	0.112	
						Ni	0.540	
						Pb	0.160	5
						Se	0.001	1
						Zn	0.161	
IV-1	80	20	5.9	3.9	12.5-2.0	Al	0.163	
						As	<0.001	5
						Ba	0.136	100
						Cd	0.012	1
						Cr	0.041	5
						Cu	0.067	
						Fe	16.466	
						Mn	0.717	
						Mo	1.258	
						Ni	1.640	
						Pb	0.160	5
						Se	<0.001	1
						Zn	0.283	

[a]After mixing with deionized water. [b]After 24-h extraction period. [c]EPA corrosivity criteria. [d]EPA hazardous waste toxicity criteria (100 times drinking water standards).

were then soaked in water for four days prior to CBR testing. Most of the specimens experienced large decreases in soaked CBR. These results bring the durability of unstabilized coal refuse-fly ash mixtures into question. Attempts were made to determine mixture freeze-thaw durability. Test results were inclusive.

Environmental Quality

Two blends were employed to evaluate the quality of leachate from coal refuse and fly ash mixtures. Leachate samples were obtained by means of the U.S. Environmental Protection Agency (EPA) toxicity test extraction procedure (4). Results of leachate quality tests indicated that both samples were environmentally acceptable construction materials with respect to current EPA corrosivity and toxicity criteria. The samples tested were unstabilized and in a loose state. We anticipated that concentrations of elements in leachate from compacted mixtures would be significantly reduced over those obtained by the EPA extraction procedure and that leachate volume would be small. The very low permeabilities measured in the laboratory and reported in Table 2 are noteworthy in this regard. The addition of stabilizing agents to the mixtures should also decrease both concentration levels and leachate volume. However, generalizations apropos of all refuse-ash mixtures are not possible based on the limited data.

STABILIZED COAL REFUSE-FLY ASH MIXTURES

The effects of various stabilizing agents on selected refuse-ash mixtures were investigated. Stabilizing agents included portland cement, hydrated lime, asphalt cement, and emulsified asphalt. Only the cement and lime stabilization efforts are summarized here; detailed results are reported elsewhere (3).

Ten mixtures were chosen for testing with cement and lime. Initially, refuse and ash proportions were selected that yielded the highest CBR value in the unstabilized mixture. Subsequently, the coal refuse content was held constant and the fly ash content was reduced as the amount of stabilizer increased. This procedure was followed to maintain a constant fines content and to maximize the refuse content.

Portland Cement Stabilization

Type 1 portland cement was added to the mixtures in amounts that ranged from 8 to 14 percent by dry weight of the mixture. Cement contents that exceeded 14 percent were judged to be uneconomical. The stabilized specimens were prepared and cured according to ASTM 192 C, in 4-in diameter compaction molds. The unconfined compression test was employed in evaluating the strength of the mixtures. An adequately stabilized specimen was assumed to be one whose 7-day strength was 400 lb•f/in² (1, pp. 8-12). Additional strength tests were conducted at 14 and 28 days for those mixtures that satisfy the 7-day criterion. Vacuum saturation tests, conducted according to ASTM C593, were also performed on several of the specimens to aid assessments of mixture durability. Test results are summarized in Table 4.

Lime Stabilization

High-calcium-hydrated lime contents of 4, 6, 8, and 10 percent by dry weight of mixture were employed in evaluating the effects of lime on coal refuse and fly ash mixtures. Lime contents that exceeded 10 percent were not considered because they were judged to be uneconomical. The stabilized samples were prepared according to ASTM D698 C in 4-in diameter compaction molds and cured in sealed containers at 70°F for 28 days. Strength testing procedures were the same as those employed in the investigation of cement-stabilized mixtures. The strength criteria assumed for lime-stabilized blends was 400 lb•f/in² after a 7-day accelerated or 28-day standard cure and based on modified Proctor sample preparation (5). Samples tested in the program reported here were not prepared according to modified Proctor specifications; consequently, assessments of the efficacy of lime-stabilization based on the 400 lb•f/in² criteria are not possible. However, on the basis of additional tests not reported here, it is believed that several of the mixtures would satisfy the strength criteria if specimens were prepared with modified Proctor com-

Table 4. Characteristics of portland-cement-stabilized mixtures.

