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Influence of Curing Time on the Resilient Modulus of Chemically Stabilized Soils

ABSTRACT: Research was conducted to investigate the influence of soil properties, additive type and curing time on the resilient modulus (M_R) of chemically stabilized soils. Interest in characterizing the rate of M_R improvement through curing time was the primary motivation for this study. Soils stabilized with cement kiln dust and Class C fly ash were collected at five construction sites in Oklahoma. Specimens were prepared at optimum compaction parameters and tested after various curing periods; a total of 58 M_R tests were performed. Properties of both soils and admixtures were evaluated in order to correlate those with the enhanced behavior of the mixed soils measured as improved M_R values. Regression equations were developed so that M_R evolution with time could be quantitatively described. After 28 days of curing, tested soils showed improved M_R values ranging from 7 to 46 times larger than those of untreated soil. Rates of improvement were characterized using a power type regression analysis. Although data are limited, correlations between improvement rate (*Rt*) and raw soil properties including fines fraction, *p*H, and to a lesser extent, specific surface area and cation exchange capacity, indicate these factors show promise as predictors of M_R improvement with time.

KEYWORDS: soil stabilization, resilient modulus, curing time, fly ash, cement kiln dust

Introduction

Structural design and performance of pavements are highly dependent on the stiffness of the subgrade soil. The resilient modulus (M_R) provides a way of characterizing the stiffness of pavement materials under stress states produced by moving wheel loads. In Oklahoma, where weak, fine-grained soils are commonly found, chemical stabilization for improving the mechanical behavior and engineering performance of the subgrade is frequently implemented under empirical criteria. However, most of the current publications address the prediction of M_R values for raw, not stabilized, soil under different stress conditions, including matric suction (Fredlund et al. 1974; Li and Selig 1994; Khoury and Zaman 2004; Liang et al. 2008; Yang et al. 2008). Empirical correlations and improvement estimates have been developed to predict the M_R of cement and lime treated soils (National Cooperative Highway Research Program (NCHRP) Mechanistic-Empirical Pavement Design Guide (MEPDG) (NCHRP 2004) and AASHTO 1993); however, an approach for predicting M_R of cement kiln dust (CKD) and Class C fly ash (CFA) stabilized soils has not been widely recognized and accepted. Therefore, it was the purpose of this study to evaluate the rate and degree of improvement of M_R that can be achieved by using CKD and CFA as chemical admixtures for fine-grained soils collected at five construction sites around Oklahoma. For this study, real soil stabilization projects for road construction and rehabilitation were selected and materials were sampled.

The importance of this study is that by quantitatively describing the improvement of M_R of stabilized soils as a function of curing time, M_R values can be more confidently estimated and incorporated into pavement design. Being a crucial pavement design property, it is important that engineers have a thorough understanding of fundamental behavior associated with the resilient modulus, particularly how it changes with curing time in the case of chemically treated soils. Furthermore, the M_R obtained after a short curing time can be used to predict M_R values at 28 days, which can be greatly advantageous when results are needed quickly; this is very common during highway construction for example when unexpected soils are encountered. Finally, knowing how the resilient modulus varies with time can provide a basis for field curing requirements and opening of the stabilized layer to construction traffic.

Background

It is well known that local materials and environmental conditions can have a wide range of variation within a project site. Consequently, the accurate determination of the M_R, tied to local conditions, is a subject of major importance for highway design, construction and rehabilitation projects; and hence, an important research subject. The M_R provides a way of characterizing the stiffness of soils and aggregate materials. It is analogous to the modulus of elasticity and is a basic relationship between change in axial stress and resulting recoverable axial strain, mathematically defined by the ratio of applied deviator stress to recoverable strain after a defined number of load cycles. The M_R is usually nonlinear and dependent on stress level, as well as intrinsic soil properties. In a 1974 publication, Fredlund et al. stated that the M_R of a compacted subgrade soil could be effectively linked to the stress variables. Aside from the direct influence of confining stress and deviator stress, variations in response to changes in matric suction showed that higher suctions (or lower water contents) resulted in higher M_R values (Seed et al. 1962; Fredlund et al. 1974; Drumm et al. 1997). Since then, various studies have been performed on the modeling and prediction of M_R variation with respect to changes in

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moisture content and soil suction (Li and Selig 1994; Khoury et al. 2003; Khoury and Zaman 2004; Yang et al. 2008; Liang et al. 2008).

Regarding soil stabilization, extensive research has been performed on traditional calcium-based stabilization additives and techniques. Studies have focused on the ultimate improvement of various additive-soil configurations and the factors affecting the final products. It has been demonstrated that generally, M_R of stabilized soils increases as additive content and curing time increase, regardless of the additive and soil type (e.g., Tuncer and Basma 1991; Nelson and Miller 1992; Achampong et al. 1997; Mohammad et al. 2000; Çokça 2001; Puppala et al. 2003; Arora and Aydilek 2005; Edil et al. 2006; Rogers et al. 2006; Solanki and Zaman 2010). The most significant M_R increase occurs within a short time following compaction (Parsons et al. 2003; Parsons and Kneebone 2004) and does not increase significantly after 4 to 8 weeks depending on the additive cementitious properties. However, evidence of improvement has been found on specimens cured over 90 days (Arora and Aydilek 2005). Nelson and Miller (1992) suggested that curing periods should extend for at least 10 to 14 days in order to provide idealized conditions for the cementitious and pozzolanic reactions to take place.

