Epoxy-Resin-Based Chemical Stabilization of a Fine, Poorly Graded Soil System

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Results are described of a research effort on the epoxy-based treatment of fine, poorly graded soil found at some localized low-duty airport sites and in the north slopes of Alaska. Statistical models are developed for the stabilization of clay-silt pavement systems at low-duty airports. A nontraditional method of soil stabilization that improves the subgrade strength properties of poorly graded clay-silt was identified. This soil system is considered one of the most difficult soil types to stabilize, in part because of its poor particle size distribution. Among several organic additives tested, the two-part epoxy system—bisphenol A/epichlorohydrin resin plus a polyamide hardener—gave the best result as measured by the dry California bearing ratio (CBR) test. The choice of the dry CBR test performed to ASTM specification was motivated by a need to capture optimum moisture content as an experimental variable. Within the limits of the laboratory test conditions, the statistical regression models developed support the hypothesis that the marginal increase in CBR values caused by a 1 percent increase in epoxy resin application is 11.1 and the marginal degradation of CBR caused by a 1 percent increase in moisture level is −5.6. Also, only additive level, moisture content, and temperature are significant variables influencing soil strength.

Materials engineers are frequently confronted with the problem of improving the bearing strength of unsuitable soils through soil stabilization. FAA provides guidance to airport owners, operators, and designers on methods to increase the load-bearing capabilities of the subgrade to support aircraft loads (*1,2*). Existing methods include the application of various combination of lime, cement, and fly ash to native materials and the replacement of unsuitable material with improved, higher-quality material. Commercial airport pavements that serve aircraft with high landing gear loads are required to be stabilized in a manner that ensures adequate strength of the supporting layers.

However, in small remote airports serviced by low-duty aircraft such as some on the north slopes of Alaska and in major portions of Florida where incompetent subgrade conditions exist, the difficulty of obtaining materials for standard methods of soil stabilization are evident. The need therefore exists to quantify the manner in which some nontraditional additives interact to increase the stability of native incompetent subgrade material.

The engineering properties of a clay-silt system were altered by use of a nontraditional chemical additive that when mixed uniformly into the soil system changed the surface molecular properties of the soil grains and, in most cases, cemented the grains together, resulting in increased strength. The clay used was kaolinite. The use of mechanical and traditional chemical stabilization techniques on the clay-silt system was precluded in this research.

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RESEARCH OBJECTIVES

An aggregate framework was developed for understanding the strength behavior of clay-silt systems and the subsequent formulation of a statistically based model for airport pavement subgrade stabilization through the combined use of an epoxy resin, bisphenol A/epichlorohydrin, and a polyamide hardener as a stabilization agent. The model presented enables the airport pavement designer to predict expected soil strength and effect design under a wide range of feasible combinations of these variables at a variety of potentially low-duty airport sites.

The research scope includes a state-of-the-art investigation, automated data collection, and analysis of full-scale laboratory data and formulation of a statistically based model for soil stabilization of airport pavement subgrades. This research is applicable to low-duty airport pavements. These pavements are defined as "landing facilities to accommodate personal aircraft or other small aircraft engaged in nonscheduled activities such as agricultural, industrial, executive, or industrial flying." Such pavements will not be required to handle aircraft load exceeding a gross weight of 30,000 lb. The total depth of pavements for low-duty airport pavements rarely exceeds 22 in., this being the limit for clay-silt soils with low CBR value, typically 3 to 4 (*3*).

LITERATURE REVIEW

Review of literature revealed that little work has been done on clay-silt soil stabilization using organic additives; however, much work has been documented in the literature on the use of traditional additives such as lime, cement, and fly ash.

A study by McLaughlin suggested that engineers will be more inclined to use stabilization techniques to strengthen pavement structures in the wake of such factors as increasing aircraft payloads, traffic frequency, scarcity of sites with good subgrade bearing values, and the dwindling supply of conventional aggregate (*4*). McLaughlin (*4*) revealed that soil mixtures with lime, cement, and fly ash (LCF) base courses have been used extensively, and complex, long-lasting chemical reactions that produce resultant materials with acceptable mechanical properties were obtained under the right conditions of temperature and moisture. However, hostile in situ pavement conditions, if allowed, could lead to a weak pavement system because of infiltration of sulfate- and carbonate-bearing moisture or a strong alkaline ground water condition.

Simpson et al. (*5*) report about the successful application of the Shell EPON® epoxy resin as an asphalt binder. The paving material, epoxy asphalt concrete (EAC), is a combination of graded mineral aggregate and an asphaltic binder containing epoxy resin that is converted into a polymer with unusual solvent and heat resistance (*5*). The EAC could be used as an overlay on existing pavements or as the major structural element in a pavement. Construction using the EAC required conventional hot-mix plants, conventional self-propelled paving machines or hand-raking, and normal rubber-tired rollers for compaction. In a series of comparative tests conducted, EAC out-performed asphaltic concrete in terms of added strength, load-carrying capacity with minimum thickness, resistance to chemical attacks, rutting, and high-temperature jet blasts. Specific areas of successful application of EAC reported included overhaul and maintenance areas used for jet planes at several military airbases.

Kinter (*6*) documents the results of 20 years of cooperative efforts between the FHWA and the chemical industry to investigate and develop specific compounds (or combinations thereof), industrial products, and wastes for the purpose of soil stabilization or compaction aids, or both. About 50 chemicals and proprietary products were tested (*7*). The study concluded that no single chemical or combination of chemicals has been found effective as a major soil stabilizer.

Carpenter and Lytton (*8*) report that clay-silt systems will experience a volumetric contraction on freezing in a condition of constant moisture content. The freezing process reorients the clay particles, leading to volumetric contraction. This research helps to quantify the magnitude of the freeze coefficient to be used in pavement design under frost conditions and damage assessment.

