STABILIZATION OF PIEDMONT SOILS FOR USE AS BASE MATERIAL ON SECONDARY ROAD PROJECTS

Richard L. Stewart and Oren S. Fletcher, South Carolina State Highway Department; and T. Y. Chu, University of South Carolina

This study was conducted for the purpose of evaluating the effectiveness of various types of stabilizing agents for the micaceous soils found in the Piedmont region. To this end, laboratory investigations with portland cement, hydrated lime, and phosphoric acid as stabilizing agents were carried out, and an experimental road was constructed. Results from these investigations indicate that portland cement is the most effective stabilizing agent and hydrated lime is rated second. Furthermore, the cement requirements of the Piedmont soils appear to be relatively low in comparison with the average values for all types of soil from a wide variety of geologic origin. A simple method for estimating the cement requirement of a given soil was developed. In addition, efforts were made to establish a minimum compressive strength requirement as the criterion for determining the actual cement requirements of the Piedmont soils. In this respect, a tentative criterion of specifying 300 psi as the minimum 7-day compressive strength appears to be satisfactory in designing soil-cement bases for secondary roads in South Carolina. The experimental road was constructed by the type of equipment and procedure that can be expected on secondary road projects. An analysis of test data was made to relate the method of construction with the uniformity and degree of mixing of the stabilized soils.

•PORTLAND cement and hydrated lime have been used for many years in the stabilization of soils for highway construction. While the application of these stabilizing agents for various types of soil has been studied and reported by many investigators, there are relatively few publications presenting specific information in regard to the stabilization of micaceous soils as found in the Piedmont region. A study was recently conducted in South Carolina to evaluate the effectiveness of various stabilizing agents for Piedmont soils, with special emphasis on the application to secondary road projects. Included in the study are laboratory investigations using representative samples of Piedmont soils and the construction of an experimental road with soil-cement and lime-stabilized earth bases. This paper presents results of the laboratory investigations and information from the experimental road.

EFFECTIVENESS OF STABILIZING AGENTS FOR PIEDMONT SOILS

The subsurface materials in the Piedmont region are mostly residual soils derived from metamorphic and igneous rocks. Based on pedological classification, the Cecil series occupies more than 60 percent of the area in this region. Soil samples for laboratory investigations were obtained from various locations throughout the South Carolina Piedmont. The samples represent a wide range in textural compositions, plasticity, and soil series. Classification data and Atterberg limits of the soils are given in Table 1. Results from X-ray diffraction analysis indicate that the clay minerals in the soils sampled are primarily kaolinites.

Sponsored by Committee on Soil-Portland Cement Stabilization.

TABLE 1

SUMMARY OF COMPRESSIVE STRENGTH TESTS AND RELATED DATA OF STABILIZED SOILS

Site	Raw Soil			Cement-Stabilized Soil		Lime-Stabilized Soil		Phosphoric Acid-Stabilized Soil	
	Liquid Limit	Plasticity Index	AASHO Classification	Content of Cement (percent)	Compressive Strength[a] (psi)	Content of Lime (percent)	Compressive Strength[a] (psi)	Content of Phosphoric Acid (percent)	Compressive Strength[a] (psi)
A	48	9	A-7-5(8)	7	329	3	62	1	—[b]
				9	398	5	75	2	—[b]
				12	465	7	72		
				15	492	10	66		
B		NP	A-2-4	10	253			1, 2	—[b]
E-1	29	12	A-6(7)	8	438	8	82	2	36
E-3	50	22	A-7-6(12)	10	448	8	91	2	142
E-4	48	2	A-5(6)	4	142	4	123	1	—[b]
				6	242	8	194	2	102
				8	474				
				10	699				
				13	1,031				
E-5		NP	A-4(4)	6	406	6	133	1	—[b]
F	42	NP	A-5(3)	8	378	7	65	1	196
G		NP	A-1-b	4	337	4	126	1	—[b]
H	50	11	A-7-5(10)	12	423	8	117	1	—[b]
I	38	16	A-6(7)	6	357	6	110	1	102
J	44	9	A-5(3)	4	383	4	171	1	47
K	46	15	A-7-5(8)	8	392	8	149	½, 1	—[b]
L	62	25	A-7-5(15)	8	365	8	149	½, 1	—[b]
M		NP	A-1-b	8	355	8	100	½, 1	—[b]
N	46	17	A-7-6(9)	11	546	8	205	½, 1	—[b]
O	36	16	A-6(7)	4	328	4	83	1	41
P	50	13	A-7-5(2)	6	468	6	214	1	60
Q	65	17	A-7-5(12)	6	310	6	117	½, 1	—[b]
R	40	12	A-6(4)	6	342	6	101	½, 1	—[b]
S	49	6	A-5(1)	6	318	6	123	½, 1	—[b]
T	63	31	A-7-5(18)	12	337	4	24	½, 1	—[b]
U	42	12	A-7-5(7)	8	355	4	23	1	24
V	37	4	A-4(1)	6	400	4	143	½, 1	—[b]
W		NP	A-2-4	6	315	6	108	½, 1	—[b]

[a]Mostly the average of those obtained from tests of 3 specimens.
[b]Because of slacking after immersion, the specimens could not be used for compressive strength tests.

Portland cement, hydrated lime, and phosphoric acid were used as the stabilizing agents in the laboratory experiments with Piedmont soils. The experiments for portland cement stabilization of the soils were made primarily with Type I cement. The hydrated lime used in the laboratory experiments contains approximately 73 percent CaO; the phosphoric acid used contains 75 percent H_3PO_4. The latter was manufactured by electric furnace process.