Achampong et al. (1997) found that the improvement of M_R using cementitious additives was influenced by soil type; they showed that lean clays (CL) responded better than montmorillonitic high plasticity clays (CH) to cement and lime stabilization. Edil et al. (2006) performed California Bearing Ratio (CBR) and M_R tests on fly ash mixtures. They found a general trend of increasing M_R improvement ratio, defined as the maximum improved M_R value, divided by the untreated soil M_R value, as the soil became finer grained or more plastic. Velasquez et al. (2006) concluded that clay fraction had a significant effect on the improvement of M_R for enzyme-based soil stabilization.

The efficiency of soil additives has been studied by Miller and Azad (2000) and Miller and Zaman (2000) who used *p*H values from CKD-soil mixtures as an indicator of the reactivity of CKD as a stabilizing agent. The *p*H response curves that showed an asymptotic behavior at lower percentages of CKD proved to be more effective in that a smaller amount of additive was necessary to achieve a stable *p*H value. A more recent study by Miller and Diaz (2002) on the *p*H response of soil-water-CKD mixtures showed that soil type had an influence on the *p*H response; soils with higher plasticity indices (PI) showed a slower increase in *p*H as the CKD fraction was increased. This was explained by the fact that soils with high PI values contain more reactive clay particles. Researchers concluded that the *p*H response, characterized by the change in *p*H from 0 to 2 % additive content, of the mixtures was a reasonably good indicator of the optimum additive content to achieve target improvement for unconfined compression strength increases and PI reductions.

Properties related to surface phenomena have also been associated with the effectiveness of soil stabilization techniques. Specific surface area (SSA) and cation exchange capacity (CEC), which affect many physical and chemical properties of soils, have proved to have an important influence on the behavior of fine-grained soils (Cerato and Lutenegger 2002). Additionally, CEC can be related to the rate of interaction between soil and additive in stabilization. Mitchell (1993) presented a detailed description of the parameters determining CEC and its effects on fine-grained soil behavior; his study demonstrated that rates of cation exchange are dependent on clay type, solution concentrations, and temperature among other factors. The rate of exchange was found to be almost instantaneous for kaolinite, and much lower for illite and smectite minerals.

Materials and Methods

The time frame for this project restricted the selection of construction sites to those where chemical stabilization was performed during late spring and summer of 2007. The projects involved chemical stabilization using traditional admixtures (fly ash and cement kiln dust) on fine-grained soils. Preference was given to sites where chemically treated subgrade would be available for field testing of soil strength development (e.g., before paving) for 7 to 14 days or more. A report detailing in situ testing is presented by Snethen et al. (2008). The Oklahoma Department of Transportation (ODOT) bid tabs were used to select potential sampling sites. After careful evaluation, five field test sites were selected that represented city, county, and state (e.g., ODOT) projects. In Tables 1–3 soil properties and additive characteristics are presented for all project sites. Index properties were determined according to the corresponding ASTM standard methods. The SSA was tested following Cerato and Lutenegger (2002) EGME method; and CEC was determined using 1 N ammonium acetate extraction method performed by Harris Laboratory, Inc., Lincoln, Nebraska.

Preparation of Specimens

Following AASHTO T307-99 (AASHTO 2003), cylindrical specimens of 100 mm diameter and 200 mm height were compacted at 95 % of the maximum dry densities and optimum moisture contents (OMC), as determined by the standard compaction effort test. Additive fractions were added for stabilization as determined by a *p*H response curve developed for every site. Estimated optimum additive contents are posted in Table 3. The soil collected was air dried and thoroughly mixed with the chemical additives to ensure additive uniformity. The mix was brought to the target water content and placed into a split mold lined with a rubber membrane (0.4 mm thickness) held under vacuum. In order to achieve the desired density, the sample height was controlled on every one of the five equal thickness compaction layers. Duplicate specimens were prepared for every molding condition. Target dry densities were validated after compaction by measuring diameter and height at three locations, weighing the specimen and collecting moisture content samples. Once compacted, all samples were stored and cured in a moisture and temperature controlled room for the curing times specified. A double layer of plastic wrap was tightly held to the sample to prevent any moisture loss during the curing time. Moisture contents were taken after the test was finished to check for any significant variations during the curing period.

Resilient Modulus (M_R) *Tests*—The M_R tests were performed according to the AASHTO T-30799 (AASHTO 2003) standard method. The procedure requires testing each sample under five different deviator stresses and three different confining stresses, resulting in 15 values of M_R from each sample. Repeated loading involved application of a haversine-shaped deviator stress pulse over a 0.1 s duration, followed by a 0.9 s rest before a subsequent stress pulse. The M_R values used for regression analyses were obtained by averaging results from duplicate specimens tested at the highest suggested deviatoric stress (68.9 kPa) and three different confining pressures (41.4, 27.6, and 13.8 kPa). The highest de-

TABLE 1—*Soil properties (untreated soil).*

Symbol	EN	ES	AD	PR	PN
Site	Oakdale Drive, North, Enid, OK	Oakdale Drive, South, Enid, OK	U.S. 62, Anadarko, OK	15th Street, Perry, OK	Country Club Road, Payne County, OK
Plastic limit (%)	14	Non-plastic	Non-plastic	18	14
Liquid limit (%)	24	Non-plastic	Non-plastic	40	24
PI (%)	11	Non-plastic	Non-plastic	22	10
Passing No. 200 (%)	42.9	21.7	55.9	76.8	53.0
USCS soil type	SC	SM	ML	CL	CL
AASHTO soil type	A-6 (1)	A-2-4	A-4 (0)	A-6 (16)	A-4 (2)
*p*H	8	6.2	7.6	7	8
Organic matter (%)	0.9	0.6	0.6	1.4	0.9
Surface phenomena properties					
Total SSA (m^2/g)	82.50	24.93	37.14	93.70	43.17
External SSA (m^2/g)	3.93	0.57	1.54	6.17	2.14
Internal SSA (m^2/g)	78.57	24.36	35.59	87.53	41.03
CEC (meq/100 g)	17	5.3	8.4	23.9	12.2
Activity	0.25	NA	NA	0.29	0.18
Compaction properties					
OMC (%)	12.8	10.3	13.3	17.8	13.6
Max dry density (kg/m^3)	1844	1877	1800	1700	1865
Mineral content					
Sodium (parts per millions (ppm))	33	18	33	301	150
Potassium (ppm)	172	81	74	188	68
Magnesium (ppm)	413	78	199	571	300
Calcium (ppm)	2599	719	1278	3464	1779
***p*H response**					
Additive type	CKD	CKD	CFA1	CFA2	CFA2
ΔpH from 0–2 % add.	2.3	3.0	1.8	1.1	1.3

