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Research News

Engineering Properties of Stabilized Subgrade Soils for Implementation of the AASHTO 2002 Pavement Design Guide

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Pavement conditions data for Oklahoma show that 46% of major roads in the state are in poor condition or mediocre condition due to weak subgrade soils as one of the main factors. Driving roads in need of repairs threaten public safety and cost Oklahoma motorist over $ 1 Billion annually in extra vehicle repairs. In the last few decades, state transportation agencies and industry have been challenged to build, repair and maintain pavement systems with enhanced longevity and reduced costs. Specifically, efforts have been made to improve the design methodology and to establish techniques for modification of pavement materials (NCHRP). Cementitious stabilization is considered one of these techniques; it enhances the engineering properties of subgrade layers, which produces structurally sound pavements. However, the enhancement in engineering properties and the field performance of a stabilized subgrade layer in pavement system are influenced by many factors such as stabilizing agent type, the type of soil to be stabilized, curing time, the required strength, the required durability, cost, and environmental conditions.

Cementitious stabilization is widely used in Oklahoma and elsewhere as a remedial method to ameliorate subgrade soil properties (e.g., strength, stiffness, swell potential, workability, and durability) through the addition of cementitious additives. It consists of mixing stabilizing agents such as lime, class C fly ash (CFA) and cement kiln dust (CKD) with soil. In the presence of water, these agents react with soil particles to form cementing compounds that are responsible for the improvement in engineering properties such as strength and stiffness.

With the movement toward implementation of the new Mechanistic-Empirical Pavement Design Guide (MEPDG), new material properties required for critical performance prediction of cementitiously stabilized layers are recommended. These properties include resilient (M_r) or elastic (M_E) modulus, unconfined compressive strength (UCS), and durability. The evaluation of these inputs is required to pursue a Level-1 (most accurate) design under the hierarchical scheme. For a Level-2 (intermediate) design, however, design inputs are user selected possibly from an agency database or from a limited testing program or could be estimated through correlations (AASHTO, 2004). Level-3, which is the least accurate, requires only the default values and is generally not recommended.

To this end, the current study was undertaken to determine engineering properties of cementitiously stabilized common subgrade soils in Oklahoma for the design of roadway pavements in accordance with the AASHTO 2002 MEPDG. These properties include resilient modulus (M_r), modulus of elasticity (M_E), unconfined compressive strength (UCS), moisture susceptibility and three-dimensional (3-D) swell. Additionally, mineralogical studies such as scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) and X-ray diffraction (XRD) were used to verify the findings from the macro test results.

Materials and Test Procedure

In this study, four different types of soils encountered in Oklahoma, namely, Port Series (P-soil), Kingfisher Series (K-soil), Vernon Series (V-soil, sulfate content ≈ 15,400 ppm), and Carnasaw Series (C-soil) were used. A summary of the soil properties determined in the laboratory are presented in Table 1. These soils were stabilized with three locally produced and economically viable stabilizers used in Oklahoma, namely, hydrated lime (or lime), class C fly ash (CFA), and cement kiln dust (CKD). The percentage of stabilizer used (3%, 6% and 9% for lime; 5%, 10% and 15% for CFA and CKD) was selected on the basis of pH test and literature review. Cylindrical specimens of stabilized soil were compacted and cured for 28 days in a moist room having a constant temperature (73.4±3^{o}F) and controlled relative humidity (>96%). The curing period is consistent with the new MEPDG that the required M_r, M_E and UCS for design are the 28-day values.

Table 1 *Testing Designation and Soil Properties*

Method	Parameter/Units	P-soil	K-soil	V-soil	C-soil
ASTM D 2487	USCS Symbol	CL-ML	CL	CL	CH
AASHTO M 145	AASHTO Designation	A-4	A-6	A-6	A-7-6
ASTM D 2487	USCS Name	Silty clay with sand	Lean clay	Lean clay	Fat clay
ASTM D 2487	% finer than 0.075 mm	83	97	100	94
ASTM D 4318	Liquid limit	27	39	37	58
ASTM D 4318	Plastic limit	21	18	26	29
ASTM D 4318	Plasticity index	5	21	11	29
…	Activity	0.24	0.47	0.28	0.69
ASTM D 854	Specific gravity	2.65	2.71	2.61	2.64
ASTM D 698	Optimum moisture content (%)	13.1	16.5	23.0	20.3
ASTM D 698	Max. dry unit weight (pcf)	113.4	110.6	101.9	103.7
ASTM D 6276	pH	8.91	8.82	8.14	4.17
OHD L-49	Sulfate content (ppm)	<40	<40	15,400	267

USCS: Unified Soil Classification System; OHD: Oklahoma Highway Department

After curing, specimens were tested for M_r, M_E and UCS. Selected specimens were also tested for moisture susceptibility (tube suction test) and three-dimensional swell during 60 days of capillary soaking. A total of four replicates were prepared for each additive content, of which two specimens were tested for M_r and then followed by tube suction test (TST) and three-dimensional (3-D) swell test by subjecting samples to 60 days of capillary soaking. The other two specimens were tested for M_r and then followed by M_E and UCS tests, without capillary soaking. After UCS test broken specimens were air dried for approximately 2 days, and then pulverized and passed through a No. 40 sieve. The finer material was reconstituted with moisture for 1 day, and then tested for liquid limit and plastic limit in accordance with ASTM D 4318.

