Stabilizing Soft Fine-Grained Soils with Fly Ash

Tuncer B. Edil, M.ASCE[1]; Hector A. Acosta, M.ASCE[2]; and Craig H. Benson, M.ASCE[3]

Abstract: The objective of this study was to evaluate the effectiveness of self-cementing fly ashes derived from combustion of sub-bituminous coal at electric power plants for stabilization of soft fine-grained soils. California bearing ratio (CBR) and resilient modulus (M_r) tests were conducted on mixtures prepared with seven soft fine-grained soils (six inorganic soils and one organic soil) and four fly ashes. The soils were selected to represent a relatively broad range of plasticity, with plasticity indices ranging between 15 and 38. Two of the fly ashes are high quality Class C ashes (per *ASTM C 618*) that are normally used in Portland cement concrete. The other ashes are off-specification ashes, meaning they do not meet the Class C or Class F criteria in *ASTM C 618*. Tests were conducted on soils and soil–fly ash mixtures prepared at optimum water content (a standardized condition), 7% wet of optimum water content (representative of the typical in situ condition in Wisconsin), and 9–18% wet of optimum water content (representative of a very wet in situ condition). Addition of fly ash resulted in appreciable increases in the CBR and M_r of the inorganic soils. For water contents 7% wet of optimum, CBRs of the soils alone ranged between 1 and 5. Addition of 10% fly ash resulted in CBRs ranging between 8 and 17 and 18% fly ash resulted in CBRs between 15 and 31. Similarly, M_r of the soil alone ranged between 3 and 15 MPa at 7% wet of optimum, whereas addition of 10% fly ash resulted in M_r between 12 and 60 MPa and 18% fly ash resulted in M_r between 51 and 106 MPa. In contrast, except for one fly ash, addition of fly ash generally had little effect on CBR or M_r of the organic soil.

DOI: 10.1061/(ASCE)0899-1561(2006)18:2(283)

CE Database subject headings: Fine-grained soils; Fly ash; California bearing ratio; Soil stabilization; Recycling; Sustainable development; Subgrades.

Introduction

Every year large amounts of coal are burned in electrical power plants in the United States. Air pollution control systems at these plants produce large amounts of fly ash. Some fly ashes have been used for many years as a partial replacement for Portland cement in concrete, but most are disposed in landfills at considerable cost (ACAA 2000). In recent years, however, environmental regulations in many states have promoted other reuse applications of fly ash, as well as many other industrial byproducts, in the interests of sustainable construction. These applications include using fly ash as an embankment or fill material, as a soil or aggregate stabilizing agent, as filler and/or cement in flowable fill, and as mineral filler in asphalt paving mixtures (ACAA 1999).

Combustion of sub-bituminous coal produces a self-cementing fly ash that can be used for soil stabilization without activators (Ferguson 1993; Misra 1998). In most subgrade applications, fly ash is used to stabilize a soft soil so that a stable working platform is provided for construction equipment (Ferguson 1993; Nicholson and Kashyap 1993). Reducing plasticity and shrink-swell potential of fine-grained soils is also a common objective (Nicholson and Kashyap 1993; Cokca 2001). The stabilized material typically is strong and stiff (Kaniraj and Havanagi 1999, 2001; Edil et al. 2002; Pandian and Krishna 2003; Bin-Shafique et al. 2004; Trzebiatowski et al. 2004).

This paper describes a laboratory study conducted to evaluate the improvement in mechanical properties relevant to highway design and construction that can be obtained when soft fine-grained subgrade soils are stabilized with fly ash. The experimental program included California bearing ratio (CBR) tests to evaluate the bearing strength of stabilized soils used as working platforms during highway construction and resilient modulus (M_r) tests to evaluate the subgrade modulus that is important for supporting long-term vehicular traffic loads. Field behavior of fly ash stabilized soils is beyond the scope of this paper, and is addressed elsewhere (Bin-Shafique et al. 2004; Trzebiatowski et al. 2004).

Materials and Methods

Fly Ashes

Four fly ashes were used in this study: Columbia, Edgewater, Dewey, and King. The Columbia, Edgewater, and Dewey ashes are from power plants in Wisconsin, whereas the King ash is from Minnesota. Physical and compositional properties of the fly ashes are summarized in Table 1 along with typical physical properties of Class C and F fly ashes. All four ashes are derived from com-

---

[1] Professor and Chair, Geological Engineering Program, Dept. of Civil & Environmental Engineering, Univ. of Wisconsin-Madison, 1415 Engineering Dr., Madison, WI 53706 (corresponding author). E-mail: edil@engr.wisc.edu

[2] Project Engineer, Ramón E. Zequeira & Associates, Asunción 513 Puerto Nuevo, San Juan, Puerto Rico 00920. E-mail: hacosta@prtc.net

[3] Professor, Geological Engineering Program, Dept. of Civil and Environmental Engineering, Univ. of Wisconsin-Madison, 1415 Engineering Dr., Madison, WI 53706. E-mail: benson@engr.wisc.edu

Note. Associate Editor: Hilary I. Inyang. Discussion open until September 1, 2006. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on February 15, 2005; approved on July 29, 2005. This paper is part of the ***Journal of Materials in Civil Engineering***, Vol. 18, No. 2, April 1, 2006. ©ASCE, ISSN 0899-1561/2006/2-283–294/$25.00.

Table 1. Chemical Composition and Index Properties of Fly Ashes

	Percent of composition					
Parameter	Columbia	Dewey	Edgewater	King	Typical[a] Class C	Typical[a] Class F
CaO	23.1	9.8	20.8	23.7	24.3	8.7
SiO_2	31.1	19.8	38.7	27.3	39.9	54.9
Al_2O_3	18.3	13.0	15.8	16.3	16.7	25.8
Fe_2O_3	6.1	6.0	7.8	5.9	5.8	6.9
MgO	3.7	3.1	3.4	1.8	4.6	1.8
SO_3	3.7	11.8	1.0	6.4	3.3	0.6
CaO/SiO_2 ratio	0.74	1.15	0.54	1.08	0.61	0.16
Loss on ignition (%)	0.7	53.4	0.1	5.4	6	6
Specific gravity	2.70	2.53	2.71	2.68	—	—
Percent fines (%)	95.3	39.6	92.8	91.9	—	—
Classification (*ASTM 618*)	C	Off specification	C	Off specification	C	F

[a] From Bin-Shafique et al. (2004).

bustion of sub-bituminous coal and were collected using electrostatic precipitators. The Columbia and Edgewater ashes are from pulverized boilers, whereas the Dewey and King fly ashes are from cyclone boilers.

The Columbia and Edgewater fly ashes are Class C fly ashes following *ASTM C 618*, whereas the Dewey and King fly ashes are referred to as "off-specification" fly ashes because they do not meet the Class C or Class F criteria in *ASTM C 618*. The King, Columbia, and Edgewater fly ashes have high calcium oxide (CaO) content (23.7, 23.1, and 20.8%, respectively) and high silicon dioxide (SiO_2) content (27.3, 31.1, and 38.7%, respectively), whereas the Dewey ash has lower CaO content (9.8%) and SiO_2 content (19.8%). The CaO/SiO_2 ratio, which is indicative of cementing potential (Janz and Johansson 2002), varies between 0.54 (Edgewater) and 1.15 (Dewey) and the loss on ignition (LOI), which is indicative of the amount of unburned coal in the ash, varies between 0.1% (Edgewater) and 53.4% (Dewey).

Particle size distributions for the fly ashes are shown in Fig. 1(a). The King, Edgewater, and Columbia fly ashes have similar particle size distributions, with the Columbia ash being slightly finer than the other ashes. All three of these ashes primarily consist of silt-size particles ($75\mu m > \text{particle size} > 2\ \mu m$). Dewey fly ash is appreciably coarser than the other fly ashes and is gap graded.

Subgrade Soils

Seven subgrade soils were used that represent the range of soft subgrades typically encountered in Wisconsin highway construction. Samples of each soil were collected along highway shoulders at a depth of 0.6–0.9 m. Index properties, compaction characteristics, and classifications of the soils are summarized in Table 2. All of the soils are fine grained and classify as CL, CH, or OH according to the Unified Soil Classification System. The names of the soils are from USDA soil surveys. Theresa silt loam, Joy silt loam, red silty clay till, and Plano silt loam are low plasticity clays, whereas brown silt and Lacustrine red clay are high plasticity clays in the Unified Soil Classification System. Organic Theresa silt loam is a highly plastic organic clay (LOI=10%). All of the other soils have LOI<4%, and are considered to be inorganic soils.