The effectiveness of the stabilizing agents for the Piedmont soils was evaluated on the basis of compressive strength of the stabilized soils. In this study, the compressive strength serves only as an index representing the influence of a stabilizing agent on the behavior of the raw soil. Procedures for conducting the compressive strength tests are essentially the same as those published by the Portland Cement Association (1). Specimens 2 in. in diameter and approximately 2 in. in height were prepared with a density approaching that obtained by the AASHO standard compaction method T-99. After 7 days of curing in a high humidity cabinet and 24 hours of immersion in water, the specimens were subjected to unconfined compression tests with a rate of deformation of 0.02 in./minute.

The compressive strength test data of soils stabilized with Type I portland cement, hydrated lime, and phosphoric acid are also given in Table 1. The content of all stabilizing agents given in the table is expressed in percentage by weight of oven-dry soil. In the tests using portland cement or hydrated lime as the stabilizing agent, various contents of stabilizing agents were used with soils from all sites. Table 1, however, gives only the data from tests with a single content of stabilizing agent for all soils except those from sites A and E-4. The data of the stabilized soils related to these sites are given as typical examples of the effect on compressive strength due to variations in the content of stabilizing agents. Further information concerning the laboratory investigations is available in a separate report (2). The following are brief discussions regarding the relative effectiveness of the 3 stabilizing agents for the Piedmont soils.

Stabilization with Portland Cement

The relatively high compressive strength of soil-cement specimens given in Table 1 indicates that portland cement is a more effective stabilizing agent for the Piedmont soils in South Carolina than hydrated lime or phosphoric acid. A substantial reduction in the plasticity of soils upon the addition of portland cement was noted from results of accompanying tests with cohesive soils. The mechanism of cement stabilization of soils has been investigated by Herzog and Mitchell (3), Moh (4), and Noble (5). Information presented in their reports, as well as in other publications related to this subject, indicates that the amount of portland cement required for the stabilization of a given soil is dependent on the mineralogical composition of the soil. The comparatively low cement requirements for the Piedmont soils as indicated later in this paper appear to be related to the fact that the primary constituents in the clay fraction of these soils are kaolinites.

Stabilization with Hydrated Lime

The compressive strength data indicate that the use of hydrated lime as a stabilizing agent results in moderate compressive strength of the stabilized soils. The mechanism of lime stabilization has been studied by many investigators including Diamond and Kinter (6); Eades, Nichols, and Grim (7); and Davidson and Handy (8). Although the complex reactions in soil-lime mixtures are not clearly understood, the information and hypotheses given in these references lead one to believe that lime stabilization of the soils investigated is primarily due to the reaction of lime with siliceous and possibly also aluminous minerals in the soils. In the case of highly micaceous soils, the addition of lime probably results in the formation of abundant cementitious materials identified as calcium silicate hydrates by Eades, Nichols, and Grim (7).

The amount of lime required for adequate stabilization of a given soil may be determined according to the compressive strength, the reduction in plasticity index, or the CBR test data of soil-lime mixtures as reported by Thompson (9). In addition, lime requirements for some soils may be estimated by simple pH tests according to a procedure developed by Eades and Grim (10). Among these methods, the compressive strength test approach is believed to be most suitable for determining the lime requirements of Piedmont soils.

Stabilization with Phosphoric Acid

The data given in Table 1 reveal that phosphoric acid is less effective in stabilizing the Piedmont soils than either portland cement or hydrated lime. Although contents of the stabilizing agent other than the values given in the table were tried in testing some of the soils, the results obtained did not alter this conclusion. Demirel and Davidson (11) reported that the reaction of phosphoric acid with kaolinite was found to be rather slow and incomplete. In view of the fact that the Piedmont soils tested contain primarily kaolinites in the clay fraction, the unfavorable response of the Piedmont soils to this stabilizing agent appears to be essentially due to the relatively slow and incomplete reaction mentioned earlier.

CEMENT REQUIREMENTS OF PIEDMONT SOILS

Although portland cement is effective in stabilizing all soils investigated, appreciable variations are expected in the amount of cement required for adequate stabilization. Table 2 gives a comparison of the cement requirements for all samples determined by various procedures. Although the use of freezing-thawing and wetting-drying tests (12) is generally recognized as a reliable method for determining cement requirements, the test procedures are rather time-consuming. Because the PCA shortcut procedures (1) are applicable only for sandy soils, there is a need for relatively

TABLE 2

CEMENT REQUIREMENTS OF PIEDMONT SOILS

Site	Cement Requirement Determined by Laboratory Testing (percent)			Estimated Cement Content for Setting Up Trial Mixtures (percent)	
	PCA Short-Cut Procedure For Sandy Soils	Freeze-Thaw and Wet-Dry Tests	Minimum 300-psi Compressive Strength	PCA Handbook Procedure	Empirical Equation for Piedmont Soils
A	Not applicable	7	7	14	7
B	10	12	More than 10	—[a]	6
E-1	Not applicable	Not conducted	7	9	7
E-3	Not applicable	10	9	13	9
E-4	Not applicable	5	7	11	6
E-5	4	Not conducted	5	10	6
F	Not applicable	Not conducted	7	10	6
G	4	Not conducted	4	10	6
H	Not applicable	Not conducted	10	15	8
I	Not applicable	Not conducted	6	9	7
J	Slightly less than 4	Not conducted	Less than 4	9	6
K	Not applicable	Not conducted	7	13	7
L	Not applicable	Not conducted	7	15	11
M	5	Not conducted	7	9	6
N	Not applicable	Not conducted	9	11	8
O	Not applicable	Not conducted	4	8	7
P	Not applicable	Not conducted	Less than 6	10	6
Q	Not applicable	Not conducted	6	14	9
R	Not applicable	Not conducted	6	9	6
S	Not applicable	Not conducted	6	10	6
T	Not applicable	Not conducted	12	16	12
U	Not applicable	Not conducted	7	11	7
V	Not applicable	Not conducted	5	8	6
W	6	Not conducted	6	8	6
X-1[b]	6	8	6	10	6
X-2[b]	Not applicable	8	6	12	7
X-3[b]	Not applicable	7	7	12	8
X-4[b]	6	6	7	9	6

[a]Because of extremely low density, the cement requirement of the soil from site B cannot be estimated according to the PCA data of B- and C-horizon soils.