Figure 1 *Setup for M_r Test*

The M_r tests were performed in accordance with the AASHTO T 307 test method. A 500-lb load cell was used to apply the load. Two linear variable differential transformers (LVDTs) were used to measure the resilient vertical deformation. These LVDTs were attached to two aluminum clamps that were mounted on the specimen at a distance of approximately 2.0 in from both ends of the specimen. The LVDTs had a maximum stroke length of 0.2 in.

A complete setup of M_r testing on stabilized subgrade soil specimen is shown in Figure 1. M_E and UCS tests were conducted in accordance with the ASTM D 1633 test method. Specimens were loaded in a MTS frame at a displacement rate of 0.05 in/min. Deformation values were recorded during the test using two LVDTs fixed to opposite sides of and equidistant from piston rod with a maximum stroke length of 0.5 in. Each specimen was subjected to two unloading-reloading cycles and loaded up to failure in the third sequence of reloading to determine the M_E and UCS.

The TST procedure used in this study consists of placing M_r tested specimens in an oven at 95^{o}F until no more significant weight changes are observed. After drying, specimens were allowed to cool down at room temperature. Specimens were then placed on a porous plate and covered with a membrane in an ice chest containing approximately 12.7 mm (0.5 in.) of de-ionized (DI) water under controlled temperature (73.4±3^{o}F) and relative humidity (>96%). During wetting of specimens in DI water, the dielectric values (DV) increased with time due to capillary soaking of water in the specimens. Four measurements were taken along the circumference of the sample in separate quadrants and the fifth reading was taken at the center of specimen and an average of all five readings was reported. Measurements were taken daily, until the DV became constant. Figure 2 shows photographic view of setup used for TST.

Figure 2 *Setup for TST*

To investigate the swelling potential of specimens, 3-D swell test were conducted on the same specimens under TST testing. The 3-D swell values were measured by determining the height to the nearest 0.001 in at 3 places that are 120^{o} apart. The diameter was measured to the nearest 0.001 in near the top, in the middle, and near the base of each sample. The three height and diameter measurements were averaged and the 3-D volume change was calculated.

To facilitate macro-behavior comparison and explanation, the Scanning Electron Microscopy (SEM) technique was employed to qualitatively identify the micro-structural developments in the matrix of the stabilized soil specimens. A JEOL JSM 880 scanning electron microscope operating at 15 kV was used to visually observe the specimens. The JEOL JSM 880 was fitted with an energy-dispersive X-ray spectrometer (EDS). The EDS was used to analyze chemical compositions of the specimens. To confirm ettringite formation in some of the specimens, XRD tests were also performed on raw soil and capillary soaked specimens.

Results and Discussion

Results for the tested stabilized soil specimens showed that all three stabilizers improved the strength/stiffness properties, namely, M_r, UCS and M_E values, of P-, K-, V- and C-soil specimens. The mean M_r at a deviatoric stress of 6.0 psi and a confining pressure of 4.0 psi has been compared for this purpose (Figure 3). As evident from Figure 3, at lower application rates (3% to 6%), the lime-stabilized soil specimens showed the highest improvement in the M_r values. At higher application rates (10% to 15%), however, CKD treatment provided maximum enhancements. Overall, K-soil and C-soil specimens showed the highest and the lowest improvements in the M_r values. Similar trend of behavior were observed for M_E and UCS values of different stabilized soil specimens. One of the explanations could be differences in the pH values of K- and C-soil. For example, raw K- and C-soil had the highest and the lowest pH value of 9.07 and 4.17, respectively, among the four soils used in this study. It is believed that the difference in M_r values are attributed to the differences in physical and chemical properties of the soils and stabilizing agents which leads to various pozzolanic reactions.

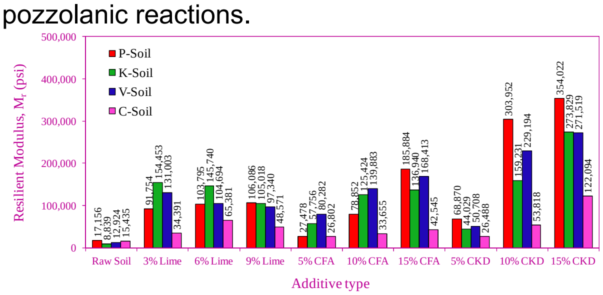

Figure 3 *Variation of M_r Values with Soil and Additive Type*

The mechanical (or macro) behavior could also be explained using the SEM micrographs shown in Figure 4. Visually, it is quite obvious that stabilization of soil resulted in hydration coating and crystals formation in soil matrix. It is reasoned that the crystals within the matrix provide better interlocking between the particles and possible higher resistance to shear deformation and also reduce void within the matrix resulting in overall strength gain. The results of the analysis conforms to the results of the M_r, M_E and UCS tests.