Particle size distributions for the soils are shown in Fig. 1(b). The Theresa silt loam, organic Theresa silt loam, Plano silt loam, brown silt, and Joy silt loam have similar particle size distribu-

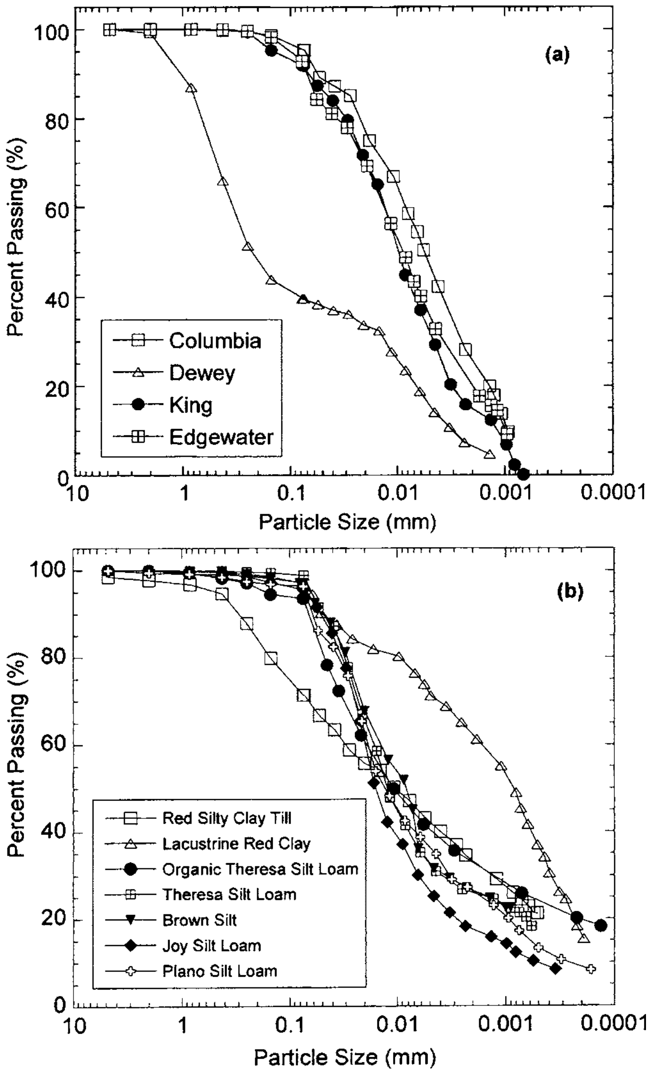

Fig. 1. Particle size distributions of the fly ashes (a) and soils (b)

Table 2. Index Properties of Soils

Soil name	LL	PI	Percent fines	G_s	LOI (%)	Classification USCS	Classification AASHTO	CBR	w_N (%)	γ_d (kN/m^3)	w_{OPT} (%)
Org. Theresa silt loam	61	19	97	2.24	10	OH	A-7-5	0.3	35	13.5	29
Theresa silt loam	45	19	99	2.58	2	CL	A-7-6	3	19	15.9	18
Brown silt	60	35	97	2.58	4	CH	A-7-6	0.4	32	16.4	19
Lacustrine red clay	69	38	97	2.71	2	CH	A-7-6	2	35	15.7	24
Red silty clay till	47	22	71	2.69	2	CL	A-6	5	19	18.4	13
Joy silt loam	39	15	96	2.70	1	CL	A-6	3	25	16.5	19
Plano silt loam	44	20	96	2.71	2	CL	A-7-6	1	27	16.2	20

Note: LL=liquid limit; PI=plasticity index; Percent fines=percentage passing No. 200 sieve; G_s=specific gravity, LOI=loss on ignition; CBR=California bearing ratio (performed approximately 7% wet of optimum water content); w_N=in situ water content; γ_d=maximum dry unit weight; and w_{OPT}=optimum water content (*ASTM D 698*).

tions and contain at least 90% fines. The red silty clay is coarser (70% fines) and more well graded than the other soils and the Lacustrine red clay is finer than all of the soils.

In situ water contents of the soils are shown in Table 2. The in situ water contents typically are about 7% wet of optimum water content, which is typical for Wisconsin subgrade soils (an exception is Theresa silt loam, which has an in situ water content 1% wet of optimum water content). Thus, when specimens were prepared to simulate the natural wet condition observed in the field, they were prepared approximately 7% wet of optimum water content.

Compaction curves corresponding to standard Proctor effort were determined for each soil following the procedure in *ASTM D 698*. Typical bell-shaped compaction curves were obtained for all of the soils (Acosta et al. 2003). The maximum dry unit weights and the optimum water contents are summarized in Table 2.

Test Procedures Soils and Soil–Fly Ash Mixtures

CBR Test

Unsoaked CBR tests were conducted on the soils and soil–fly ash mixtures following the methods described in *ASTM D 1883* to assess the subgrade soils and soil–fly ash mixtures in the context of a working platform (i.e., a short term condition, where soaking over a wet season would not occur). Specimens were prepared in accordance with *ASTM D 1883* at water content 7% wet of optimum water content using standard Proctor effort to simulate the wet and soft condition typically observed in the field. Specimens were also prepared near optimum water content as a standardized condition. All water contents reported herein are soil water contents (i.e., weight of water ÷ weight of soil solid). Soil water contents are used instead of soil–fly ash water contents because, in construction applications, the engineer normally must design for the existing in situ water content of the soil. Standard Proctor compaction procedure was used for compacting the specimens.

During construction, a delay lasting 1–2 h normally occurs between moistening/blending of the soil–fly ash mixture and compaction (ACAA 1999). To simulate this effect in the laboratory, soil–fly ash mixtures sat for 2 h between moistening/blending and compaction. This 2 h delay was adopted in all cases so that specimens would be prepared consistently.

Soil specimens were subjected to CBR testing shortly after compaction without soaking. Soil–fly ash specimens, however, were left in the mold after compaction, sealed using plastic wrap, and cured at 25°C and 100% relative humidity for 7 days. The

Table 3. CBR of Soil and Soil–Fly Ash Mixtures Compacted 2 h after Mixing and Cured for 7 Days

	Soil optimum water content (w_{OPT})													7% wet of w_{OPT}						
	Soil alone	Columbia							Dewey			Edgewater		Soil alone	Columbia		Dewey		King	
		Fly ash content (%)													Fly ash content (%)					
Soil name	0	6	10	12	14	16	18	20	10	14	18	10	18	0	10	18	10	18	10	18
RSCT	26 (−1.0)	—	33 (2.0)	—	—	—	35 (4.0)	—	24 (2.0)	—	20 (4.0)	—	—	5 (4.7)	11 (7.0)	30 (7.0)	17 (7.0)	23 (7.0)	14 (7.0)	26 (7.0)
LRC	17 (−0.9)	—	19 (2.0)	—	—	—	20 (4.0)	—	25 (2.0)	—	20 (4.0)	—	—	2 (7.0)	8 (7.0)	24 (7.0)	14 (7.0)	26 (7.0)	9 (7.0)	27 (7.0)
BS	17 (1.0)	—	-	—	—	—	—	—	20 (2.0)	20 (3.0)	25 (3.0)	—	—	3 (5.0)	12 (7.0)	15 (7.0)	10 (7.0)	31 (7.0)	9 (7.0)	20 (7.0)
OTSL	2 (0.5)	—	2 (2.0)	—	—	—	5 (4.0)	—	4 (2.0)	—	10 (4.0)	2 (2.0)	2 (4.0)	0.3 (6.9)	—	—	—	—	—	—
TSL	12 (−0.4)	15 (2.0)	25 (2.0)	—	23 (3.0)	—	30 (3.0)	—	—	—	—	—	—	3 (6.3)	—	—	—	—	—	—
JSL	5 (1.0)	—	32 (2.0)	—	36 (2.7)	—	38 (3.4)	—	—	—	—	—	—	3 (6.0)	—	—	—	—	—	—
PSL	5	—	-	34 (2.4)	—	51 (3.2)	—	56 (4.0)	—	—	—	—	—	1 (7.0)	—	—	—	—	—	—

Note: RSCT=red silty clay till; LRC=Lacustrine red clay; BS=brown silt; OTSL=organic Theresa silt loam; TSL=Theresa silt loam; JSL=Joy silt loam; and PSL=Plano silt loam. Number in parenthesis indicates water content of the soil prior to fly ash addition relative to the soil optimum water content ($w_{SOIL}-w_{OPT}$).