Sample Identification	Mixture Composition (% of dry weight): Coal Refuse	Fly Ash	Portland Cement	Molding Water Content (%)	Dry Unit Weight (lb/ft^3)	Specimen Age (days)	Unconfined Compressive Strength (lb/in^2)
I-2	80	20	0	12.4	108.8	7	21
	80	12	8	13.4	110.0	7	404
	80	9	11	13.3	110.8	7	672
	80	6	14	13.1	108.2	7	809
	80	12	8	9.9	109.5	14	771
	80	12	8	8.9	108.5	28	900
I-2, vacuum saturated	80	12	8	11.2	107.4	7	421
	80	12	8	11.5	107.8	14	552
	80	12	8	10.9	106.9	28	611
II-5	70	30	0	9.5	10.38	7	27
	70	22	8	9.0	99.1	7	171
	70	19	11	8.2	99.9	7	267
	70	16	14	9.4	101.2	7	262
II-6	70	30	0	10.9	102.5	10	16
	70	22	8	10.8	105.4	10	342
	70	19	11	11.2	107.4	10	369
	70	16	14	10.5	108.6	10	515
	70	18	12	10.7	112.8	7	530
	70	18	12	10.2	111.6	14	599
	70	18	12	11.6	110.8	28	979
II-6, vacuum saturated	70	18	12	10.8	113.0	7	356
	70	18	12	8.4	115.2	14	493
	70	18	12	11.7	111.6	28	728
II-7	60	40	0	13.3	101.2	6	47
	60	32	8	12.0	100.2	6	351
	60	29	11	14.3	96.3	6	393
	60	26	14	14.2	99.9	6	592
	60	29	11		91.8	7	157
	60	29	11			14	196
	60	29	11		91.9	28	258
	60	28	12	8.7	96.5	7	230
	60	28	12	8.3	97.2	14	193
	60	28	12	8.7	96.5	28	275
II-7, vacuum saturated	60	29	11		91.2	7	157
	60	29	11		89.4	14	231
	60	29	11		90.5	28	241
	60	28	12	9.1	95.8	7	111
	60	28	12	8.2	96.2	14	142
	60	28	12	8.6	97.2	28	132
IV-1	80	20	0	16.7	98.4	7	10
	80	12	8	10.4	108.3	7	64
	80	9	11	12.0	105.1	7	215
	80	6	14	12.3	106.2	7	292
V-1	60	40	0	9.8	104.2	15	19
	60	32	8	9.7	105.3	7	429
	60	29	11	9.5	106.2	7	846
	60	32	8	9.6	105.8	15	624
	60	29	11	9.3	106.8	15	1044
	60	26	14	10.4	106.8	15	1053
	60	32	8	9.9	103.2	14	565
	60	32	8	10.2	103.8	28	789
V-1, vacuum saturated	60	32	8	10.7	103.3	7	448
	60	32	8	10.1	103.3	14	424
	60	32	8	10.6	104.4	28	540
V-3	70	30	0	10.5	100.2	7	41
	70	22	8	10.5	96.9	7	209
	70	19	11	10.3	107.8	7	258
	70	16	14	10.2	98.6	7	354
VI-1	80	20	0	9.6	102.6	7	23
	80	12	8	8.3	103.7	7	320
	80	9	11	7.0	107.4	7	374
	80	6	14	8.2	107.2	7	380
VII-1	60	40	0	7.3	111.4	7	15
	60	32	8	7.4	110.8	7	279
	60	29	11	8.9	110.2	7	294
	60	26	14	7.4	112.0	7	534
	60	28	12	7.9	113.4	7	599
	60	28	12	7.8	113.0	14	662
	60	28	12	5.7	116.2	28	898
VII-1, vacuum saturated	60	28	12	7.0	115.6	7	425
	60	28	12	6.6	114.0	14	478
	60	28	12	7.6	113.1	28	500
IX-1	60	40	0	13.4	96.1	7	28
	60	32	8	11.8	94.3	7	55
	60	29	11	12.2	94.9	7	78

pactive effort. Mixture strengths and other test results appear in Table 5.