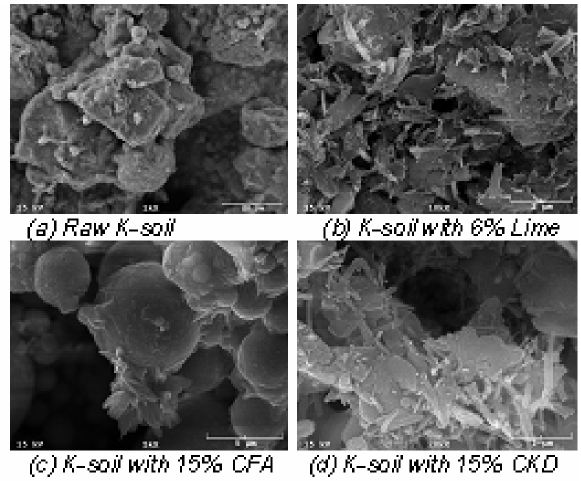

Figure 4 *SEM Micrographs of the Indicated 28-Day Stabilized Soil Specimens*

All the three additives used in this study, namely, lime, CFA and CKD, are effective in reducing the plasticity of soils. However, lime-stabilization is more effective as compared to CFA and CKD-stabilzation in reducing the PI of soils. In addition, the percentage of reduction in PI was observed maximum with K-soil among all the three soils (K-, V- and C-soil). This could also be one of the reasons for the highest improvement in M_r values of stabilized K-soil specimens.

The tube suction test (TST) results revealed that lime- and CFA-treatment is helpful because it reduces the moisture susceptibility. On the other hand, CKD-stabilization makes stabilized specimens more susceptible to moisture, as compared to raw soil specimens. For sulfate bearing soil (V-soil), however, only CFA-treatment showed promising results.

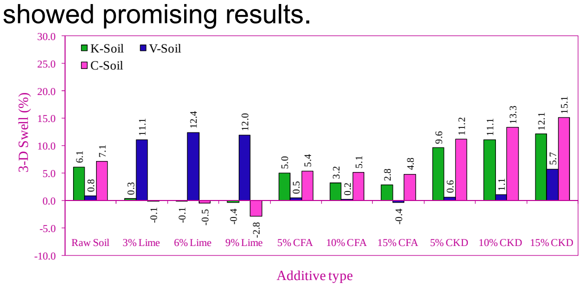

Figure 5 *Variation of Final 60-Day 3-D Swell Values with Soil and Additive Type*

The three-dimensional swelling tests on non-sulfate bearing soil (P-, K- and C-soil) showed that lime is more effective in reducing the swell of raw specimens, as compared to CFA and CKD (Figure 5). In contrast to lime and CFA, an increase in the percentage of CKD makes specimens more susceptible to moisture and three-dimensional swell. It is believed that such an increase in volume is due to the presence of high sulfate content

(28,133 ppm) in CKD causing sulfate-induced heaving (ettringite formation).

The three-dimensional swelling test on sulfate bearing soil (V-soil) showed an increase in volume for lime- and CKD-stabilized specimens while a reduction in volume for CFA-stabilized specimens was observed, as compared to raw soil specimens. This increase in volume is attributed to sulfate-induced heaving which results in the formation of expansive mineral ettringite. Further, presence of ettringite was verified using SEM/EDS tests in conjunction with XRD analyses. Figure 6 shows SEM/EDS test results for lime-stabilized specimens (V-soil), after 60-days of capillary soaking.

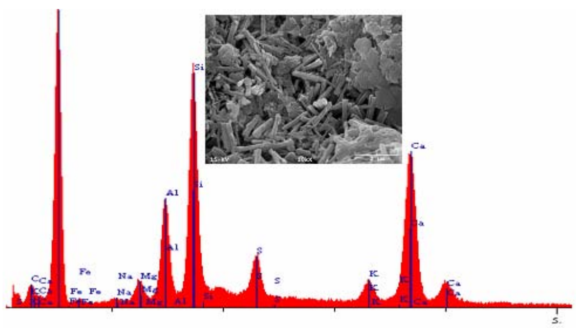

Figure 6 *SEM/EDS of Ettringite Deposited in the Lime-Stabilized V-soil Specimens (After 60-Day Swell)*

As indicated in this study, assessment of stabilized soil specimens on the basis of strength/stiffness (M_r, M_E, UCS) alone can be misleading. In addition, this study generated useful information that would enrich the database pertaining to M_r, M_E, UCS, 3-D swell and moisture susceptibility of selected soils in Oklahoma. An enriched database would benefit highway agencies, specifically pavement engineers, when dealing with construction of new pavements or rehabilitation of existing pavements. It will also facilitate the implementation of the new AASHTO 2002 pavement design guide.

About the authors

Pranshoo Solanki earned his bachelor of science in civil engineering from the Malviya National Institute of Technology (India), and master's degree in rock mechanics (civil engineering) from the Indian Institute of Technology, India. Currently, he is pursuing his doctoral degree in civil engineering from the University of Oklahoma. Soil stabilization using cementitious additives covers an important segment of Solanki's doctoral research.

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