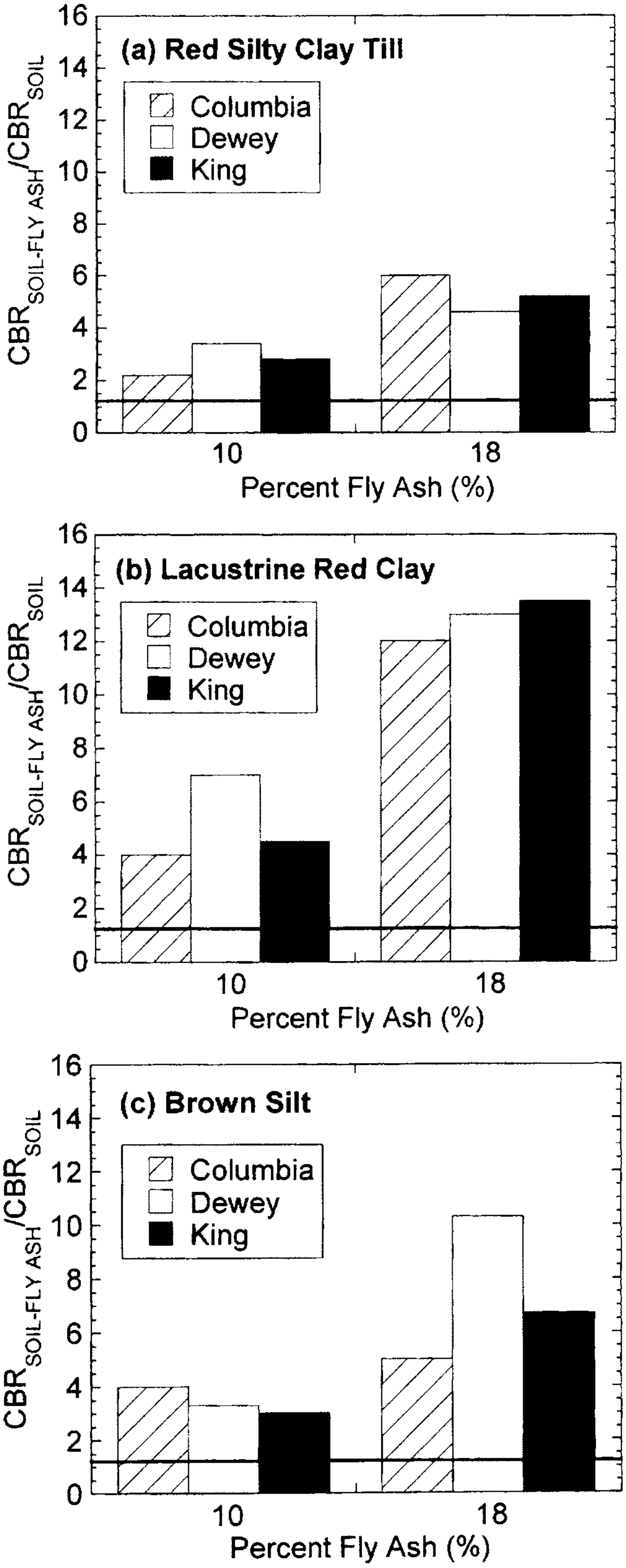

Fig. 2. CBR gain as function of fly ash content for red silty clay till (a); Lacustrine red clay (b); and brown silt (c) prepared with Columbia, Dewey, and King fly ashes. Soils were 7% wet of optimum water content.

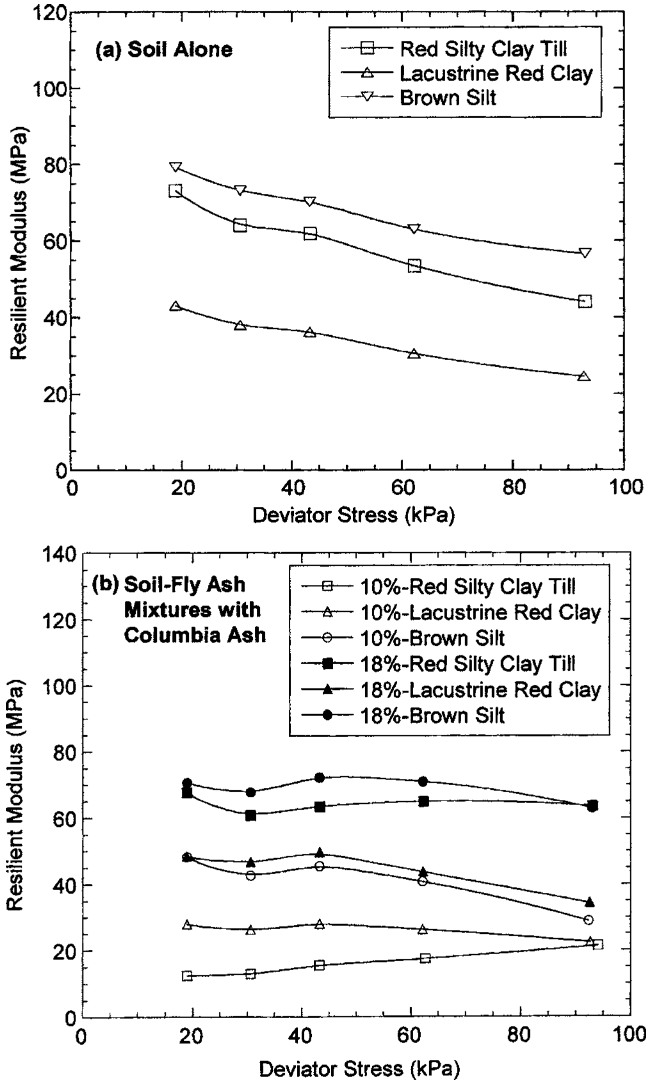

Fig. 3. Typical curves showing resilient modulus versus deviator stress for soil compacted at optimum water content (a) and soil–fly ash mixture prepared 7% wet of optimum water content (b)

CBR tests were conducted immediately after the 7-day curing period. A 7-day curing period was adopted to simulate the relatively short period between subgrade preparation to provide a working platform and pavement construction activities in practice (Bin-Shafique et al. 2004).

Resilient Modulus Test

Specimens for resilient modulus testing were prepared using the same compactive effort as specimens prepared using the standard Proctor procedure. The mold used to prepare the resilient modulus specimens had a diameter of 102 mm and height of 203 mm. Specimens were compacted in the mold in 6 layers with 22 blows/layer using a standard Proctor hammer, which provided the same energy per volume (600 kN m/m^3) as standard Proctor compaction. As with the CBR tests, the soil–fly ash mixtures were blended and moistened, and then allowed to sit for 2 h before compaction to simulate the delay that typically occurs in the field. As with the CBR tests, specimens were prepared at optimum

Table 4. Coefficients K_1 and K_2 in Eq. (1) for Soil and Soil–Fly Ash Mixtures

Soil name	Fly ash content (%)	Curing time (days)	w_{SOIL}-w_{OPT} (%)	Columbia		w_{SOIL}-w_{OPT} (%)	Dewey		w_{SOIL}-w_{OPT} (%)	King	
				K_1	K_2		K_1	K_2		K_1	K_2
Red silty clay till	0	1	−0.1	185.0	−0.306	—	—	—	—	—	—
	10	7	9.0	6.6	0.251	9.0	12.3	0.070	—	—	—
	10	14	7.0	4.2	−0.349	7.0	25.5	−0.062	7.0	22.0	0.001
	18	7	11.0	12.4	0.166	11.0	87.3	−0.242	—	—	—
	18	7	7.0	161.7	−0.305	7.0	186.7	−0.299	—	—	—
	18	14	7.0	68.8	−0.019	7.0	135.5	−0.189	7.0	167.0	−0.199
	18	28	7.0	77.5	0.063	7.0	124.5	−0.129	—	—	—
	18	56	7.0	73.3	0.098	7.0	160.5	−0.185	—	—	—
Lacustrine red clay	0	1	1.0	124.0	−0.346	—	—	—	—	—	—
	10	7	10.0	9.0	0.039	10.0	35.2	−0.276	—	—	—
	10	14	10.0	33.7	−0.127	—	—	—	—	—	—
	10	14	7.0	40.1	−0.115	7.0	238.3	−0.529	7.0	62.2	−0.225
	18	7	13.0	7.7	−0.138	13.0	87.9	−0.408	—	—	—
	18	14	13.0	89.8	−0.253	—	—	—	—	—	—
	18	14	7.0	90.5	−0.191	7.0	123.0	−0.166	7.0	144.6	−0.101
Organic Theresa silt loam	0	1	−0.9	12.5	0.040	—	—	—	—	—	—
	10	7	10.0	F	F	10.0	F	F	—	—	—
	18	7	13.5	F	F	13.5	F	F	—	—	—
	30	7	—	—	—	9.0	31.9	−0.072	—	—	—
	30	7	—	—	—	18.0	21.7	0.423	—	—	—
Theresa silt loam	0	1	−1.0	21.1	−0.151	—	—	—	—	—	—
Brown silt	0	1	7.0	150.0	−0.210	—	—	—	—	—	—
	10	14	7.0	115.0	−0.277	7.0	334.5	−0.565	7.0	22.0	−0.054
	18	14	7.0	83.0	−0.050	7.0	125.0	−0.136	7.0	83.4	−0.066
Plano silt loam	0	1	−3.0	36.7	−0.026	—	—	—	—	—	—
	12	7	−1.0	879.8	−0.241	—	—	—	—	—	—
	12	7	3.0	983.1	−0.482	—	—	—	—	—	—
	12	7	5.0	1550.2	−0.779	—	—	—	—	—	—

Note: w_{SOIL}-w_{OPT}=water content of the soil prior to fly ash addition relative to the soil optimum water content. F=Failed during testing.

water content and 7% wet of optimum water content. Specimens were also compacted at a very wet condition (9–18% wet of optimum water content).

Soil specimens were subjected to resilient modulus testing shortly after compaction. In contrast, specimens prepared with soil–fly ash mixtures were extruded from the mold after compaction, sealed with plastic wrap, and cured at 25°C and 100% humidity. Most specimens were cured for 14 days as suggested by Turner (1997), but some specimens were cured for as long as 56 days to evaluate how the resilient modulus changes as curing occurs. The procedure described in *AASHTO T 292-91* was followed for the resilient modulus tests using the loading sequence for cohesive soils.