[b]Located at stations 45+00, 53+00, 84+00, and 104+00 respectively along the experimental road described elsewhere in this paper.

short and simple tests applicable to silty and clayey soils or, preferably, to both coarse and fine-grained soils.

Studies for the aforementioned purpose have been made by many investigators including Kemahlioglu, Higgins, and Adam (13) and George and Davidson (14). The use of compressive strength tests for determining the cement requirements of soils in California and, separately, in England was reported by Hveem and Zube (15) and Maclean and Lewis (16) respectively. In this study, an attempt was also made to develop a simplified test procedure for determining the cement requirements of Piedmont soils. Because of the similarities with respect to the geologic origin of Piedmont soils, it was conceived that a design criterion might be established on the basis of the compressive strength of stabilized soils regardless of sandy, silty, or clayey texture. In this respect, a minimum 7-day compressive strength of 300 psi was selected as a tentative criterion for soil-cement to be used in base construction for secondary roads. The cement requirements determined according to this criterion are also given in Table 2. Although this procedure appears to be suitable for determining the cement requirements of Piedmont soils in South Carolina, the reliability of this approach and the adequacy of the tentative criterion require verification by field experiments with soil-cement bases and continual observation of their performance. Field experiments for this purpose are described elsewhere in this paper.

In the design of soil-cement mixtures, it is desirable to obtain approximate estimates of cement requirements to assist in setting up trial soil-cement mixtures for laboratory tests. This may be achieved by a method developed by Diamond and Kinter (17) or according to the PCA procedure (1, pp. 13-14). The first method is applicable for plastic soils only. To estimate the cement requirements of all soils used in this study, the PCA procedure was followed. Results obtained by this method (Table 2) indicate that the actual cement requirements determined by previously described procedures are consistently lower than the estimated values. This is apparently due to the fact that the PCA method represents a general procedure formulated on the basis of information from all kinds of soil located in a wide variety of geologic regions. For soils with similar mineralogical composition and located within a particular geologic region, it is believed possible to develop a specific method that may be used for improving the accuracy of cement requirement estimates. To this end, efforts were made to formulate a procedure for estimating the cement requirements of Piedmont soils. After an analysis of the results from laboratory investigations, the following empirical equation was obtained:

$$\text{Cement content (percent)} = 3 + (\text{group index of soil}/2)$$

$$\text{Minimum cement content} = 6 \text{ percent}$$

The cement contents computed from this equation are given in Table 2. The data indicate that the cement contents estimated by the empirical equation are (a) appreciably lower than those estimated by the PCA method and (b) fairly close to the actual cement requirements of Piedmont soils. In view of the fact that kaolinites are the predominant type of clay mineral in the Piedmont soils, it can be expected that the cement requirements of these subsurface materials would be lower than those of soils having comparable clay fraction but containing montmorillonites as the predominant type of clay mineral.

STABILIZED EARTH BASES IN EXPERIMENTAL ROAD

For the study of construction procedures and performance of stabilized earth bases, an experimental road was constructed along route S-671, a secondary road in Greenville County, South Carolina. Type I portland cement and hydrated lime were used as stabilizing agents for the experimental bases. The subsurface materials at the selected site are representative of the Piedmont soils in South Carolina.

Layout and Construction of Experimental Bases

As discussed previously, portland cement was found to be the most effective stabilizing agent for the Piedmont soils, and hydrated lime was rated second. The experimental road was, therefore, planned in such a manner that the major emphasis was placed on soil-cement bases. In the layout of the experimental sections, the amount of stabilizing agent to be mixed with the soils was selected mainly on the basis of the compressive strength of soil-cement and soil-lime mixtures. For soil-cement bases, considerations were also given to the results of freezing-thawing and wetting-drying tests. Although a uniform thickness of 5 in. was adopted for the soil-lime bases, sections of soil-cement bases 4 and 6 in. thick were used for evaluating the thickness effect on their performance. Figure 1 shows the detailed layout of all experimental sections.

In selecting the equipment for the construction of the stabilized earth bases, it was recognized that the use of stationary mixing plants or single-pass traveling mixing machines would result in more uniform mixtures and better construction control than the use of multipass rotary mixers. Nevertheless, multipass rotary mixers together with motor graders were actually used because of the intent of evaluating the type of equipment and procedure that can be expected in the construction of secondary roads in South Carolina.

The application of stabilizing agents was done by placing bags of portland cement or hydrated lime along the roadway and then spreading the cement and lime over the soil to be stabilized. The degree of pulverization of the raw soils required in the South Carolina standard specifications is that 100 percent by dry weight pass 1-in. sieve and a minimum of 80 percent pass the No. 4 sieve, exclusive of gravel and stone retained on the sieve. All stabilized earth bases were compacted at or near the optimum mois-