Observations

The following observations appear warranted:

1. Unconfined compressive strengths of stabilized mixtures are functions of both the type and amount of stabilizing agent present.
2. Mixtures that respond favorably to stabilization with cement may not respond favorably to stabilization with lime; the converse is also true.
3. Results of vacuum saturation tests indicate that the durability of cement-stabilized mixtures I-2, II-6, V-1, and VII-1 may be satisfactory.

Results of tests not reported here where other stabilizing agents were employed indicate that certain coal refuse and fly ash mixtures are amenable to stabilization with asphalt cement or emulsified asphalt.

Table 5. Characteristics of lime-stabilized mixtures.

Sample Identi-fication	Mixture Composition (% of dry weight)			Molding Water Content (%)	Dry Unit Weight (lb/ft^3)	Unconfined Compressive Strength[a] (lb/in^2)
	Coal Refuse	Fly Ash	Lime			
I-2	80	16	4	14.0	102.6	142
	80	14	6	13.2	101.8	117
	80	12	8	14.5	98.2	111
	80	10	10	13.5	96.7	112
II-5	70	26	4	10.9	96.6	62
	70	24	6	10.2	95.6	112
	70	22	8	12.3	92.7	73
	70	20	10	11.0	89.0	28
II-6	70	26	4	13.3	103.7	129
	70	24	6	11.0	104.4	100
	70	22	8	12.6	101.9	88
	70	20	10	9.4	104.2	95
II-7	60	34	4	15.8	91.7	104
	60	34	6	15.3	90.9	105
	60	32	8	15.0	88.2	85
	60	60	10	16.2	87.1	83
IV-1	80	16	4	10.4	96.8	141
	80	14	6	9.4	98.5	146
	80	12	8	8.7	96.5	111
	80	10	10	9.4	96.6	88
V-1	60	36	4	11.9	99.0	223
	60	34	6	12.4	98.9	205
	60	32	8	10.7	99.8	156
	60	30	10	11.1	97.8	149
V-3	70	26	4	11.2	93.2	161
	70	24	6	10.5	92.5	205
	70	22	8	10.8	90.0	209
	70	20	10	10.6	90.3	196
VI-1	80	16	4	7.9	103.3	104
	80	14	6	7.3	102.6	94
	80	12	8	8.2	95.9	71
	80	10	10	9.0	94.7	68
VII-1	60	36	4	6.9	107.3	168
	60	34	6	8.2	106.7	165
	60	32	8	7.0	104.6	119
	60	30	10	6.7	105.8	168
IX-1	60	36	4	13.8	114.6	222
	60	34	6	13.7	114.4	276
	60	32	8	14.8	113.2	225
	60	30	10	14.6	113.3	163

[a] 28-day-old specimens.

Table 6. Temperature arrays in VESYS comparisons.

Month	Avg. Monthly Temperature		Month	Avg. Monthly Temperature	
	Vum	Mgt		Vum	Mgt
January	49.7	28.3	July	84.6	71.7
February	53.3	30.7	August	84.7	70.8
March	59.5	41.4	September	78.0	65.4
April	68.6	51.2	October	70.1	52.8
May	75.2	54.9	November	59.1	44.2
June	81.6	68.0	December	52.3	35.2

PAVEMENT PERFORMANCE

The theoretical performances of 160 highway pavements were compared. Coal refuse and fly ash mixtures, both unstabilized and stabilized, were the base-course materials for 92 of the pavements; a crushed stone material constituted the base courses for the remaining pavements. The comparisons were accomplished with the aid of the VESYS II M pavement-performance-simulation program. The VESYS II M program predicts the behavior of a three-layer flexible pavement as a function of time in terms of rutting depth, slope variance, cracked area, and serviceability index. Material characteristics of the combined asphalt surface course and binder, the base course, and the subgrade are required input information. Additional variables are average monthly temperatures of the environment, the traffic loading, and the pavement serviceability limit.