Results

General Effects of Fly Ash Stabilization

CBR

The CBRs are summarized in Table 3. CBRs of the soils prepared 7% wet of optimum water content range from 0 to 5 with most of them less than 2, indicating that the soils are very poor subgrades in their in situ condition (Bowles 1992). These CBRs are consistent with CBRs reported by other investigators for soft subgrades (e.g., Ferguson 1993; Nicholson et al. 1994). Soil–fly ash mixtures compacted 7% wet of optimum water content typically have CBRs ranging between 10 and 20. These CBRs are comparable to those obtained on the soils alone compacted at optimum water content, suggesting that fly ash stabilization has similar benefits in terms of bearing strength as drying and compacting the soil.

The general effect of fly ash stabilization on CBR is illustrated in Fig. 2, which shows CBR of the soil–fly ash mixture normalized by the CBR of untreated soil (this ratio is referred to as the "CBR gain"). The data are from tests conducted on specimens compacted 7% wet of optimum water content. Data for red silty clay till, Lacustrine red clay, and brown silt are shown in Fig. 2 to represent the range of typical inorganic soft subgrade soils (lower to higher plasticity). In general, the CBR gain increases with an increase in fly ash content. Addition of 10% fly ash caused the CBR to increase by a factor of 4, on average, whereas 18% fly ash caused the CBR to increase by a factor of 8. The CBR gain is also affected by soil type. The largest CBR gain generally was obtained with the highly plastic Lacustrine red clay, and the smallest with the more well-graded red silty clay till. More discussion of the influence of soil type is in a subsequent section.

Resilient Modulus

The M_r curves for the soils compacted at optimum moisture content [Fig. 3(a)] had the characteristic shape for cohesive soils (i.e.,

Table 5. Resilient Moduli (MPa) of Soil and Soil–Fly Ash Mixtures (Deviator Stress=21 kPa)

		w_{OPT}			7% wet of w_{OPT}									Very wet condition				
			Columbia			Columbia			Dewey		King			Columbia		Dewey		
		Soil alone	Fly ash content (%)		Soil alone	Fly ash content (%)								Fly ash content (%)				
Soil name	Curing time (days)	0	12	Curing time (days)	0	10	12	18	10	18	10	18	Curing time (days)	10	18	10	18	30
RSCT	—	72.7 (−0.1)	—	14	15.0 (7.0)	12.1 (7.0)	—	65.0 (7.0)	21.1 (7.0)	76.3 (7.0)	22.0 (7.0)	90.9 (7.0)	7	14.2 (9.0)	20.7 (11.0)	15.2 (9.0)	41.8 (11.0)	—
LRC	—	43.3 (−1.0)	—	14	6.0 (7.0)	28.3 (7.0)	—	50.6 (7.0)	47.7 (7.0)	74.2 (7.0)	31.3 (7.0)	106.3 (7.0)	7	10.1 (10.0)	11.7 (13.0)	15.2 (10.0)	25.4 (13.0)	—
													14	22.9 (10.0)	41.6 (13.0)	—	—	—
BS	—	79.0 (−1.2)	—	14	9.0 (7.0)	49.4 (7.0)	—	71.4 (7.0)	60.0 (7.0)	82.8 (7.0)	18.7 (7.0)	68.3 (7.0)	—	—	—	—	—	—
OTSL	—	14.1 (−0.9)	—	—	0.9 (7.0)	—	—	—	—	—	—	—	7	F (10.6)	F (13.5)	F (10.6)	F (13.5)	25.6 (9.0) 7.8 (18.0)
TSL	—	13.3 (1.0)	—	—	9.0 (7.0)	—	—	—	—	—	—	—	—	—	—	—	—	—
JSL	—	—	—	—	9.0 (7.0)	—	—	—	—	—	—	—	—	—	—	—	—	—
PSL	7	34.0 (−3.0)	422.5 (−1.0) 226.1 (3.0)	7	3.0 (7.0)	—	144.9 (5.0)	—	—	—	—	—	—	—	—	—	—	—

Note: RSCT=red silty clay till; LRC=Lacustrine red clay; BS=brown silt; OTSL=organic Theresa silt loam; TSL=Theresa silt loam; JSL=Joy silt loam; and PSL=Plano silt loam. Number in parenthesis indicates water content of the soil prior to fly ash addition relative to the soil optimum water content (w_{SOIL}-w_{OPT}). F=Failed during testing.

a monotonic decrease in M_r with increasing deviator stress, σ_d) (Acosta et al. 2003). In contrast, M_r curves for the soil–fly ash mixtures showed much less dependency on deviator stress for the range of deviator stresses employed (21–103 kPa) [Fig. 3(b)]. Cementing of the soil particles by fly ash is believed to be the primary factor responsible for the reduced effect of stress on M_r of the soil–fly ash mixtures. In some cases, fly ash stabilization causes a reversal in the slope of the M_r curve. Slope reversals have also been reported by Trzebiatowski et al. (2004).

For all tests, a power function was used to describe the $M_r - \sigma_d$ relationship

$$M_r = K_1 \sigma_d^{K_2} \tag{1}$$

The parameters K_1 and K_2 for each test are summarized in Table 4. The reduced sensitivity to stress exhibited by many of the fly ash mixtures is reflected in the smaller magnitude of the parameter K_2.

Resilient moduli of the soils and soil–fly ash mixtures at a deviator stress of 21 kPa (a typical subgrade condition) are summarized in Table 5. For the soils (i.e., without fly ash) compacted at optimum water content, M_r varies between 13 and 80 MPa. These M_r are comparable to M_r reported in the literature for soils having similar properties (Fredlund and Wong 1977; Lee et al. 1997; Muhanna and Rahman 1999). A comparison of M_r of the soils (without fly ash) compacted at optimum water content and at 7% wet of optimum water content and the soil–fly ash mixtures compacted 7% wet of optimum water content is shown in Fig. 4. A summary of all of the data is in Table 5. All of the moduli correspond to a deviator stress of 21 kPa. The M_r of the soil–fly ash mixtures prepared with 10% fly ash typically fall below the moduli of the soils compacted at optimum water content. At 18% fly ash content, however, M_r of the soil–fly ash mixtures range between 0.8 and 2.5 times the M_r of the soils compacted at optimum water content. That is, addition of 18% fly ash to a soft and wet subgrade soil results in comparable or higher M_r than the same subgrade soil dried and compacted at optimum water content.

Effect of Fly Ash Type

A comparison of the effect of fly ash type is shown in Fig. 5, which shows CBR of the soil–fly ash mixtures prepared with the off-specification Dewey and King fly ashes normalized by the CBR of similar mixtures prepared with Class C Columbia fly ash. CBRs of the soil–fly ash mixtures prepared with the off-specification fly ashes are similar to or higher than those obtained with the typical Class C fly ash (Columbia). Soil–fly ash mixtures prepared with 10 and 18% Dewey or King fly ashes have CBRs ranging between 0.8 and 2.0 times the CBR obtained using Columbia fly ash. Thus, these off-specification ashes are as effective, if not more effective, for stabilizing soft soils.

The M_r data also show that "off-specification" ashes are effective stabilizers, even though they would not be acceptable for Portland cement concrete applications and are normally landfilled (Fig. 6). In Fig. 6, resilient moduli of soil–fly ash mixtures prepared with the Dewey and King fly ashes relative to M_r of the mixtures prepared with the Class C Columbia fly ash are shown for fly ash contents of 10 and 18%. Except for the mixtures of brown silt with King fly ash, higher M_r were obtained with the