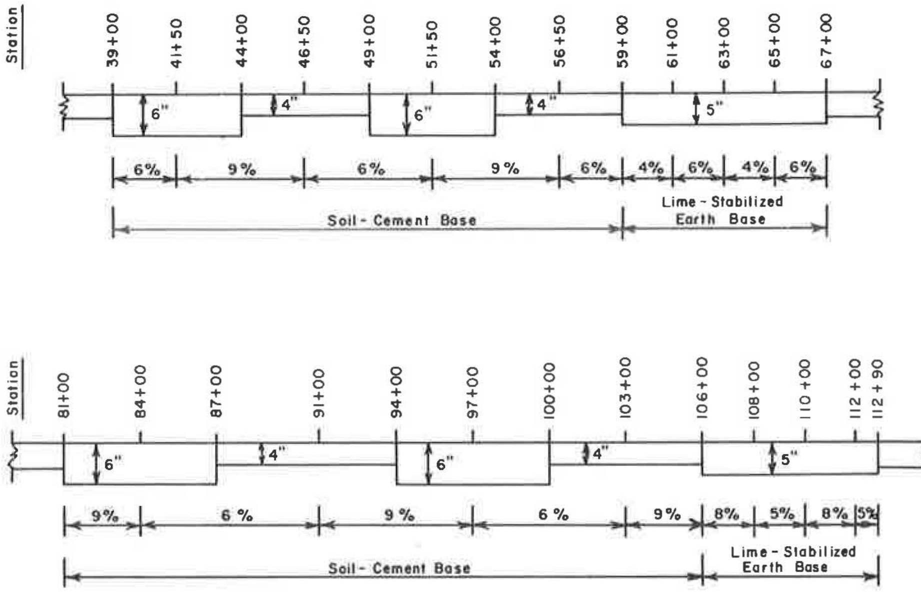

Figure 1. Layout of stabilized earth bases along experimental road.

ture content. For soil-cement bases, the specification requires that compaction of the base should be completed within 6 hours after application of water to the mixture of soil and cement. For soil-lime bases, the moist soil-lime mixture was allowed to age for 48 to 72 hours before final mixing and compaction. During the aging period, the roadway surface was sealed by light compaction to prevent excessive amounts of water from percolating into the mixture in the event of rain.

After final compaction, the stabilized earth bases were primed with MC-30 cutback asphalt for maintaining the proper moisture content during curing. When all experimental sections were completed, they were covered with a bituminous surfacing according to the procedures indicated in the South Carolina standard specifications for "double treatment" using emulsified asphalt as the binder. The width of stabilized earth bases is 23 ft and that of the bituminous surfacing is 22 ft. The experimental bases were constructed in July 1967 when the weather was generally dry and hot.

Properties of Raw and Stabilized Soils

The AASHO classification, liquid limit, and plasticity index of soils sampled after the final grading of the experimental road are given in Table 3. The soils listed in this table are from either B- or C-horizon. In the area where the experimental road is located, the materials from B-horizon are usually A-6 or A-7 soils; those from C-horizon are often A-2, A-4, or A-5 soils. Also given in Table 3 are the liquid limit and plasticity index of the stabilized soils. Test samples were taken just before compaction of the stabilized earth bases and on testing were found to contain the percentage of stabilizing agent given in the table. As expected, the data given in the table indicate a reduction in the plasticity index of the soils due to the addition of stabilizing agents.

The stress-strain characteristics of the raw and stabilized soils were evaluated by conducting triaxial tests using samples representative of the subsurface materials along the experimental road. The samples selected for this purpose are the A-7-5(9) soil from B-horizon at station 84+00 and the A-2-4 soil from C-horizon at station 110+00. All specimens were compacted in such a manner as to provide the anticipated field density. Specimens of raw soils were subjected to capillary absorption before being used for triaxial tests. In the case of stabilized soils, the test specimens were cured for 1 week, subjected to capillary absorption, and then used for triaxial tests.

TABLE 3

CLASSIFICATION OF SOILS ALONG EXPERIMENTAL ROAD AND EFFECT OF STABILIZING AGENTS ON PLASTICITY

Station	Raw Soil			Stabilized Soil		
	AASHO Classification	Liquid Limit	Plasticity Index	Stabilizing Agent (percent)	Liquid Limit[a]	Plasticity Index[a]
40+00	A-7-5(9)	49	18	7.4 cement	37	4
43+00	A-7-5(8)	44	14	14.2 cement	38	1
45+00	A-4(2)	40	4	6.3 cement	Not conducted	Not conducted
48+00	A-7-6(7)	45	16	5.2 cement	34	3
50+00	A-4(5)	36	9	10.4 cement		NP
53+00	A-7-5(3)	43	11	5.7 cement		NP
55+00	A-7-6(10)	49	21	11.2 cement		NP
58+00	A-7-6(6)	45	17	7.9 cement		NP
60+00	A-4(3)	35	7	4.9 lime	Not conducted	Not conducted
62+00	A-4(1)	32	10	5.2 lime		NP
64+00	A-2-4(0)	36	1	4.3 lime		NP
66+00	A-6(3)	38	14	4.5 lime		NP
82+00	A-6(3)	35	11	6.0 cement	34	2
86+00	A-7-6(10)	49	20	3.8 cement	36	8
88+00	A-7-5(9)	47	17	5.5 cement		NP
92+00	A-7-6(10)	47	19	9.0 cement		NP
99+00	A-7-6(7)	44	16	5.5 cement		NP
102+00	A-6(4)	37	11	5.5 cement		NP
104+00	A-6(3)	37	11	7.5 cement		NP
107+00	A-7-5(4)	47	11	6.3 lime		NP
109+00	A-2-4		NP	4.3 lime	Not conducted	Not conducted
111+00	A-4(0)	38	9	6.3 lime		NP

[a]Atterberg limits tests for the stabilized soils were made approximately one month after the soils had been mixed with the stabilizing agents.

The moisture content, dry density, and modulus of deformation data for all materials tested are given in Table 4. The effectiveness of stabilizing agents is indicated by the extremely high moduli of deformation of stabilized soils in comparison with those of the raw soils.

TABLE 4

TRIAXIAL TEST DATA OF RAW AND STABILIZED SOILS

Station	Soil	Moisture Content During Molding (percent)	Dry Density (pcf)	Modulus of Deformation[a] (psi)
84+00	Raw	18.6	97.2	1,100
	Stabilized with 6 percent cement	20.3	96.8	71,400
	Stabilized with 9 percent cement	20.6	96.4	166,700
	Stabilized with 6 percent lime	24.5	95.2	15,000
	Stabilized with 9 percent lime	23.6	93.9	35,000
110+00	Raw	17.1	103.9	1,460
	Stabilized with 5 percent cement	16.9	103.9	28,600
	Stabilized with 6 percent cement	16.8	105.3	50,000
	Stabilized with 5 percent lime	18.2	102.2	28,790
	Stabilized with 8 percent lime	17.8	101.0	35,540

Note: Triaxial tests were conducted under unconsolidated undrained conditions with test procedures as described by Chu, Humphries, and Fletcher (20).