viatoric stress corresponded to the largest vertical displacements measured, and thus, these measurements were more accurate for the extremely stiff samples and associated very small deformations. Axial loads were measured using an internal load cell with a resolution of 0.1 N and axial displacements were measured using two diametrically opposed linear variable differential transformers (LVDTs) attached to the sample with clamps. The LVDTs have a resolution of 0.00001 mm.

TABLE 2—*Additive properties.*

Project Site	AD	PR&PN	EN&ES
Additive type	CFA	CFA	CKD
Source	Muskogee (Silo)	Sooner—Red Rock	Holcin, Ada
Silicon dioxide, SiO_2 (%)	37.3	36.7	16
Aluminum oxide, Al_2O_3 (%)	19.1	18.6	3.6
Iron oxide, Fe_2O_3 (%)	7.21	6.96	2.3
$SiO_2+Al_2O_3+Fe_2O_3$ (%)	63.61	62.26	21.9
Calcium oxide, CaO (%)	23.8	25.0	52.8
Magnesium oxide, MgO (%)	5.3	5.5	2.2
Sulfur trioxide, SO_3 (%)	1.4	1.5	6.0
Sodium oxide, Na_2O (%)	1.8	1.8	0.3
Potassium oxide, K_2O (%)	0.5	0.5	3.5
Loss on ignition (%)	0.47	0.41	17.5

Note: All Characteristics as provided by the suppliers.

Presentation and Discussion of Results

Test Results – Influence of Curing Time

The experimental results obtained from 58 M_R tests performed on five stabilized soils collected from selected construction sites in Oklahoma were used to compare M_R with curing time. M_R test results at the various curing times and the untreated soil M_R values are presented in Table 4. The incremental improvement of M_R with

TABLE 3—*Treated soil geotechnical properties.*

Symbol	EN	ES	AD	PR	PN
Optimum additive content (%)	14 (CKD)	12 (CKD)	15 (Silo—CFA1)	15 (RR—CFA2)	16 (RR— CFA2)
Plastic limit (%)	20.1	Non-plastic	Non-plastic	21.8	15.9
Liquid limit (%)	22.2	Non-plastic	Non-plastic	37	24.8
PI (%)	2.1	Non-plastic	Non-plastic	15.2	8.9
OMC (%)	10.7	10.2	11.6	15.4	11.9
Max dry density (kg/m^3)	1789	1889	1849	1712	1898

TABLE 4—*Averaged resilient modulus test results at various curing times.*

	Site				
	EN	ES	AD	PR	PN
Curing Days	M_R (MPa)	M_R (MPa)	M_R (MPa)	M_R (MPa)	M_R (MPa)
Untreated[a]	114.8	91.1	84.9	122.3	43.5
1	840.6	196.5	248.1	681.8	NA
3	696.4	402.1	417.5	1118.7	262.1
7	1854.6	954.0	463.4	964.1	307.0
14	2087.7	2631.4	515.9	1339.0	382.0
28	2380.3	4208.2	580.0	1052.5	442.2

[a]Specimen cured for 7 days with no additive.

curing time is presented in Fig. 1, where averaged M_R values are plotted against their corresponding curing time for the five construction sites sampled.

As mentioned, M_R values obtained at the highest deviatoric stress were used as representative values of each sample tested due to the high stiffness associated with specimens stabilized, compacted and cured for up to 28 days. The deformations induced by low deviatoric stresses at high confining pressures were very small (e.g., 8×10^{-5} mm) for some samples and close to the measurement accuracy of the linear variable displacement transducers (LVDTs) producing considerable variation in these results. Another reason for analyzing M_R at high deviatoric stresses is that for the stabilized soil tested, the M_R shows an asymptotic trend as deviatoric stress increases at any confining pressure as shown in the typical results presented in Fig. 2. This same asymptotic trend was shown by Puppala et al. (2003), who presented M_R results of fat clay (CH) treated with three stabilizers.

As noted by Fredlund et al. (1974), M_R is not highly dependent on confining pressure, particularly at higher deviatoric stresses. It is worth mentioning that not all soils can be considered M_R-insensitive to confining pressure, and some may present large variability even when loaded at high deviatoric stress. In Fig. 3, the M_R values obtained at the three confining pressures specified for each sample at the highest deviatoric stress are presented. Duplicate samples were tested for each confining pressure, therefore producing six test results for each curing time.