Procedures for obtaining predicted performance of the pavements and material characteristics are presented in detail elsewhere (3). In sum,

1. Material characteristics of the asphalt layer, the crushed stone base course, and the clay subgrade were taken from the VESYS user's manual (6).
2. Two subgrade conditions were considered: The dry condition refers to a stiff and essentially elastic subgrade and the wet condition refers to a weak, viscoelastic subgrade.
3. Two temperature arrays were considered: The first array, designated Vum, represented a relatively warm climate. Vum was taken from the user's manual (6). The second array, Mgt, represented average monthly temperatures for a cooler climate.
4. Both the pavement performance limits and the traffic conditions adopted in the comparisons were the same as those in the manual (6).
5. The coal refuse and fly ash mixture selected for laboratory characterization in unstabilized, cement-stabilized, and lime-stabilized forms was the 60-40 blend of material V-1. This blend represents a silty sand-sandy silt material that exhibited fairly low CBR and Hveem R values and responded reasonably well to both lime and cement stabilization. Material V-1 was judged neither the best nor the poorest of the blends tested.

Details of the temperature arrays appear in Table 6. Characteristics of the base-course materials that served as input for the VESYS II M program appear in Table 7. The definitions and instructions for calculating creep compliance and permanent deformation characteristics in Table 7 can be found in Kenis (6). Results of the pavement performance simulations appear in Table 8.

Limiting performance criteria were adopted as aids in comparing predicted pavement performance. The criteria were the same as those employed in the design example in the manual (6):

1. Maximum rut depth of 0.5 in in 20 years,
2. Maximum slope variance of 10^{-3} radians in 20 years,
3. Maximum cracked area of 500 $yd^2/1000$ yd^2 of pavement surface in 20 years, and
4. Minimum present serviceability index of 2.5 after 20 years.

Pavement systems that have minimum layer thicknesses that satisfy the criteria appear in Table 9.

Table 7. Base-course characteristics for VESYS program.

Base-Course Material	Creep Compliance $[(10^{-6}$ in/in)/(lb·f/in$^2)]$											Permanent Deformation Characteristics	
	Time When Creep Compliance Was Determined												
	0.001 s	0.003 s	0.010 s	0.030 s	0.10 s	0.30 s	1 s	3 s	10 s	30 s	100 s	Gnu	Alpha
Crushed stone[a]	17	17		17	17	17	17	17	17	17	17	0.055	0.730
Unstabilized CR-FA at indicated water content[b]													
w = 7 percent[c]	74	80.5	87.5	94	96	100	100	100	100	100	100	0.012	0.875
w = 10 percent[d]	67.5	72	75	77	79	81	83	83	83	83	83	0.006	0.668
w = 13 percent[e]	200	205	212	217	229	233	240	250	250	250	260	0.619	0.185
Portland-cement stabilized CR-FA[f]	2	2	2	2	2	2	2	2	2	2	2	0	1.0
Lime-stabilized CR-FA[g]	2	3	5	6	8	12.5	12.5	12.5	12.5	16	16	0.003	0.554

[a]Characteristics taken from example design problem in Kenis (6).
[b]Sample V-1, 60-40 percent mixture coal refuse-fly ash, percentage of dry weight.
[c]Mixture water content less than standard Proctor optimum.
[d]Mixture water content equal to standard Proctor optimum.
[e]Mixture water content greater than standard Proctor optimum.
[f]Sample V-1, 60-32-8 percent mixture coal refuse, fly ash, and cement, percentage of dry weight, 28-day cure time.
[g]Sample V-1, 60-36-4 percent mixture coal refuse, fly ash, and lime, percentage of dry weight, 28-day cure time.