[a]With a continuing pressure of 10 psi and a deviator stress of 5 psi; data given are the average of similar specimens.

TABLE 5

COMPARISON OF LABORATORY AND FIELD COMPACTION OF STABILIZED SOILS

Stabilizing Agent	Station	Laboratory Compaction: Maximum Dry Density (pcf)	Laboratory Compaction: Optimum Moisture Content (percent)	Field Compaction: Actual Dry Density (pcf)	Field Compaction: Actual Moisture Content (percent)	Percent Compaction
Cement	40+00	102.1	20.1	100.2	16.9	98.1
	43+00	102.1	20.1	98.8	19.4	96.8
	45+00	111.6	18.0	97.0	19.4	86.9
	48+00	102.1	20.1	102.2	20.8	100.0
	50+00	111.6	18.0	97.0	19.6	86.9
	53+00	102.1	20.1	97.2	20.5	95.2
	55+00	102.1	20.1	98.9	21.2	96.9
	58+00	102.1	20.1	99.6	20.8	97.6
	82+00	112.2	16.0	106.3	15.6	94.7
	86+00	102.1	20.1	102.8	20.7	100.7
	88+00	102.1	20.1	111.7	18.0	109.4
	92+00	102.1	20.1	102.8	17.1	100.7
	95+50	111.6	18.0	96.0	16.1	86.0
	96+50	111.6	18.0	101.3	18.7	90.8
	99+00	102.1	20.1	105.2	18.9	103.0
	102+00	109.5	18.5	109.0	19.1	99.5
	104+00	109.5	18.5	109.1	17.8	99.6
Lime	60+00	101.8	21.0	92.1	17.1	90.5
	62+00	101.8	21.0	98.9	19.4	97.2
	64+00	106.3	17.5	94.6	19.8	89.0
	66+00	104.0	22.0	99.9	15.9	96.1
	107+00	103.0	22.0	103.5	21.4	100.5
	109+00	107.0	18.3	102.0	19.4	95.3
	111+00	101.8	21.0	98.5	19.4	96.8
	112+50	101.8	21.0	98.4	18.6	96.7

Compaction of Stabilized Soils

The maximum density of stabilized soils was determined in the laboratory according to AASHO T-134 test procedures (12). In the field, the soil-cement and soil-lime bases were compacted by pneumatic rollers. After compaction, field density tests were performed at selected locations. The density and moisture content data from laboratory and field tests are given in Table 5. The percentage of compaction of stabilized earth bases may be influenced by many factors including the moisture content during compaction and the lift thickness. Data related to the optimum and field moisture contents of the stabilized soils are given in Table 5. Figure 2 shows that at most locations the actual thickness, as determined by the height of cored specimens obtained from the soil-

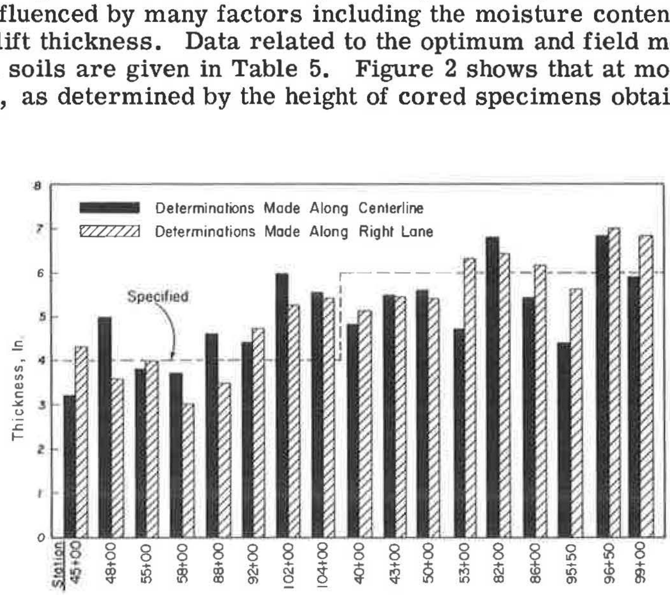

Figure 2. Thickness of soil-cement bases.

cement bases, differs by less than 1 in. from the specified value. The percentage of compaction given in Table 5 is also influenced by the possible difference between the stabilized soil used for the laboratory compaction test and that actually encountered at a particular location. The extremely low values of percentage of compaction at stations 45+00, 50+00, and 95+50 and the unusually high value at station 88+00 are probably due to the aforementioned factor.

Compressive Strength of Stabilized Soils

Compressive strength tests were conducted by using laboratory prepared specimens of stabilized soils as well as cored specimens representing the experimental bases. The laboratory specimens were compacted by a drop hammer with a compactive effort comparable to that specified in the AASHO T-99 compaction test. After compaction, specimens were cured for 7 days and immersed in water for 24 hours before the compressive strength test. Although the cored specimens were also immersed for 24 hours before the test, the time between compaction and testing is much longer for cored specimens than it is for laboratory specimens. Compressive strength test data related to the experimental bases are given in Table 6. The tabulated compressive strength is the average of values from tests of 2 similar specimens. Also given in the table are the ratios of compressive strength of cored specimens to that of laboratory prepared specimens.