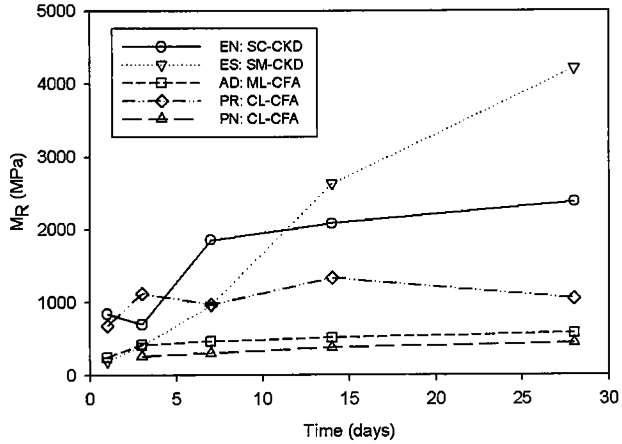


FIG. 1—M_R *improvement.*

Exponential Regression Curves to Model the Influence of Curing Time on M_R

In order to quantitatively analyze M_R improvement, regression equations were developed to fit the improved M_R values over the curing period. The M_R timelines shown in Fig. 3 were fitted using the least-squares technique with exponential type equations of the form $M_R = M_{R1}\text{Time}^{Rt}$ where M_{R1} corresponds to the improved M_R after one curing day, and Rt is the exponential rate of improvement. Figure 4 presents the regression curves with the average of the six values shown along with range bars, including their characteristic equations and coefficients of correlation. Table 5 presents the regression equation exponents, Rt, representing the rates of improvement for the five mix types.

As noted from the values in Fig. 4 and Table 5, the general improvement trend shows a large M_R increase from untreated to treated specimens; then, the timeline presents an early steep increase in M_R occurring between the 7th and 14th day; followed by a mild increase that extends to the 28th day. Although exponential regression curves do not show a clear break between early and late hardening stages, it does present a steeper slope for the earlier data and a flattened slope for the later stage data with a smooth transition in between the two stages. The power regression presents two major advantages: First, the shape of the curve fits the strength gain with a realistic smooth transition; second, the two equation parameters can be estimated based on standard laboratory testing. Coefficient M_{R1} can be back calculated from M_R results on stabilized material

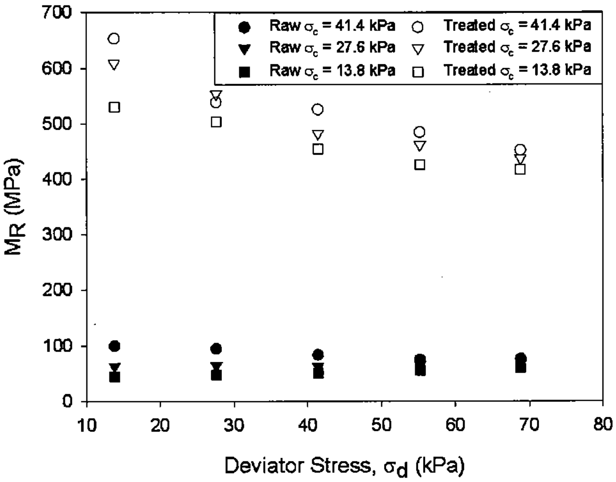
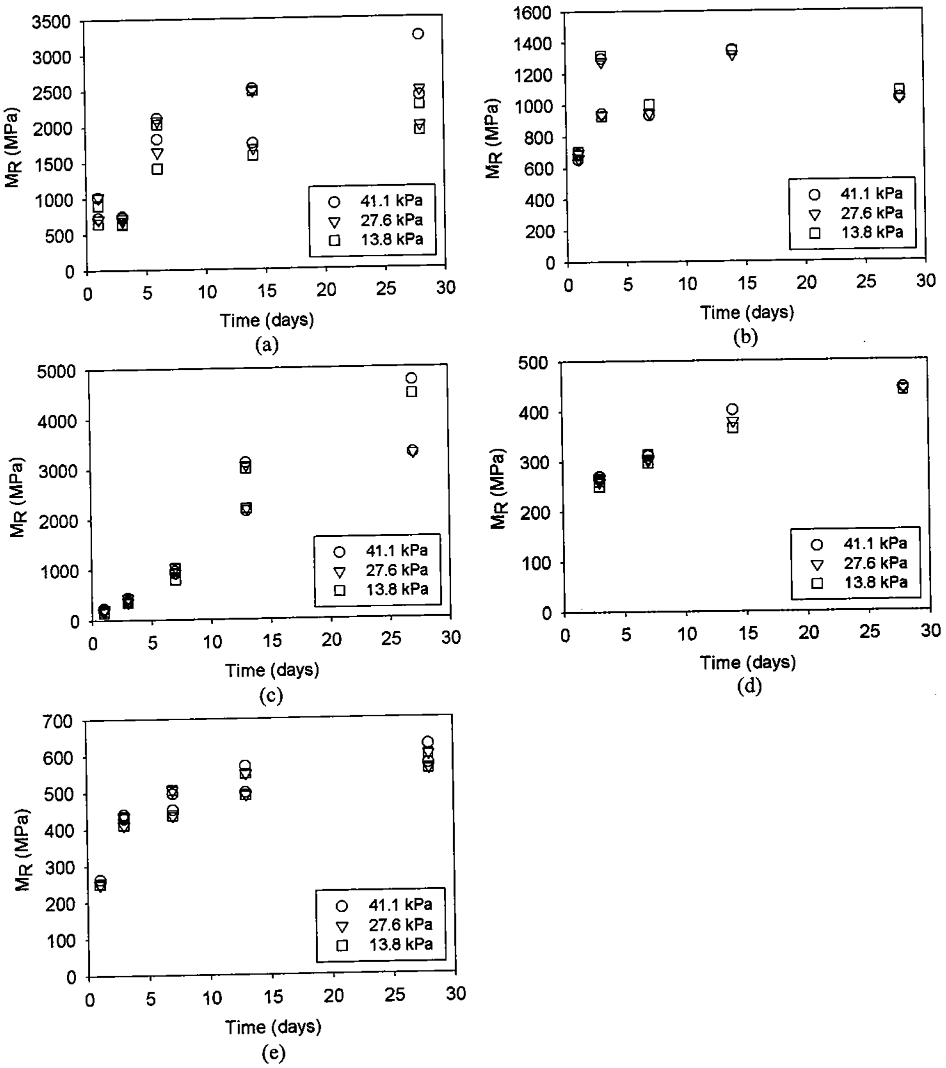