Table 8. Selected values from the VESYS program simulation of pavement performance.

Base-Course Material	Temperature Array[a]	Subgrade Condition	Thickness of Layer (in) Upper	Thickness of Layer (in) Base Course	Rut Depth (in)	Slope Variance (10^{-6} radians)	Cracking (yd^2/1000 yd^2 of surface)	Present Serviceability Index After 20 Years	Expected Pavement Life[b] (years)
Crushed stone	Vum	Dry[c]	4	6	0.18	1.19	1000	3.84	>20
			4	8	0.19	1.18	1000	3.83	>20
			4	10	0.20	1.09	1000	3.86	>20
			4	14	0.21	0.98	1000	3.89	>20
			6	6	0.24	2.08	0	3.86	>20
			6	8	0.25	2.08	0	3.85	>20
			6	10	0.25	2.00	0	3.87	>20
			6	14	0.26	1.80	0	3.91	>20
			8	8	0.25	2.17	0	3.83	>20
			8	10	0.26	2.14	0	3.84	>20
			8	14	0.26	2.00	0	3.86	>20
	Mgt	Dry	4	10	0.15	0.64	969	4.07	>20
			4	14	0.16	0.58	949	4.09	>20
			6	6	0.17	0.98	0	4.24	>20
			6	8	0.17	0.99	0	4.23	>20
			6	10	0.17	0.96	0	4.24	>20
			6	14	0.18	0.87	0	4.27	>20
			8	8	0.16	0.90	0	4.27	>20
			8	10	0.16	0.89	0	4.27	>20
			8	14	0.17	0.84	0	4.29	>20
	Vum	Wet[d]	4	10	1.08	27.47	1000	<1	3.7
			4	14	0.84	15.50	1000	1.2	8
			6	10	1.04	29.48	1000	<1	3.5
			6	14	0.86	17.49	833	1.09	7.4
			8	10	0.95	26.71	0	<1	4.6
			8	14	0.82	17.77	0	1.47	7.7
			10	10	0.90	25.57	0	<1	5.1
			10	14	0.81	18.90	0	1.46	7.4
			10	24	0.63	9.78	0	2.34	17.1
			10	30	0.56	6.79	0	2.73	>20
			12	14	0.78	18.76	0	1.51	7.6
			12	24	0.64	10.58	0	2.27	15.7
	Mgt	Wet	4	8	0.87	19.67	1000	<1	6.6
			4	10	0.77	14.05	1000	1.46	9.4
			4	14	0.63	8.62	1000	2.13	14.7
			6	8	0.73	15.84	0	1.77	10.1
			6	10	0.68	12.60	0	2.06	13.1
			6	14	0.59	8.25	0	2.55	>20
			6	20	0.49	5.13	0	3.04	>20
			8	8	0.62	11.98	0	2.23	15.2
			8	10	0.58	10.11	0	2.42	18.4
			8	14	0.53	7.44	0	2.73	>20
			8	16	0.50	6.38	0	2.88	>20
Unstabilized coal refuse and fly ash at 7 percent water content[e]	Vum	Dry	8	12	>10	$>10^5$	0	<0	0.3
			8	18	>10	$>10^5$	0	<0	0.3
			8	36	>10	$>10^5$	0	<0	0.3
			12	12	>10	$>10^5$	0	<0	0.3
	Mgt	Dry	8	12	>10	$>10^5$	0	<0	0.3
			8	18	>10	$>10^5$	0	<0	0.3
			8	36	>10	$>10^5$	0	<0	0.3

Table 8. Continued.