Data given in Table 6 indicate that, for soil-cement bases, the compressive strength of cored specimens obtained in August 1967, approximately 1 month after the construction of the experimental bases, is substantially lower than that of laboratory specimens. This is apparently due to differences between field and laboratory conditions with respect to the extent of pulverization, uniformity in spreading or applying cement, degree of mixing, effectiveness of compaction, and efficiency of curing. In reviewing these various factors, it is noted that the effects related to the methods for pulverization,

TABLE 6

COMPARISON OF COMPRESSIVE STRENGTH OF LABORATORY PREPARED AND CORED SPECIMENS OF STABILIZED SOILS

Stabilizing Agent	Station	Compressive Strength of Laboratory Prepared Specimens, q_0[a] (psi)	Compressive Strength of Cored Specimens[b] (psi)			Ratio of Compressive Strength of Cored Specimens to Laboratory Prepared Specimens		
			q_1	q_2	q_3	q_1/q_0	q_2/q_0	q_3/q_0
Cement	40+00	270	107	157	219	0.4	0.6	0.8
	43+00	344	97	190	227	0.3	0.6	0.7
	45+00	429	209	—c	—c	0.5	—	—
	48+00	256	121	235	—c	0.5	0.9	—
	50+00	255	144	165	—c	0.6	0.7	—
	53+00	330	217	398	577	0.7	1.2	1.8
	55+00	374	112	353	—c	0.3	0.9	—
	58+00	269	133	358	—c	0.5	1.3	—
	82+00	526	147	184	195	0.3	0.4	0.4
	86+00	183	118	153	330	0.7	0.8	1.8
	92+00	314	138	399	430	0.4	1.3	1.4
	99+00	275	115	203	298	0.4	0.7	1.1
	102+00	245	114	274	466	0.5	1.1	1.9
Lime	60+00	102	—c	—c	—c	—	—	—
	62+00	28	—c	—c	—c	—	—	—
	64+00	123	—c	65	—c	—	—	—
	66+00	124	—c	—c	—c	—	—	—
	107+00	195	218	288	486	1.1	1.5	2.5
	109+00	290	180	281	—c	0.6	1.0	—
	111+00	154	149	—c	—c	1.0	—	—
	112+50	115	68	60	—c	0.6	0.5	—

Note: Average of the ratios is q_1/q_0, 0.5; q_2/q_0, 0.9; and q_3/q_0, 1.2.

[a]Laboratory prepared specimens were cured for 7 days before testing. The contents of stabilizing agents are shown in Figure 1.

[b]Cored specimens q_1, q_2, and q_3 were obtained in August 1967, October 1968, and December 1969 respectively. The contents of stabilizing agents in cored specimens are given in Table 7.

[c]Specimens not satisfactory for compressive strength tests.

cement spreading, and mixing are of special significance in this study. A brief discussion in regard to these effects follows.

The actual cement contents in soil-cement bases were determined by laboratory tests using cored specimens in accordance with procedures of AASHO Test Method T-144-57 (12). A comparison of the specified and actual cement contents of the soil-cement bases as given in Table 7 indicates that there are substantial variations in actual cement contents within each experimental section. Although the accuracy of laboratory tests for determining the cement contents may have some influence on test results, the major factors causing the great variation in cement contents appear to be related to the equipment and procedure of construction. As discussed previously, the experimental bases were constructed by the type of equipment and procedure that can be expected in secondary road construction in South Carolina. Consequently, the uniformity of mixture within each experimental section and the degree of mixing are expected to be inferior to those obtainable by the use of stationary mixing plants or single-pass traveling mixing machines. Based on a laboratory study of soil-cement mixtures, Baker (18) reported the pronounced effect on compressive strength due to variations in the degree of mixing. According to the laboratory data and other information given here, it is believed that the adverse effects related to uniformity of mixture and degree of mixing are major causes for the relatively low compressive strength of the cored specimens taken in 1967.

The data obtained from the cored specimens of soil-cement bases taken in 1967, 1968, and 1969 (Table 6) show a general increase in compressive strength with time. As a result, the compressive strength of cored specimens taken approximately 2½ years after construction is higher than that of laboratory prepared specimens tested 7 days after compaction. The rate of increase in compressive strength in the post-construction period is indicated by the average of the ratios of the compressive strength of cored specimens to that of laboratory prepared specimens as noted in the table. The

TABLE 7

COMPARISON OF SPECIFIED AND ACTUAL CONTENTS OF STABILIZING AGENTS IN EXPERIMENTAL BASES

Stabilizing Agent	Station	Specified Percentage of Stabilizing Agent	Actual Percentage of Stabilizing Agent Determined From Core					
			August 1967		October 1968		December 1969	
			Core 1	Core 2	Core 1	Core 2	Core 1	Core 2
Cement	40+00	6	8.1	5.2	7.0	4.9	—[a]	4.6
	43+00	9	8.7	11.2	10.4	7.9	7.4	9.6
	45+00	9	6.5	10.2	6.0	9.0	7.1	8.0
	48+00	6	—[a]	4.8	6.0	8.4	5.0	9.3
	50+00	6	—[a]	7.1	9.1	8.6	9.1	5.8
	53+00	9	—[a]	12.6	10.4	8.4	9.3	18.2
	55+00	9	—[a]	7.0	10.1	9.7	6.9	8.6
	58+00	6	6.8	10.6	7.5	8.6	7.1	9.0
	82+00	9	—[a]	9.1	4.9	7.4	4.8	6.3
	86+00	6	5.5	5.2	4.0	6.7	10.8	6.5
	88+00	6	4.9	4.3	5.4	5.8	4.9	3.8
	92+00	9	7.2	6.3	6.5	6.7	7.2	5.7
	95+50	9	7.5	10.0	6.9	8.2	8.0	8.6
	96+50	9	6.3	7.2	7.1	8.6	6.4	9.1
	99+00	6	—[a]	13.4	5.6	5.9	5.1	5.7
	102+00	6	—[a]	5.0	4.8	4.1	3.4	4.9
	104+00	9	7.2	5.6	7.1	6.6	4.9	4.3
Lime	60+00	4	—[a]	2.9	7.6	—[a]	7.2	4.5
	62+00	6	—[a]	5.6	5.9	6.8	2.2	—[a]
	64+00	4	—[a]	3.8	5.4	3.3	4.1	2.9
	66+00	6	—[a]	4.1	3.3	3.5	3.8	4.3
	107+00	8	6.8	5.6	7.7	6.7	6.5	5.9
	109+00	5	—[a]	4.2	5.3	6.5	5.2	3.9
	111+00	8	6.1	6.5	7.3	6.7	8.1	6.6
	112+50	5	4.1	4.3	4.3	5.0	4.5	1.6

[a]Tests for determining the content of stabilizing agent were not conducted at the locations indicated.

increase in compressive strength with time is another indication of the effectiveness of portland cement for the stabilization of the soils investigated.