FIG. 2—M_R *versus deviator stress for both raw and treated soils at three confining pressures (13.8, 27.6, and 41.4 kPa)*



(a) (b) (c) (d) (e)

FIG. 3—*M_R Results at various confining pressures for (a) Enid North Site SC-CKD mix; (b) Enid South Site SM-CKD mix; (c) Anadarko Site ML-CFA mix; (d) Perry Site CL-CFA mix; and (e) Payne Site CL-CFA mix.*

at a known curing time; the exponent *Rt* can be estimated based on additive type and soil characteristics. Exponent *Rt* is effectively linked to the intrinsic properties of the soils and additive type, therefore, *Rt* can be estimated for improved M_R prediction by interpolating between the values of *Rt* obtained for the various soil properties and the corresponding additive type analyzed in this study. One objective of this study was to investigate whether untreated soil properties could be correlated with *Rt* to develop improved M_R prediction methods. In previous studies, predictive empirical models for M_R have been proposed in exponential equation forms (Khoury and Zaman 2004; Liang et al. 2008; Yang et al. 2008).

Soil Property Correlations with Exponential Improvement Rate

Using the power equation presented above to define an improved M_R for a stabilized soil for a given design project requires an estimate of the rate of M_R improvement (*Rt*), the anticipated curing time, and at least one M_R value from a test at any known curing time. In order to begin to develop a prediction methodology for *Rt*, correlations with relevant intrinsic soil properties and additive types used on the five project sites were studied. In Figs. 5–8 graphical correlations between M_R rate of improvement (*Rt*) and soil parameters are presented including: Fines fraction, *p*H response, SSA, and CEC for all treated soils. Other properties, including PI and Activity (defined as the ratio of PI to the percent passing 0.002 mm), were considered in this study; however, they were found to have a poor correlation, and therefore, are not included here. While the data set is currently limited, the trends are reasonable and suggest that these correlations form a good starting point for further development of this prediction methodology.

Percent Fines

A decrease in the exponential rates of improvement (*Rt*) with increasing percentage in fines is seen in Fig. 5 for both CKD and CFA treated specimens. It is noted that CFA improved soils may be less sensitive to the change in fines fraction when compared to the CKD results. CKD treated samples displayed a significant effect; *Rt* went from 0.97 at 22 % fines to 0.38 at 43 % fines. Fly ash treated samples went from 0.24 to 0.14 as the percentage of fines went up from 36 to 77 %. This inverse relationship can be explained by con-