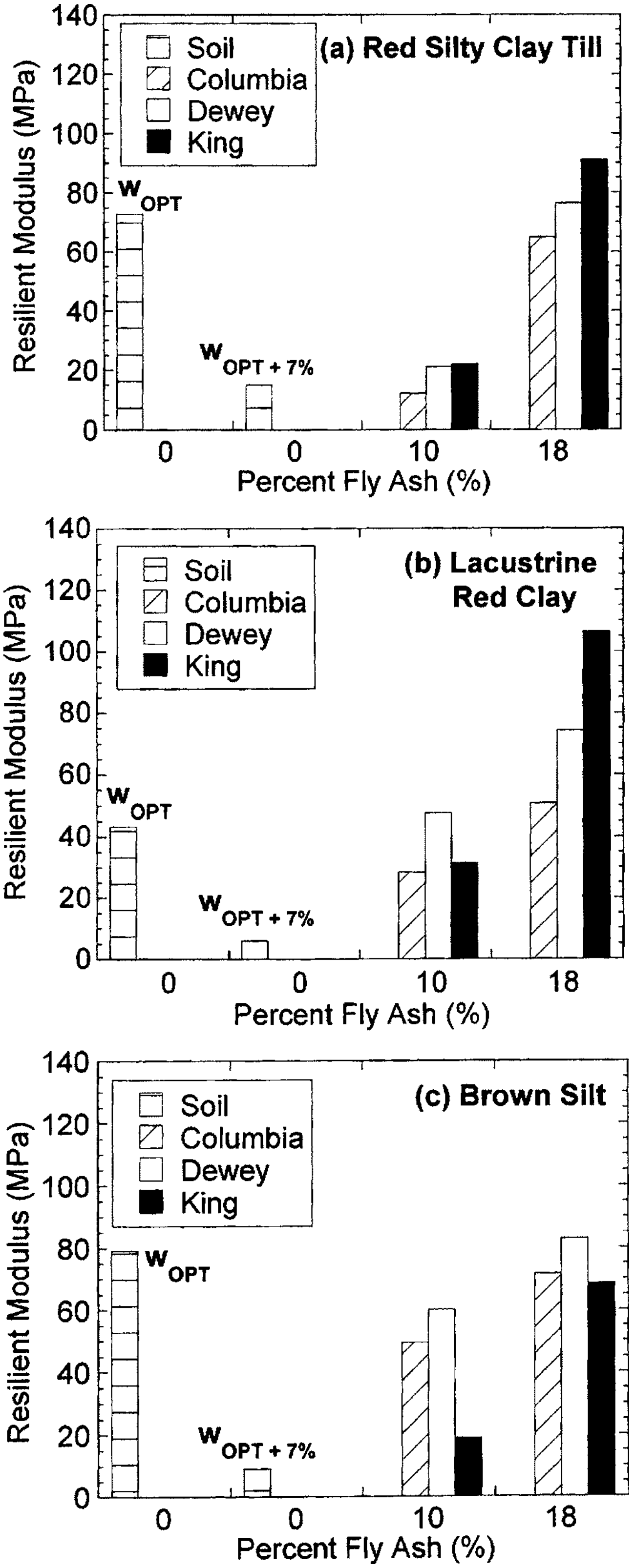

Fig. 4. Resilient moduli of soil and soil–fly ash mixtures compacted at optimum water content and 7% wet of optimum water content: red silty clay till (a); Lacustrine red clay (b); and brown silt (c). Mixtures prepared with Columbia, Dewey, and King fly ashes using 10 or 18% fly ash.

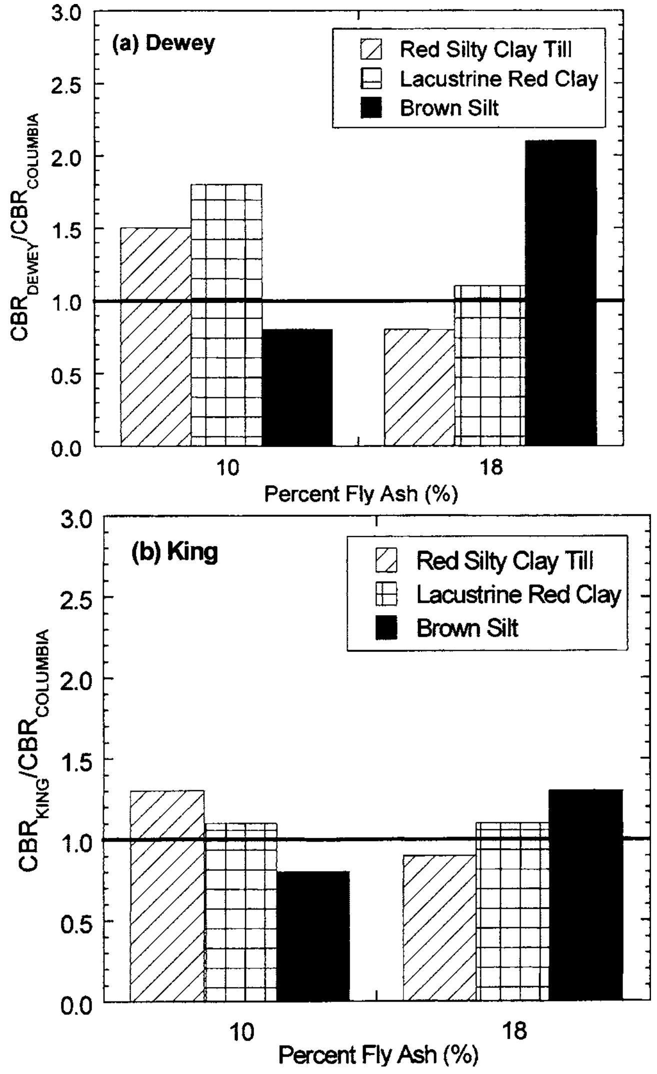

Fig. 5. CBR of soil–fly ash mixtures prepared with Dewey (a) and King (b) fly ashes normalized to CBR for soil–fly ash mixtures prepared with Columbia fly ash. Fly ash contents of 10 and 18% were used. Specimens compacted 7% wet of optimum water content.

off-specification ashes than the Columbia Class C ash, with the highest M_r in all cases obtained using the Dewey fly ash.

The effectiveness of these fly ashes appears to be related to the CaO/SiO_2 ratio (Table 1). Of these three ashes, the CaO/SiO_2 ratio is highest for Dewey (1.15), lowest for Columbia (0.74), and intermediate for King (1.05). The Dewey ash also resulted in mixtures with the highest CBR and M_r, whereas the Columbia ash generally resulted in mixtures with lower CBR and M_r.

Effect of Soil Type

Three index parameters were used when evaluating how soil type influences the stabilization afforded by fly ash: liquid limit (LL), plasticity index (PI), and group index (GI). Both the LL and PI are indices of the quantity and the activity of the clay minerals in the soil. GI is an index property used in pavement engineering which depends on three index properties: percent fines, liquid limit, and plasticity index (Holtz and Kovacs 1980). In general, as the LL, PI, or GI increases, the subgrade usually becomes poorer in terms of pavement support.

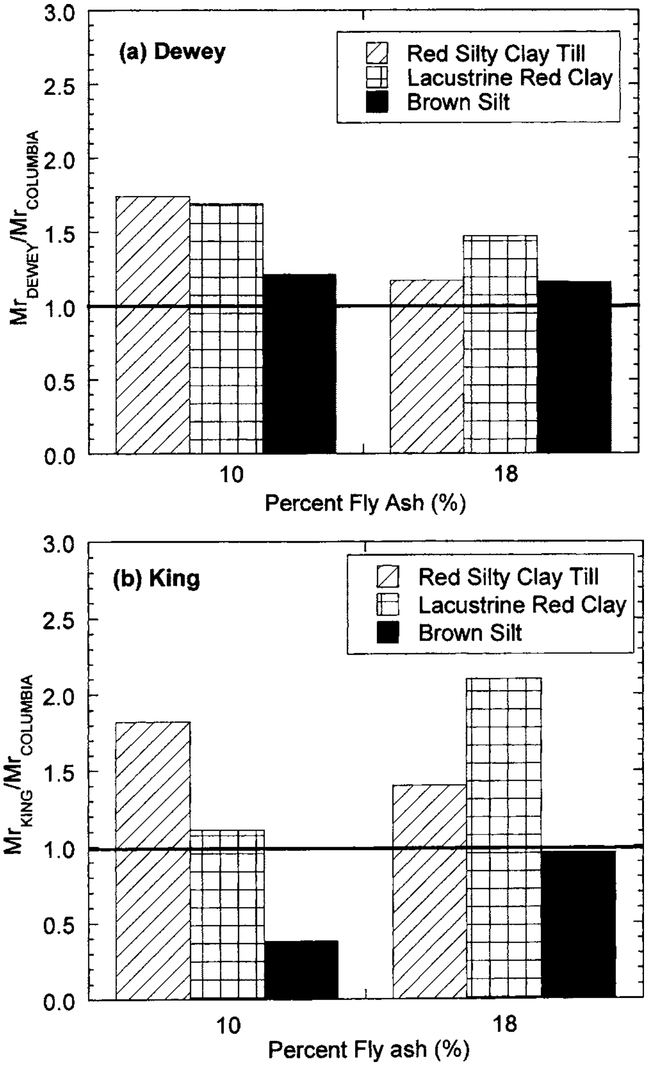

Fig. 6. Ratio of M_r of soil–fly ash mixtures prepared with Dewey (a) and King (b) fly ashes to M_r of the soil–fly ash mixtures prepared with Columbia fly ash. All resilient moduli are at deviator stress of 21 kPa.