In the case of soil-lime bases, the findings concerning substantial variations in lime contents and the general increase in compressive strength with time are similar to those regarding soil-cement bases discussed earlier. It will be noted, however, that information from the soil-lime bases is rather limited because of difficulties in obtaining satisfactory specimens for compressive strength tests.

Performance of Experimental Road

After completion of the stabilized earth bases and bituminous surfacing in the summer of 1967, traffic counts were conducted to determine the number of vehicles traveling on the experimental road. The average daily traffic during the past 3 years varied from 120 to 250 vehicles of which most were passenger cars. The traffic volume indicated is slightly higher than the average for secondary roads in South Carolina.

The performance of the experimental road has been studied by frequent inspections of the conditions in various experimental sections. The findings from the inspections made in June 1968 and July 1970 are given in Table 8. In general, the soil-cement bases were found to provide satisfactory performance except for some edge raveling as a result of shoulder erosion. The general conditions of the soil-lime bases, however, are less favorable than those of the soil-cement bases.

To assist in the evaluation of the performance of various experimental sections, Benkelman beam deflection measurements were made periodically at selected locations. In all measurements, the applied load is 18 kips on single axle and the tire pressure is 80 psi. The "normal procedure" as described by Benkelman, Kingham, and Fang (19) was followed in conducting the measurements. Data from the deflection measurements made in 1968, 1969, and 1970 are shown in Figures 3 and 4. The deflection at each location shown in the figures is the average of the values from 2 separate measurements conducted along the outer wheelpath in adjacent areas.

TABLE 8

GENERAL CONDITIONS OF EXPERIMENTAL SECTIONS

Stabilizing Agent	Station	Conditions as Observed in June 1968 (1 year after construction)	Conditions as Observed in July 1970 (3 years after construction)
Cement	39+00 to 59+00	No rutting or surface cracking except that erosion of shoulder resulted in some cracking at north side edge of bituminous surfacing in area between station 54+00 and 57+00.	Road in good condition except that erosion of shoulder has resulted in further cracking along edge of bituminous surfacing. Patching along edge has been done in some areas.
Lime	59+00 to 67+00	Some rutting along wheelpath. Rut depth up to $^3/_4$ in. Extensive raveling at edges of stabilized base.	Conditions are inferior to those in soil-cement section between stations 54+00 and 57+00. Some areas have been repaired by patching, but cracking and extrusion of fine materials through cracks are observed.
Cement	81+00 to 106+00	No rutting or surface cracking except some edge raveling in vicinity of station 91+00 and in area between station 97+00 and 106+00. Edge raveling in vicinity of station 91+00 apparently because soil-cement base is approximately 1 ft inside edge of bituminous surfacing.	Conditions generally similar to those in soil-cement section from station 39+00 to 59+00 except that occasional longitudinal cracking is observed at approximately one-third of width of stabilized base.
Lime	106+00 to 112+90	No rutting or surface cracking except some edge raveling.	Edge raveling in some areas has been repaired by patching. Cracking occurred along wheelpath. In general, conditions are similar to those of other lime-stabilized base section.

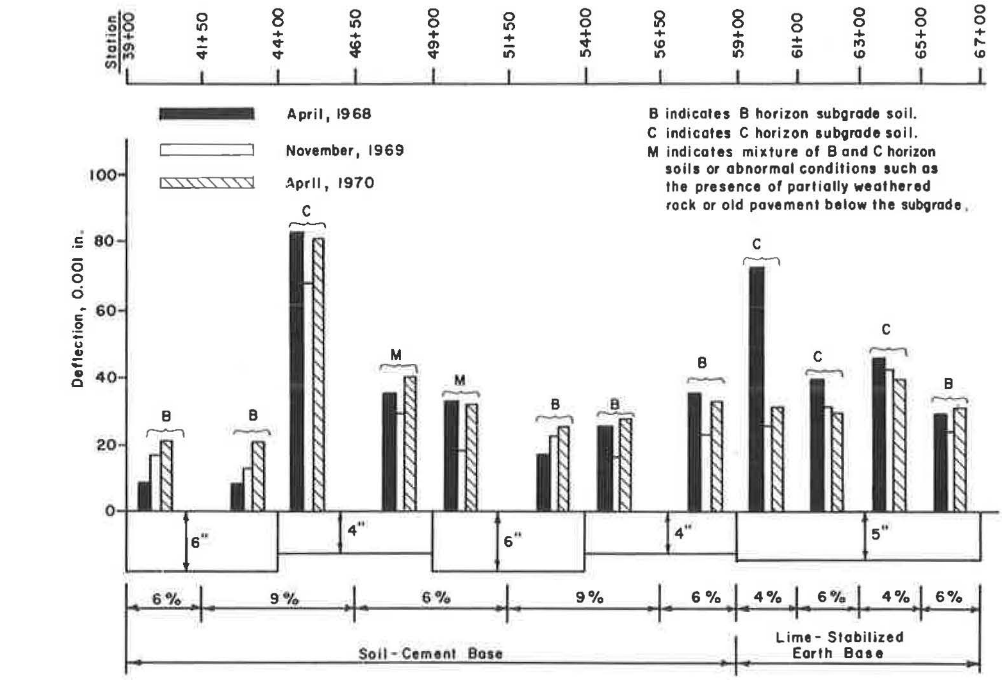

Figure 3. Benkelman beam deflections on experimental road between stations 39+00 and 67+00.