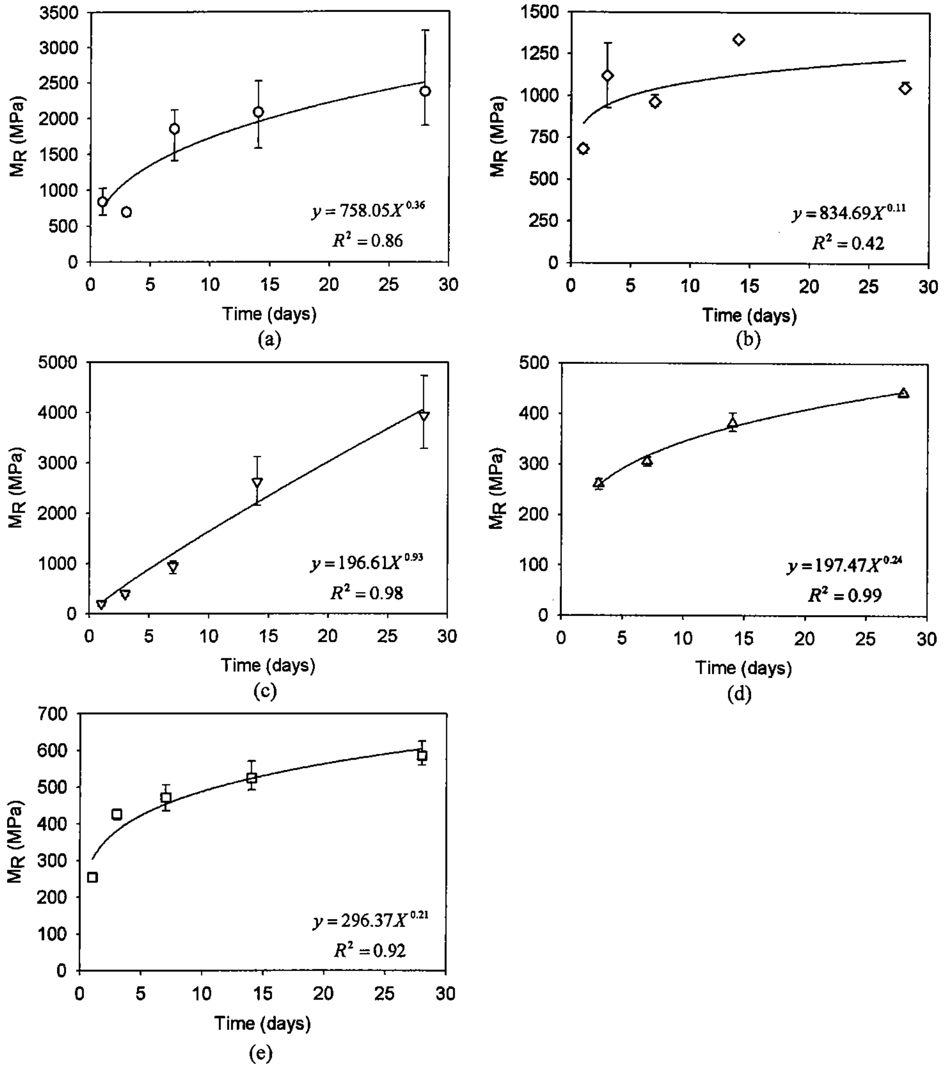


FIG. 4—*M_R evolution, range bars, and power regression for (a) Enid North Site SC-CKD mix; (b) Enid South Site SM-CKD mix; (c) Anadarko Site ML-CFA Mix; (d) Perry Site CL-CFA mix; and (e) Payne Site CL-CFA mix. (Note: given the range in M_R values for all sites, ordinate scales are different for each site.)*

sidering that a larger fraction of fines implies more consumption of additive by the clay particles, and therefore less cementitious material forming the bonding matrix within the soil structure.

pH Response

The response of *p*H of admixtures as additive content increases has been suggested before as a possible way to estimate the effectiveness of CKD as a soil stabilizer (Miller and Azad 2000; Miller and Zaman 2000; Miller and Diaz 2002). In this study, the change in *p*H of the soil additive mix when going from 0 to 2 % additive content, defined as Δ*p*H, was determined for each soil mixture. In Fig. 6, Δ*p*H versus *Rt* is shown, where Δ*p*H increased from 1.1 to 1.8 as *Rt* increased from 0.14 to 0.24 for CFA treated specimens; CKD specimens showed a change in Δ*p*H from 2.3 to 3 for an increase in *Rt* from 0.38 to 0.97. This *Rt* correlation behaves as expected since, as the value of Δ*p*H gets larger, the effectiveness of the stabilization mixture increases. In Miller and Zaman (2000), high Δ*p*H values were found for soils that reached the stabilized *p*H at lower additive contents. It should be noted that *Rt* can be considered an indicator of the stabilization effectiveness measured as an improvement rate and that the results presented herein agree with that assertion.

TABLE 5—*Exponential rates of improvement.*

Site	Soil	Additive Type	M_{R1} (MPa)	*Rt*	R^2
EN	SC	CKD	758	0.36	0.86
ES	SM	CKD	197	0.98	0.98
AD	ML	CFA	296	0.21	0.92
PR	CL	CFA	835	0.11	0.42
PN	CL	CFA	197	0.24	0.99

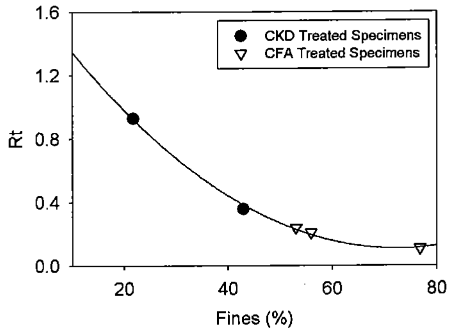


FIG. 5—*Exponential rate of improvement versus percentage of fines.*

Specific Surface Area

Regarding SSA, *Rt* displayed an inverse relationship for all samples and additives tested; however, unlike the percent fines and *p*H parameters, separate trends are observed for CKD and CFA as shown in Fig. 7. The CKD treated specimens acted differently than the CFA treated specimens, and with only two CKD and three CFA samples, it is difficult to determine a robust correlation. As with the fines fraction, the change in rate is much more significant for the CKD stabilized soils; *Rt* went from 0.97 at 24 m^2/g to 0.38 at 79 m^2/g. CFA displays a flattened, yet consistent, trend in going from 0.24 to 0.14 as the SSA went from 36 to 86 m^2/g. Larger SSA values imply more additive was consumed by the clay particles and less cementitious additive matrix formed.

Cation Exchange Capacity

The quantity of exchangeable cations is termed CEC and is usually expressed as milliequivalents (meq) per 100 g of dry clay. CEC can be related to the rate of interaction between soil and additive and hence can be linked to the amount of additive necessary to electrically neutralize the clay particles. As shown in Fig. 8, the CEC exhibits a similar trend as the SSA. Within each additive type, a linear decrease in exponential improvement rate occurs as CEC increases, albeit not falling along a singular trend line. For CKD treated samples *Rt* went from 0.97 at 17 meq/100 g to 0.38 at 5 meq/100 g. While for the CFA treated samples *Rt* went from 0.24 to 0.14 as CEC went from 8 to 24 meq/100 g. Again, with only two CKD and three CFA samples showing different trends, it is difficult to determine an overall correlation, which would make these intrinsic properties a better indicator of stabilization effectiveness.