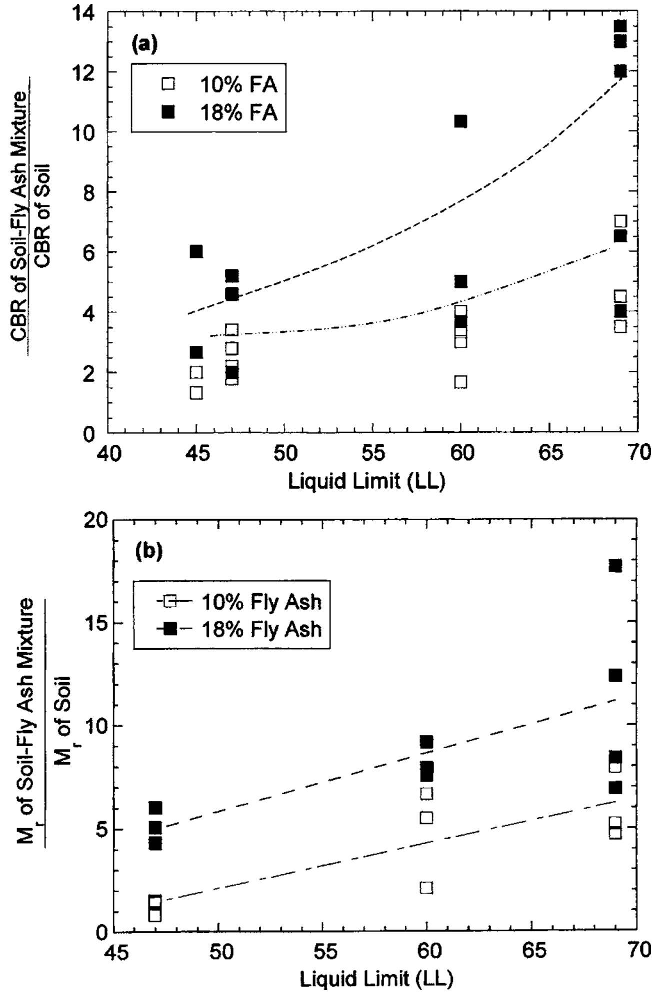

Fig. 7. Effect of liquid limit (LL) on CBR (a) and M_r (b) of soil–fly ash mixtures prepared 7% wet of optimum water content and 9–12% wet of optimum water content. CBRs and M_rs are normalized by values for soil alone.

Relationships between CBR or M_r and each of these soil properties are shown in Figs. 7–9 in terms of CBR ratio or M_r ratio (at a deviator stress of 21 kPa). In all three cases, there is a general trend of increasing CBR ratio and M_r ratio as the soil becomes finer grained or more plastic (i.e., higher LL, PI, or GI), although the data exhibit considerable scatter. This trend does not mean that the cementing characteristics of fly ash improve as the soils become finer grained or more plastic. Rather, stabilization with fly ash results in more comparable CBR and M_r regardless of soil type (Tables 3 and 5), and soils that are finer grained or more plastic tend to have lower CBR or M_r prior to stabilization (resulting in greater CBR ratio and M_r ratio).

Effect of Water Content

The general effect of water content on CBR is shown in Fig. 10 in terms of compaction water content (w_{SOIL}) relative to optimum water content (w_{OPT}), i.e., $w_{\mathrm{SOIL}}-w_{\mathrm{OPT}}$. In general, CBR decreases with increasing $w_{\mathrm{SOIL}}-w_{\mathrm{OPT}}$, and increases with increasing fly ash content. The sensitivity to water content is similar for both fly ash contents. Compaction water content has a similar effect on the resilient modulus of soil–fly ash mixtures (Table 5). In general, as the soil water content increases, the resilient moduli decrease, regardless of the curing time.

Effect of Curing Time

Resilient modulus is a property relevant to long-term performance under service loads and soil–fly ash mixtures are expected to gain stiffness with increasing curing time. Therefore, resilient modulus tests were conducted on soil–fly ash mixtures cured for periods of 7, 14, 28, and 56 days to evaluate how curing time affects the resilient modulus. The specimens were prepared with red silty clay till (7% wet of optimum water content) mixed with 18% Columbia fly ash and 18% Dewey fly ash. These fly ashes were selected to evaluate the effect of curing time for a Class C and an off-specification fly ash.

The effect of curing time on the resilient modulus at a deviator stress of 21 kPa is shown in Fig. 11. The resilient modulus at each curing time has been normalized by the resilient modulus measured at 14 days. Between 7 and 14 days, the resilient modulus did not increase significantly (ratio ≈1 for both Columbia and Dewey). A larger increase (ratio ≈1.44 for Columbia and 1.10 for Dewey) occurred between 14 and 28 days, with a greater increase

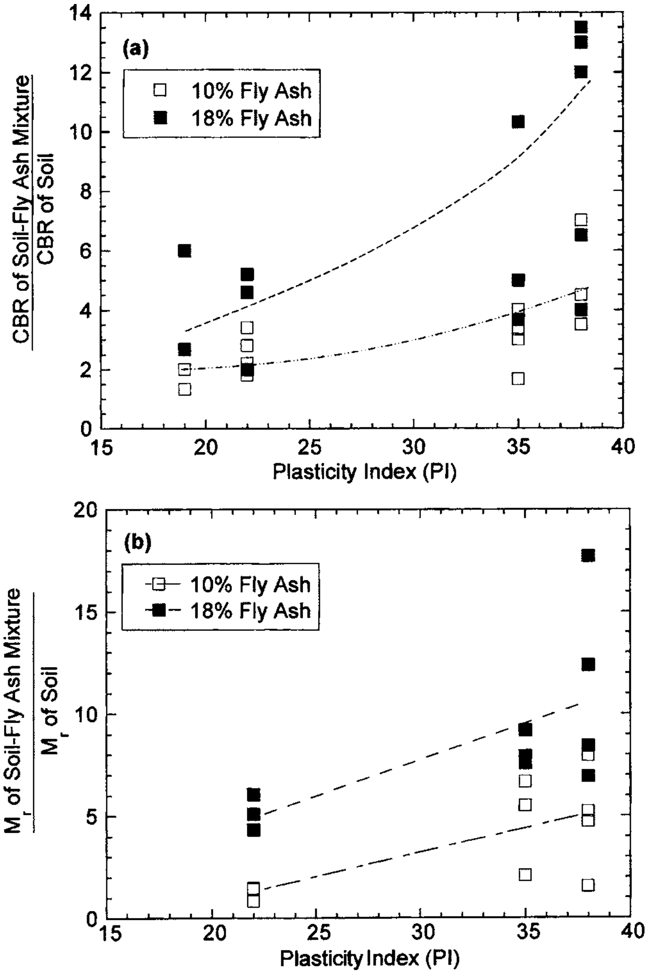

Fig. 8. Effect of plasticity index (PI) on CBR (a) and M_r (b) of soil–fly ash mixtures prepared 7% wet of optimum water content and 9–12% wet of optimum water content. CBRs and M_rs are normalized by values for soil alone.

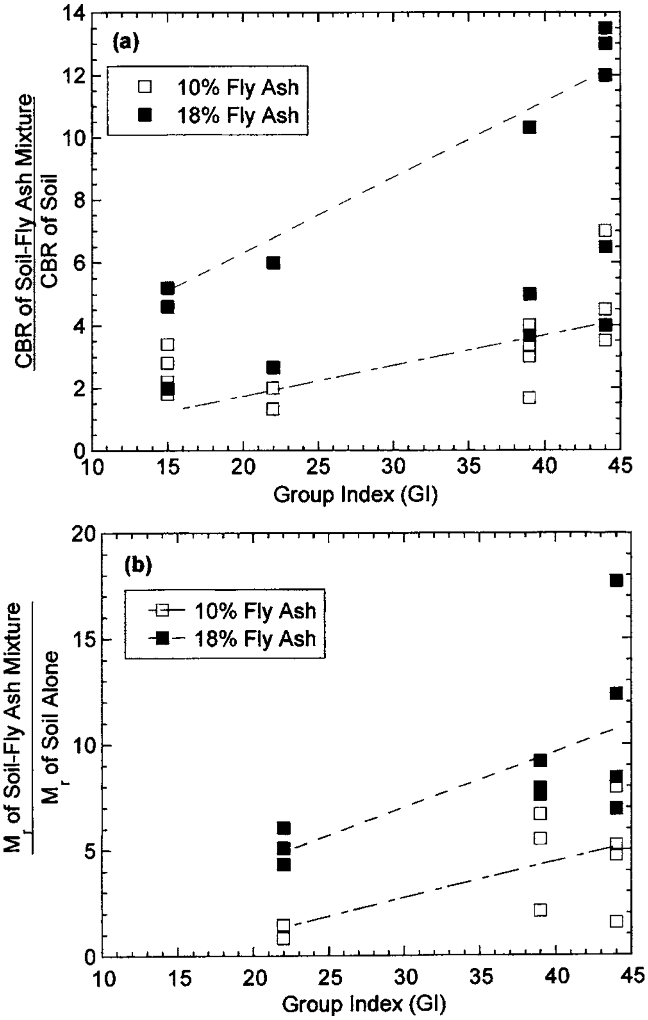

Fig. 9. Effect of group index (GI) on CBR (a) and M_r (b) of soil–fly ash mixtures prepared 7% wet of optimum water content and 9–12% wet of optimum water content. CBRs and M_rs are normalized by values for soil alone.

occurring for the Columbia fly ash. After 28 days, little additional increase in resilient moduli occurs (1.52 for Columbia and 1.20 for Dewey).

Effect of Organic Content

Addition of fly ash had a much smaller effect on the CBR and M_r of the organic Theresa silt loam (LOI=10%) than the inorganic soils (Tables 3 and 5). For fly ash contents of 10 and 18%, CBR of the organic Theresa silt loam generally was between 2 and 5 even when compacted at optimum water content (Table 3). In addition, all of the resilient modulus specimens prepared with fly ash contents of 10 and 18% failed during testing (i.e., they were too soft to test using the loading sequence for cohesive soils).