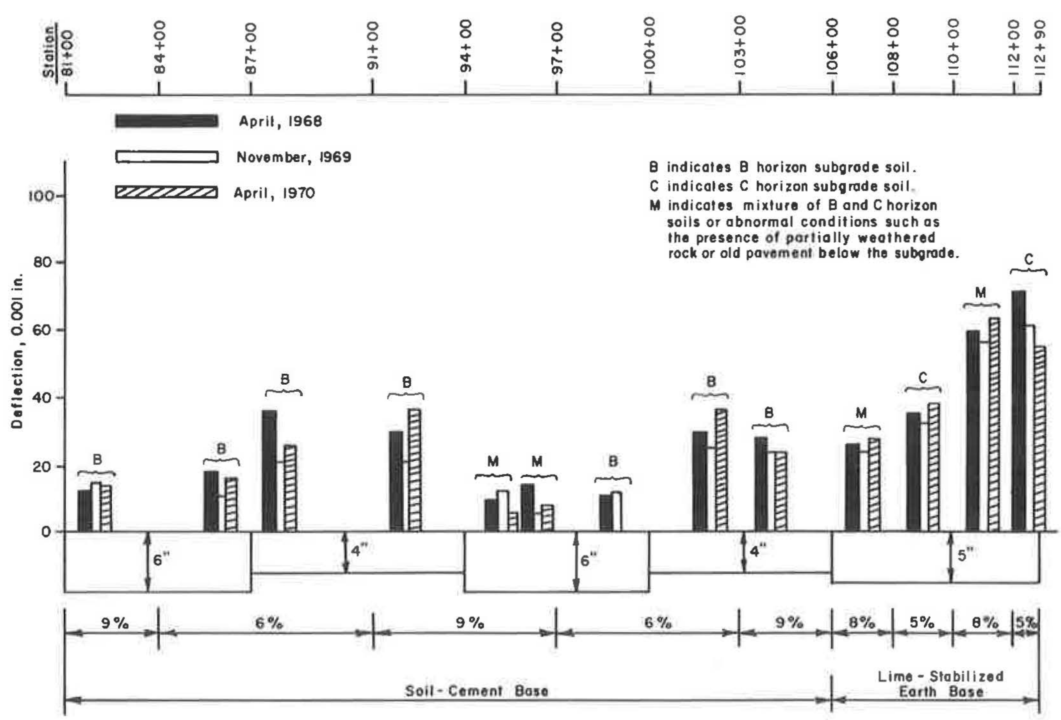

Figure 4. Benkelman beam deflections on experimental road between stations 81+00 and 112+90.

The deflection of a pavement under an applied wheel load is dependent on many variables such as the thickness of the pavement system and the stress-strain characteristics of both the subgrade and the pavement components. Variations in temperature of the pavement and moisture content of the subgrade soil may also affect pavement deflection because of their influence on the aforementioned variables. In this study, the effect related to pavement temperature and subgrade moisture is believed to be of minor importance. The other variables indicated, however, may all have significant influence on the deflection values shown in Figures 3 and 4. Because the experimental road was planned for several objectives and not specifically for evaluating the individual effect of each variable, it is difficult to formulate specific conclusions on the basis of the deflection data. Following is a general discussion in connection with the results obtained from the deflection study.

As noted previously, C-horizon soils along the experimental road are the typical micaceous A-2, A-4, or A-5 soils existing in the Piedmont region. The moduli of elasticity of these soils are often found to be extremely low. This is probably the main reason for the relatively high deflections at locations having C-horizon subgrade soils under the experimental bases. In regard to the performance of the stabilized earth bases, the deflection data shown in Figures 3 and 4, together with the information given in Table 8, indicate that there has been no significant change in the serviceability of the experimental road, especially the soil-cement sections, in the 3-year post-construction period.

Among the objectives of the experimental road are the evaluation of thickness effect of soil-cement bases and verification of the tentative 300-psi minimum compressive strength requirement for designing soil-cement mixtures to be used as base materials on secondary road projects. Information available at this time is inadequate for the desired purposes. Continued observation and measurements have been planned for obtaining additional information from the experimental road. As to the minimum compressive strength requirement, the performance study described and the laboratory test results given in Table 2 appear to have provided sufficient information to suggest that the application of the tentative design criterion be continued at least for the time being.

SUMMARY

1. Based on laboratory investigations conducted in this study, portland cement is the most effective stabilizing agent for the Piedmont soils in South Carolina and hydrated lime is rated second. The performance of soil-cement bases on the experimental road is also superior to that of soil-lime bases.

2. The experimental road was constructed by using the type of equipment and procedure that can be expected to be used on secondary road projects. As a result, the compressive strength of soil-cement bases represented by cored specimens is lower than the 7-day compressive strength of laboratory prepared specimens until approximately $2\frac{1}{2}$ years after construction. At that time, the compressive strength of soil-cement bases exceeded that of laboratory specimens.

3. A 7-day compressive strength of 300 psi was tentatively established as the minimum requirement for designing soil-cement mixtures to be used as base materials on secondary road projects in the South Carolina Piedmont. Although no definite conclusions can be drawn at this time, the field and laboratory investigations in this study are believed to have provided sufficient information to suggest that application of the tentative design criterion be continued at least for the time being.

4. Approximate cement requirements of Piedmont soils may be estimated by a simplified method formulated on the basis of test results obtained from this study. The approximate estimate of the cement requirement of a given soil is to assist in setting up trial soil-cement mixtures for compressive strength or other laboratory tests with the objective of determining the actual cement requirement.

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