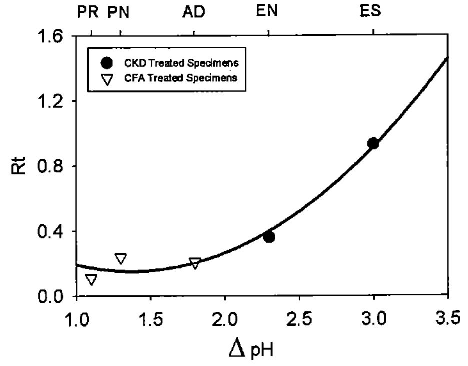


FIG. 6—*Exponential rate of improvement versus pH response.*

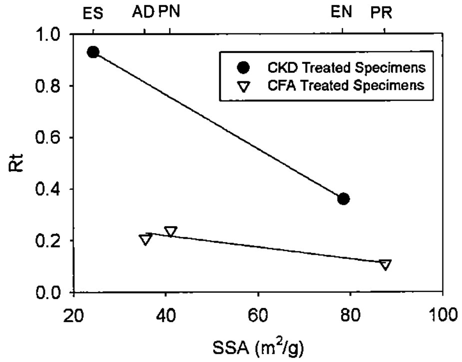


FIG. 7—*Exponential rate of improvement versus SSA.*

Summary

The limited data relating intrinsic soil properties to rate of improvement in M_R of stabilized soils under laboratory conditions show promising correlations. However, further testing is needed in order to incorporate the full range of soil types and commonly used soil stabilizers so that characteristic rates of improvement can be better estimated across broad variations in soil and additive types. The actual improvement obtained in the field can differ significantly from laboratory estimates and adjustment factors recognizing this variability should be included in the design. Curing conditions such as temperature and humidity can significantly affect the rate of M_R improvement. Further testing incorporating temperature change characteristics of typical seasonal variations is needed.

The prediction methodology outlined here offers some practical advantages for pavement engineers using stabilized subgrade. It is clear that the M_R may increase significantly depending on soil and additive type; thus, it is important that M_R values for design be determined after an appropriate curing time. However, there may be circumstances where a 14-day curing time is impractical due to the construction schedule. For example, if an unknown soil material, previously missed during the design stage, is encountered during construction of a stabilized subgrade, engineers may wish to assess the M_R of this soil mixed with the chemical stabilizer to determine whether it will perform adequately. A 14-day curing period would be undesirable in the middle of construction. However, with the proposed method, a sample could be mixed with additive, compacted immediately, and tested the following day for determination of the 1-day M_R value (e.g., M_{R1}). With an estimate of the improvement rate, *Rt*, M_R at any curing time could be estimated. Another example of the utility of the proposed method would be for estimat-

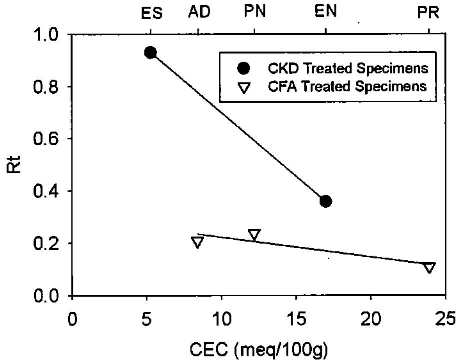


FIG. 8—*Exponential rate of improvement versus CEC.*

ing the M_R during the early stages of curing based on, for example, 14-day curing results obtained during the design stage, to evaluate the impact of construction traffic on the recently treated subgrade.

While it is important to consider environmental factors (field temperature and humidity) in these evaluations, the proposed method provides for a preliminary estimate of curing rate increases of M_R at room temperature. This can serve as a baseline for using engineering judgment in evaluating environmental effects until the research fully matures to incorporate more soil and additive types and environmental influences. These issues embody the current focus of the research group.

Conclusions

Resilient modulus (M_R) improvement with curing time was modeled with a power law equation of the form $M_R=M_{R1}\times\text{Time}^{Rt}$ for chemically stabilized soils representing five construction sites in Oklahoma. The power law regression curves developed in this study exhibit a satisfactory fit to the measured improved M_R values. Additionally, it was determined that the power equation parameters could be easily defined by performing standard laboratory testing and applying simple empirical correlations. The exponential rate of improvement (Rt) showed good correlations with additive type and selected soil parameters. Inverse relationships were found between Rt and percentage of fines, SSA, and CEC. The increase of such soil parameters indicates higher reactivity of the soil particles, which implies higher consumption of chemical additives and hence lower availability of additive to form cementitious bonds. A direct relationship between Rt and pH response measured as ΔpH (0–2 %) was found; this pH parameter indicates additive efficiency for a specific soil-additive combination. Soils with larger ΔpH showed higher rates of improvement. CKD treated samples showed higher Rt sensitivity to changes in soil properties; CKD specimens also showed larger improvement rates compared to CFA treated samples; this observation agrees with previous findings that indicate CKD is a more efficient additive for low plastic and non-plastic soils when compared to the efficiency of lime and fly ash as soil stabilizers. It is proposed that Rt is effectively linked to the intrinsic properties of the soils and additive type; therefore, Rt can be estimated for improved M_R prediction by interpolating between the values of Rt obtained for the various soil properties and the corresponding additive type analyzed in this study. Further research is needed to expand the data set used to develop empirical correlations and additional work is needed to incorporate the influence of curing temperature and humidity on M_R of stabilized soils.

References

AASHTO, 1993, *Guide for Design of Pavement Structures*, AASHTO, Washington, D.C.

Achampong, F., Usmen, M., and Kagawa, T., 1997, "Evaluation of Resilient Modulus for Lime and Cement Stabilized Synthetic Cohesive Soils," *Transp. Res. Rec.*, Vol. 1589, pp. 70–75.

Arora, S. and Aydilek, A. H., 2005, "Class F Fly-Ash-Amended Soils as Highway Base Materials," *J. Mater. Civ. Eng.*, Vol. 17(6), pp. 640–649.

Cerato, A. B. and Lutenegger, A. J., 2002, "Determination of Surface Area of Fine-Grained Soils by the Ethylene Glycol Monoethyl Ether (EGME) Method," *Geotech. Test. J.* Vol. 25(3), pp. 315–321.

Çokça, E., 2001, "Use of Class C Fly Ashes for the Stabilization of an Expansive Soil," *J. Geotech. Geoenviron. Eng.*, Vol. 127(7), pp. 568–573.