Base-Course Material	Temperature Array[a]	Subgrade Condition	Thickness of Layer (in) Upper	Thickness of Layer (in) Base Course	Rut Depth (in)	Slope Variance (10^{-6} radians)	Cracking (yd^2/1000 yd^2 of surface)	Present Serviceability Index After 20 Years	Expected Pavement Life[b] (years)
Unstabilized coal refuse and fly ash at 7 percent water content[c]	Vum	Wet	8	24	>10	$>10^5$	745	<0	0.3
			8	36	>10	$>10^5$	287	<0	0.3
			12	12	>10	$>10^5$	0	<0	0.3
	Mgt	Wet	8	24	>10	$>10^5$	0	<0	0.3
			8	36	>10	$>10^5$	0	<0	0.3
Portland-cement-stabilized coal refuse and fly ash[e]	Vum	Dry	4	4	0.11	0.45	0	4.49	>20
			4	6	0.11	0.37	0	4.53	>20
			4	8	0.11	0.34	0	4.55	>20
			4	10	0.11	0.29	0	4.58	>20
			4	12	0.11	0.25	0	4.60	>20
	Mgt	Dry	4	4	0.10	0.34	0	4.56	>20
			4	6	0.09	0.28	0	4.59	>20
			4	8	0.09	0.21	0	4.64	>20
	Vum	Wet	6	6	0.77	15.34	0	1.72	9.6
			6	8	0.60	9.46	0	2.43	18.6
			6	10	0.50	6.69	0	3.29	>20
	Mgt	Wet	4	4	0.66	11.56	0	2.17	14.5
			4	6	0.48	6.24	0	2.93	>20
			4	8	0.38	4.44	0	3.29	>20
Lime-stabilized coal refuse and fly ash[e]	Vum	Dry	4	4	0.11	0.45	0	4.49	>20
			4	10	0.12	0.34	0	4.55	>20
			6	8	0.19	1.05	0	4.20	>20
			6	10	0.18	0.90	0	4.26	>20
			8	8	0.20	1.29	0	4.11	>20
			8	10	0.20	1.17	0	4.15	>20
	Mgt	Dry	4	4	0.09	0.25	0	4.61	>20
			4	10	0.07	0.12	0	4.70	>20
			6	8	0.11	0.37	0	4.53	>20
			6	10	0.11	0.30	0	4.58	>20
			8	8	0.12	0.42	0	4.50	>20
			8	10	0.11	0.36	0	4.54	>20
	Vum	Wet	4	8	0.92	25.47	0	<1	5.4
			4	10	0.75	19.09	0	1.58	8.4
			4	14	0.57	13.09	0	2.25	15.5
			4	20	0.48	10.36	0	2.59	>20
			6	8	0.90	21.15	0	1.12	6.3
			6	10	0.78	16.63	0	1.62	8.9
			6	14	0.62	11.97	0	2.23	15.2
			8	8	0.84	18.26	0	1.40	7.5
			8	10	0.75	14.52	0	1.79	10.4
			8	14	0.62	10.54	0	2.31	16.6
			8	20	0.49	7.53	0	2.79	>20
	Mgt	Wet	4	8	0.48	7.07	0	2.84	>20
			4	10	0.41	5.55	0	3.11	>20
			4	14	0.33	4.29	0	3.38	>20
			6	8	0.46	5.44	0	3.05	>20
			6	10	0.40	4.27	0	3.29	>20
			6	14	0.32	3.18	0	3.56	>20
			8	8	0.42	4.62	0	3.21	>20
			8	10	0.38	3.62	0	3.42	>20
			8	14	0.31	2.61	0	3.68	>20

[a]Arrays are found in Table 6. [b]Approximate time for serviceability to reach 2.5. [c]Clay subgrade, 16 percent water content. [d]Clay subgrade, 23 percent water content. [e]Defined in Table 7.