The mixtures prepared with Dewey fly ash (LOI=53.4% and $CaO/SiO_2=1.15$) are an exception. Mixtures of organic Theresa silt loam and Dewey fly ash prepared at optimum water content had a CBR$\geq$10 for fly ash contents $\geq$10% (Fig. 12), whereas mixtures prepared with other fly ashes appeared to have little or no effect on CBR. Also, mixtures of organic Theresa silt loam and Dewey fly ash were the only mixtures for which a M_r test could be successfully completed (Table 5). However, even with 30%

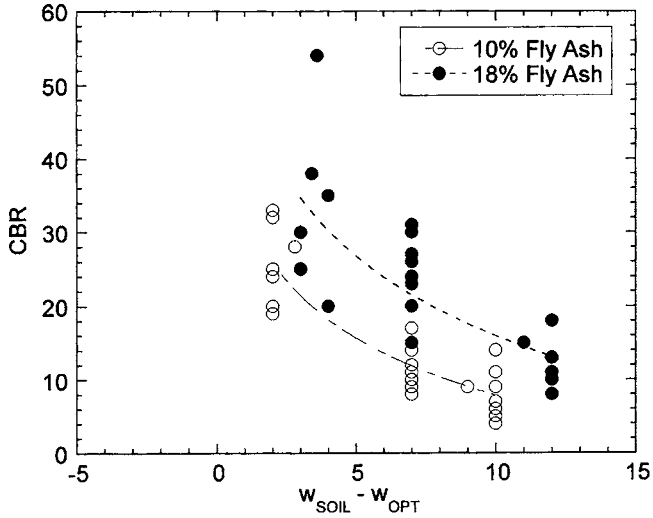

Fig. 10. CBR as function of soil water content relative to optimum water content ($w_{SOIL}-w_{OPT}$) for fly ash contents of 10 and 18%

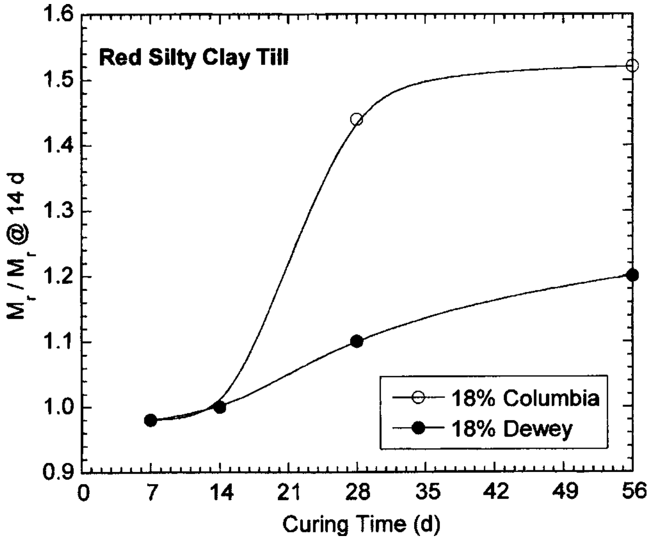

Fig. 11. Effect of curing time of M_r of mixtures of red silty clay till with 18% Columbia or Dewey fly ash

Dewey fly ash, M_r of the organic Theresa silt loam was still below the moduli typically obtained for the mixtures prepared with inorganic soils and 18% fly ash (Table 5).

Organic soils traditionally have been more difficult to stabilize chemically than inorganic soils due to lower solids content, higher water content, lower pH, and chemical interferences that occur in the cementing reactions (Janz and Johansson 2002). The ineffectiveness of the Columbia and Edgewater fly ashes in stabilizing the organic Theresa silt loam is believed to be caused by organic matter inhibiting hydration of cementitious binders, as reported by others for cement stabilization (Hampton and Edil 1988; Axelsson et al. 2002; Tremblay et al. 2002). The stabilization effect obtained with the Dewey fly ash may be due its high carbon content or high CaO/SiO_2 ratio, or a combination thereof. More study is needed to determine how these variables affect stabilization of organic soils.

Relationship between Resilient Modulus and CBR

Empirical correlations between modulus and CBR have been proposed for natural soils by a number of researchers. For example, Powell et al.(1984) developed an equation relating the elastic modulus obtained by wave propagation techniques and CBR. After accounting for stress and strain level characteristic of pavements, Powell et al. (1984) obtained

$$E = 7.6\ \mathrm{CBR}^{0.64} \tag{2}$$

where E (essentially equivalent of resilient modulus) is in Mega Pascal and CBR is in percent. Another well-known relationship that is widely used in North America was proposed by Heukelom and Foster (1960)

$$M_r = 10\ \mathrm{CBR} \tag{3}$$

where M_r=resilient modulus in Mega Pascal. Eq. (3) is included in the AASHTO (1993) *Guide for design of pavement structures*.

Eqs. (2) and (3) are shown with the data reported for soil–fly ash mixtures in Tables 3 and 5 in Fig. 13. Both equations, developed using natural soils, overpredict M_r for the soils and soil–fly ash mixtures, with the overprediction being much greater for Eq. (3). Sawangsuriya and Edil (2005) also report that Eq. (3) tends to overpredict M_r appreciably for natural soils. A better prediction for the data from this study can be obtained with

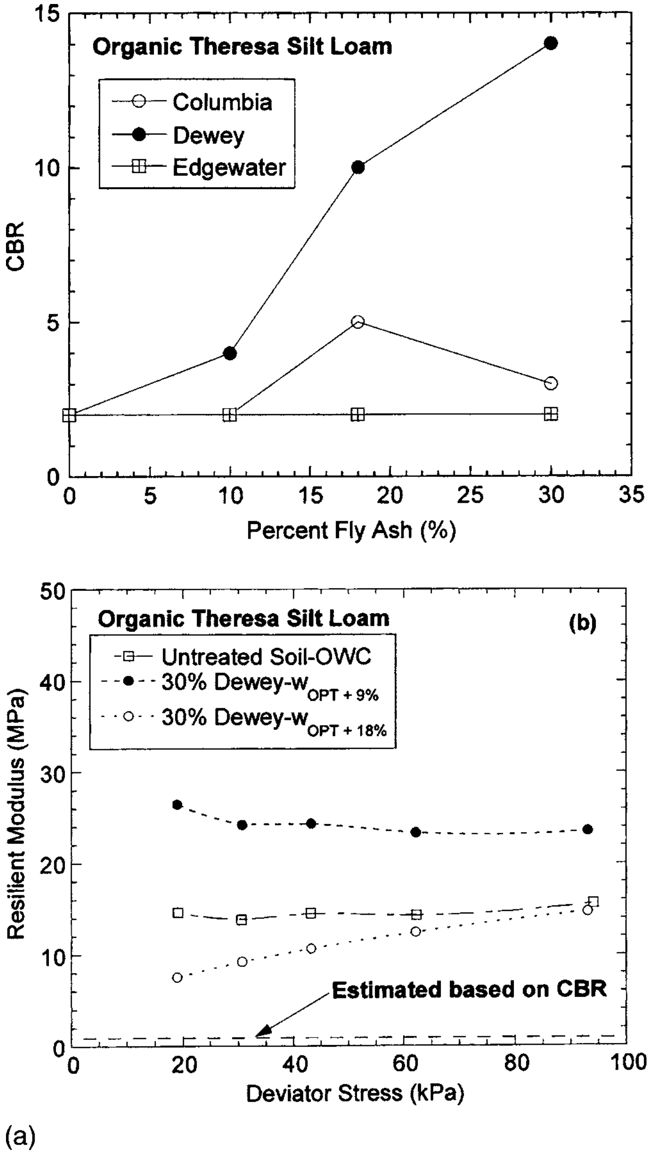

Fig. 12. CBR of soil–fly ash mixtures prepared with organic Theresa silt loam using Columbia, Dewey, and Edgewater fly ashes (a) and M_r of mixtures prepared with Dewey fly ash (b)

$$M_r = 3\ \mathrm{CBR} \tag{4}$$

Eq. (4), which has R^2=0.6, was obtained by linear least-squares regression on the data shown in Fig. 13. These data are for the fine-grained soils alone and the mixtures of fine-grained soils and fly ashes used in this study. The suitability of Eq. (4) for other soils and mixtures needs to be determined.