Drumm, C. E., Reeves, S. J., Madgett, R. M., and Trolinger, D. W., 1997, "Subgrade Resilient Modulus Correction for Saturation Effects," *J. Geotech. Geoenviron. Eng.*, Vol. 123(7), pp. 663–670.

Edil, T. B., Acosta, H. A., and Benson, C. H., 2006, "Stabilizing Soft Fine-Grained Soils with Fly Ash," *J. Mater. Civ. Eng.*, Vol. 18(2), p. 283.

Fredlund, D. G., Bergan, A. T., Wong, P. K., and MacFarlane, M., 1974, "Relation Between Resilient Modulus and Stress Conditions for Cohesive Subgrade Soils," *Transp. Res. Rec.*, Vol. 1977(642), pp. 73–81.

Khoury, N. N. and Zaman, M. M., 2004, "Correlation Between Resilient Modulus, Moisture Variation, and Soil Suction for Subgrade Soils," *Transp. Res. Rec.*, Vol. 1874, pp. 99–107.

Khoury, N. N., Zaman, M., Nevels, J., and Mann, J., 2003, "Effect of Soil Suction on Resilient Modulus of Subgrade Soil Using the Filter Paper Technique." *Transportation Research Board 82nd Annual Meeting* (CD-ROM), Washington D.C., January 12–16, Transportation Research Board, Washington, D.C.

Li, D. and Selig, T. E., 1994, "Resilient Modulus for Fine-Grained Subgrade Soils," *J. Geotech. Eng.*, Vol. 120(6), pp. 939–957.

Liang, R. Y., Rabab'ah, S., and Khasawneh, M., 2008, "Predicting Moisture-Dependent Resilient Modulus of Cohesive Soils Using Soil Suction Concept," *J. Transp. Eng.*, Vol. 134(1), pp. 34–40.

Miller, G. A. and Azad, S., 2000, "Influence of Soil Type on Stabilization with Cement Kiln Dust," *Constr. Build. Mater.*, Vol. 14, pp. 89–97.

Miller, G. A. and Diaz, C. M., 2002, "Laboratory Investigation into Certain Aspects of Soil Stabilization with Cement Kiln Dust." Research Report 02–01, Materials Division, Department of Transportation, Oklahoma, November.

Miller, G. A. and Zaman, M., 2000, "Field and Laboratory Evaluation of Cement Kiln Dust as a Soil Stabilizer," *Transp. Res. Rec.*, Vol. 1714, pp. 25–32.

Mitchell, J. K., 1993, *Fundamentals of Soil Behavior*, 2nd ed., John Wiley & Sons, New York.

Mohammad, L. N., Raghavandra, A., and Huang, B., 2000, "Laboratory Performance Evaluation of Cement-Stabilized Soil Base Mixtures," *Transp. Res. Rec.*, Vol. 1721, pp. 19–28.

NCHRP, 2004, *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*, MEPDG, Champaign, IL.

Nelson, J. D. and Miller, D. J., 1992, *Expansive Soils, Problems and Practice in Foundation and Pavement Engineering*, Wiley, New York.

Parsons, R. L. and Kneebone, E., 2004, "Use of Cement Kiln Dust for the Stabilization of Soils," *GeoTrans 2004: Geotechnical Engineering for Transportation Projects*, Vol. 126, pp. 1124–1131.

Parsons, R. L., Kneebone, E., and Milburn, J. P., 2003, "Use of Cement Kiln Dust for Subgrade Stabilization," Research Report KS-04-3, Kansas Department of Transportation, Topeka, KS.

Puppala, A. J., Ramakrishna, A. M., and Hoyos, L. R., 2003, "Resilient Moduli of Treated Clays from Repeated Load Triaxial Test." *Transp. Res. Rec.*, Vol. 1821, pp. 68–74.

Rogers, C. D. F., Boardman, D. I., and Papadimitriou, G., 2006, "Stress Path Testing of Realistically Cured Lime and Lime/

Cement Stabilized Clay," *J. Mater. Civ. Eng.*, Vol. 18(2), pp. 259–266.

Seed, H. B., Chan, C. K., and Lee, C. E., 1962, "Resilience Characteristics of Subgrade Soils and Their Relation to Fatigue Failures in Asphalt Pavement," *Proceedings of the First International Conference on Structural Design of Asphalt Pavements*, University of Michigan, Ann Arbor, MI.

Snethen, D. R., Miller, G. A., and Cerato, A. B., 2008, "Evaluation and Field Verification of Strength and Structural Improvement of Chemically Stabilized Subgrade Soil," Technical Report, Oklahoma Department of Transportation, Oklahoma City, OK.

Solanki, P. and Zaman, M. M., 2010, "Laboratory performance evaluation of subgrade soils stabilized with sulfate-bearing cementitious additives," *J. Test. Eval.*, Vol. 38(1), pp. 1–12.

Tuncer, E. R. and Basma, A. A., 1991, "Strength and Stress-Strain Characteristics of a Lime-Treated Cohesive Soil," *Transp. Res. Rec.*, Vol. 1295, pp. 70–79.

Velasquez, R. A., Marasteanu, M. O., and Hozalski, R. M., 2006, "Investigation of the Effectiveness and Mechanisms of Enzyme Products for Subgrade Stabilization," *Int. J. Pavement Eng.* Vol. 7(3), pp. 213–220.

Yang, S., Lin, H., Kung, J. H. S., and Huang, W., 2008, "Suction-controlled laboratory test on resilient modulus of unsaturated compacted subgrade soils," *J. Geotech. Geoenviron. Eng.*, Vol. 134(9), p. 1375.