Unstabilized blends are absent from Table 9 because none of the analyzed pavement systems exhibited satisfactory performance when an unstabilized mixture was the base-course material, regardless of the temperature or subgrade conditions. Analyses of unstabilized blends at optimum and wet of optimum water contents were not conducted because those mixtures were even weaker than the unsatisfactory dry of optimum mixture.

The following observations appear warranted based on assessments of results of the VESYS pavement performance simulation:

1. Effects of changes in subgrade conditions and temperature array on predicted performance were as anticipated. Pavements that incorporate the dry (stiffer) subgrade consistently yielded lower rut depths, slope variances, and cracked areas and higher serviceability indices than did identical sections that incorporated the wet subgrade. In addition, the colder climate array resulted in more favorable performance than the warmer array for identical sections.

2. Layer thicknesses of minimum, satisfactory, stabilized-mixture base-course pavement systems are less than the thicknesses of corresponding layers of minimum systems where crushed stone material was the base course.

3. For systems of equal corresponding layer thicknesses, the performance of pavements with stabilized coal refuse-fly ash mixtures exceeds the performance of the crushed-stone base-course pavements.

4. The unstabilized mixtures analyzed herein are structurally unsuitable for highway base-course applications.

CONCLUSIONS

Major conclusions that emerged from this study were as follows:

1. Several of the unstabilized coal refuse and

Table 9. Minimum pavement systems that satisfy performance criteria.

Base-Course Material	Temperature Array[a]	Subgrade Condition[b]	Thickness of Layer (in) Upper	Base Course	Present Serviceability Index after 20 Years	Controlling Performance Criterion
Crushed stone	Vum	Dry	6	6	3.86	Cracking
		Wet	10[c]	36[c]	2.88[c]	Rut depth
	Mgt	Dry	6	6	4.24	Cracking
		Wet	8	16	2.88	Rut depth
Portland-cement-stabilized coal refuse and fly ash[d]	Vum	Dry	4	4	4.49	Minimum thickness[e]
		Wet	6	10	2.85	Rut depth
	Mgt	Dry	4	4	4.56	Minumum thickness[e]
		Wet	4	6	2.93	Rut depth
Lime-stabilized coal refuse and fly ash[d]	Vum	Dry	4	4	4.49	Minimum thickness[e]
		Wet	8	20	2.79	Rut depth
	Mgt	Dry	4	4	4.61	Minimum thickness[e]
		Wet	4	8	2.84	Rut depth

[a]Arrays found in Table 6. [b]Defined in Table 8. [c]Values estimated from trends established in Table 8. [d]Defined in Table 7. [e]Minimum layer thickness considered was 4 in.

fly ash mixtures appeared to be feasible base-course candidate materials based on the results of CBR and Hveem stabilometer tests. However, results of laboratory durability tests suggest that the long-term durability of unstabilized mixtures is questionable.

2. Coal refuse and fly ash mixtures may be responsive to stabilization with one or more agents (e.g., portland cement, lime, asphalt cement, and emulsified asphalt). Consequently, use of stabilized mixtures in base-course applications appears technically feasible.

3. The likelihood of a serious negative environmental impact arising from stabilized mixtures in base-course applications is remote.

4. Hypothetical pavement systems that have cement and lime-stabilized coal refuse and fly ash mixture base courses yielded thinner surface and base course layers than pavements that have a crushed stone base for the same loading, temperature, and subgrade conditions. Conversely, for systems with equal thicknesses of corresponding layers, the systems that incorporated stabilized mixture base course exhibited better hypothetical performance than systems that incorporated the crushed stone base courses.

5. The VESYS II M pavement performance simulation program provides a rapid procedure for comparing large numbers of pavement systems.

6. Use of unstabilized coal refuse and fly ash mixtures as highway base-course materials is highly questionable.

7. In-service field testing of cement and lime-stabilized compositions should be accomplished to evaluate performance and long-term durability of the mixtures.

8. Waste products should be considered as candidate construction materials along with traditional materials. Current technology makes comparisons and assessments of competing materials possible.

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