Conclusions

A laboratory study was conducted where soil–fly ash mixtures were prepared at different fly ash contents (10–30%) to evaluate how addition of fly ash can improve the CBR and resilient modulus (M_r) of wet and soft fine-grained subgrade soils. Specimens were prepared at optimum water content, 7% wet of optimum water content (simulating the in situ condition in Wisconsin), and

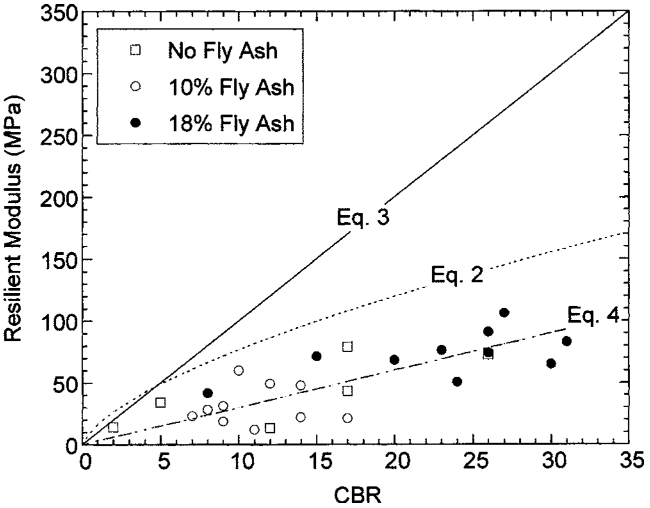

Fig. 13. Resilient modulus (at deviator stress=21 kPa) versus CBR along with Eqs. (2)–(4). Soil–fly ash mixtures were cured for 14 days prior to resilient modulus testing and 7 days prior to CBR testing

9–18% wet of optimum water content (simulating a very wet condition). Based on this investigation, the following observations and conclusions are made:

1. CBR of soil–fly ash mixtures generally increases with fly ash content and decreases with increasing compaction water content. Adding 10 and 18% fly ash to fine-grained soils compacted 7% wet of optimum (the typical in situ condition) resulted in increases in CBR by a factor of 4 and 8, respectively. The CBR increased by a greater factor when fly ash was added to a wetter or more plastic (i.e., poorer) fine-grained soil.
2. Soil–fly ash mixtures prepared with 10% fly ash and fine-grained soil compacted 7% wet of optimum (the typical in situ condition) typically will have lower resilient modulus than soil alone compacted at optimum water content. However, when the fly ash content is on the order of 18%, the resilient modulus typically will be higher (30% higher, in this study) than the resilient modulus of soil alone compacted at optimum water content. Larger increases in resilient modulus typically should be expected for wetter or more plastic fine-grained soils (i.e., poorer subgrades); however, stabilization with fly ash results in comparable final CBR and M_r regardless of soil type.
3. The effect of curing time on resilient modulus was evaluated using one soil and two fly ashes. Between 7 and 14 days, the resilient modulus increased modestly. However, between 14 and 56 days, the resilient modulus increased by 20–50%. Thus, fly ash stabilized subgrades should stiffen over time, resulting in increased pavement support.
4. The presence of 10% organic matter in one of the soils inhibited stabilization by most of the ashes. Soil–fly ash mixtures prepared with this soil typically had much lower CBR and M_r than obtained for inorganic soils. In some cases, the M_r was not measurable. However, a modest degree of stabilization was achieved for this soil with one of the off-specification fly ashes (a fly ash with high carbon content and a high CaO/SiO_2 ratio). The mechanism making the off-specification fly ash effective in stabilizing organic soils needs further study.

Acknowledgments

Financial support for this study was provided by the U.S. Department of Energy through the Combustion Byproducts Recycling Consortium, the University of Wisconsin-Madison Consortium for Fly Ash Use in Geotechnical Applications (funded by Mineral Solutions, Inc., Alliant Energy Corporation, and Xcel Energy Services, Inc.), and the Wisconsin Department of Transportation (WisDOT). The opinions and conclusions described in the paper are those of the writers and do not necessarily reflect the opinions or policies of the sponsors. Mr. Fred Gustin is acknowledged for his efforts in initiating this research effort.

References

Acosta, H., Edil, T., and Benson, C. (2003). "Soil stabilization and drying using fly ash." *Geo Engineering Rep. No. 03-03*, Dept. of Civil and Environmental Engineering, Univ. of Wisconsin-Madison, Madison, Wis.

American Association of State Highway and Transportation Officials (AASHTO). (1993). *Guide for design of pavement structures*. Washington, D.C.

American Coal Ash Association (ACAA). (1999). *Soil and pavement base stabilization with self-cementing coal fly ash*, Alexandria, Va.

American Coal Ash Association (ACAA). (2000). *ACAA's CCPs production use and survey*. Alexandria, Va.

Axelsson, K., Johansson, S., and Andersson, R. (2002). "Stabilization of organic soils by cement and Pozzolanic reactions—Feasibility study." *Swedish Deep Stabilization Research Center Rep. No. 3*, Swedish Geotechnical Institute, Linkoping, Sweden.

Bin-Shafique, S., Edil, T., Benson, C., and Senol, A. (2004). "Incorporating a fly ash stabilized layer into pavement design—Case study." *Geotechnical engineering*, Institution of Civil Engineers, London, Vol. 157, No. GE4, 239–249.

Bowles, J. E. (1992). *Engineering properties of soils and their measurement*, McGraw-Hill, New York.

Cokca, E. (2001). "Use of class C fly ashes for the stabilization of an expansive soil." *J. Geotech. Geoenviron. Eng.*, 127(7), 568–573.

Edil, T., Benson, C., Bin-Shafique, S., Tanyu, B., Kim, W., and Senol, A. (2002). "Field evaluation of construction alternatives for roadway over soft subgrade." *Transportation Research Record 1786*, Transportation Research Board, Washington, D.C., 36–48.

Ferguson, G. (1993). "Use of self-cementing fly ashes as a soil stabilization agent." *Fly ash for soil improvement, Geotechnical Special Publication No. 36*, ASCE, New York, 1–14.

Fredlund, D., and Wong, P. (1977). "Relation between resilient modulus and stress conditions for cohesive subgrade soils." *Transportation Research Record 642*, Transportation Research Board, Washington, D.C., 73–81.

Hampton, M. B., and Edil, T. B. (1998). "Strength gain of organic ground with cement-type binders." *Soil improvement for big digs, Geotechnical Special Publication No. 81*, A. Maher and D. Yang, eds., ASCE, New York, 135–148.

Heukelom, W., and Foster, C. (1960). "Dynamic testing of pavements." *J. Soil Mech. Found. Div.*, 86(1), 1–28.

Holtz, R., and Kovacs, W. (1980). *An introduction to geotechnical engineering*, Prentice-Hall, Englewood Cliffs, N.J.

Janz, M., and Johansson, S. (2002). "The functions of different binding agents in deep stabilization." *Swedish Deep Stabilization Research Center Rep. No. 9*, Swedish Geotechnical Institute, Linkoping, Sweden.

Kaniraj, S., and Havanagi, V. (1999). "Compressive strength of cement stabilized fly ash-soil mixtures." *Cem. Concr. Res.*, 29(5), 673–677.

Kaniraj, S., and Havanagi, V. (2001). "Behavior of cement-stabilized fiber-reinforced fly ash-soil mixtures." *J. Geotech. Geoenviron. Eng.*, 127(7), 574–584.

Lee, W., Bohra, N., Altschaeffl, A., and White, T. D. (1997). "Resilient modulus of cohesive soils." *J. Geotech. Geoenviron. Eng.*, 123(2), 131–136.

Misra, A. (1998). "Stabilization characteristics of clays using class C fly ash." *Transportation Research Record 1161*, Transportation Research Board, Washington, D.C., 46–54.

Muhanna, A., and Rahman, M. (1999). "Resilient Modulus Measurements of Fine Grained Subgrade Soils." *Transportation Research Record 1687*, Transportation Research Board, Washington, D.C., 3–12.

Nicholson, P. G., and Kashyap, V. (1993). "Flyash stabilization of tropical Hawaiian soils." *Fly Ash for Soil Improvement, Geotechnical Special Publication No. 36*, ASCE, New York, 15–29.

Nicholson, P., Kashyap, V., and Fuji, C. (1994). "Lime and fly ash admixture improvement of tropical Hawaiian soils." *Transportation Research Record 1440*, National Research Council, Washington, D.C., 71–78.

Pandian, N., and Krishna, K. (2003). "The pozzolanic effect of fly ash on the California bearing ratio behavior of black cotton soil." *J. Testing and Evaluation*, ASTM, Vol. 31, No. 6, 479–485.

Powell, W., Potter, J., Mayhew, H., and Nunn, M. (1984). *The structural design of bituminous roads*, *TRRL Laboratory Report 1132*, Transportation and Road Research Laboratory, Crowthorne, Berkshire, U.K., 62.

Sawangsuriya, A., and Edil, T. B.. (2005). "Evaluating stiffness and strength of pavement materials, geotechnical engineering." *Geotechnical Engineering*, Institution of Civil Engineers, London, Vol. 158, No. GE4, 217–230.

Tremblay, H., Duchesne, J., Locat, J., and Leroueil, S. (2002). "Influence of the nature of organic compounds on fine soil stabilization with cement." *Can. Geotech. J.*, Vol. 39, 535–546.

Trzebiatowski, B., Edil, T., and Benson, C. (2004). "Case study of subgrade stabilization using fly ash: State Highway 32." *Recycled Materials in geotechs, GSP No. 127*, A. Aydilek and J. Wartman, eds., ASCE, Reston, Va., 123–136.

Turner, J. P. (1997). "Evaluation of western coal fly ashes for stabilization of low-volume roads." *Testing Soil Mixed with Waste or Recycled Materials*, STP 1275, ASTM International, West Conshohocken, Pa., 157–171.