Edris and Lytton (*9*) characterized the performance-related characteristics of fine-grained subgrade soils containing 20 to 70 percent clay. They developed statistical models for resilient modulus, resilient strain relations, and permanent deformation per unit length or residual strain. The research demonstrated that dynamic properties of fine-grained soil such as modulus of resilience depend strongly on traffic volume (measured by load cycles), climatic factors (measured by soil suction and temperature), and soil composition.

Chou investigated the marginal effect of the variability of design parameters in the California bearing ratio (CBR) equation on pavement performance (*10*). The research indicated that pavement integrity is significantly affected by variations in pavement thickness, in wheel loads, and in subgrade CBR value. Variations in tire contact area had the least influence on pavement performance.

Brabston (*11*) investigated the FAA soil compaction criteria for airport pavement subgrades using laboratory compaction and triaxial tests to determine resilient and permanent axial strain. Three soil types compacted to densities at or below current FAA compaction criteria were subjected to repeated axial loading in a triaxial tests chamber. The FAA uses ASTM standards as compaction criteria (*12*).

RESEARCH METHODOLOGY

ASTM D1883–73 CBR test procedure was adopted for strength quantification (*12*). The CBR test is a generally accepted and reliable strength measurement approach and is applicable to airport pavement design methodology.

The choice between using a dry CBR test and a wet one is influenced by many factors, chiefly the condition of the soil system in the field on a short- and long-term basis. The dry CBR test was adopted because it allowed the specification of clay-silt soil optimum moisture content as an experimental variable for analysis. Also moisture control is more practical and implementable at localized low-duty airport sites.

In order to gain control over the various factors that influence field CBR, representative ranges of all the selected variables hypothesized as influencing CBR were tested and analyzed.

EXPERIMENTAL DESIGN

The variables hypothesized as influencing the resistance of a soil to deformation as measured by the CBR value were additive content (percent), moisture content (percent), clay-silt ratio, and curing temperature (°F).

Factorial Design

There are several advantages in studying the effects of several independent variables on a dependent variable, say CBR value, using factorial designs. First, and most significant, it is possible to determine whether the experimental independent variables interact in their effect on the dependent variable. Although an independent variable may affect a relatively small proportion of the variance of a dependent variable, its interactions with other independent variables may affect a large proportion of the variance. This phenomenon cannot be understood by the study of the independent variables in isolation.

Second, factorial designs afford the researcher greater statistical control, and therefore more discriminatory statistical tests than those tests typically associated with single variables. Factorial experiments allow the testing of the separate and combined effects of several variables using the same number or fewer experimental runs that would have been the case for several single-factor experiments.

The experimental design was fashioned to fit a factorial design matrix. Factorial designs facilitate the visualization and comprehension of similarities and simplifications in the experimental process and thus assist the task of model building and the estimation of main effects and interactions arising as a result of changes in the model experimental variables.

For the hypothesized experimental variables, a $4 \times 3 \times 3 \times 3$ (i.e., 4×3^3) factorial design in additive, moisture, clay-silt ratio, and temperature, requiring 108 CBR experimental runs, was used.

Levels of Variables

The levels of various variables hypothesized as affecting CBR were specified as follows:

Experimental Variables	*Factorial Design Levels*	*No. of Levels*
Additive percentage	0, ½, 1, 4	4
Moisture percentage	13, 17, 21	3
Clay-silt ratio	0.4, 0.5, 0.6	3
Temperature (°F)	40, 65, 90	3

An important consideration was the specification of the range of applicable moisture content for the experimentation. The dry density values obtained for a clay-silt ratio of 0.4 was about 114 lb/ft^3. For a clay-silt ratio of 0.6, it was about 107 lb/ft^3. Corresponding optimum moisture contents were 16 and 20 percent for clay-silt ratios of 0.4 and 0.6, respectively. The analysis indicated that maximum dry densities obtained for the three levels of clay-silt ratios corresponded to optimum moisture contents between 13 and 21 percent. The levels of moisture content were fixed at 13, 17, and 21 percent on the basis of earlier control test results obtained from the curves of maximum dry density versus moisture content under modified AASHTO compaction; also, because moisture content was desired at three equidistant levels in the factorial experimentation, 13, 17, and 21 percent were selected as representing practical values of optimum moisture content and optimum dry density variations for the clay-silt system.

Testing Procedure

The ASTM D1883–73 procedure for CBR testing was adopted for determining the strength of the clay-silt soil system (*12*). The physical properties of the clay and silt samples tested are presented in Table 1. The clay and silt samples were prepared in a manner closely following the ASTM D1557 method (*12*). The tests were carried out on unsoaked samples because the clay silt optimum moisture content was specified as an experimental variable.

The batching of various ratios of clay to silt by weight was done and resulted in a representative clay-silt sample weighing over 12 lb, to which was added the required amount of water. The sample was mixed to a uniform consistency and the epoxy-resin system was applied to the wet sample and mixed uniformly and manually to an even texture.

The samples treated with the epoxy-resin system were compacted in standard CBR molds specially lined with aluminum foil to preserve the molds and reduce demolding effects. The compacted specimens were trimmed to specification and covered with nylon wrappers for moisture preservation before being thermally soaked in a specially prepared curing chamber for 3 days, which was considered enough time for the attainment of steady state conditions.

TABLE 1 SUMMARY OF PHYSICAL PROPERTIES OF CLAY AND SILT TESTED

		SOIL TYPES		
	Properties	Clay	Silt	Clay-Silt Systems
1.	Liquid Limit %	60	22	37 - 45
2.	Plastic Limit %	32	19	24 - 27
3.	Plasticity Index %	28	3	13 - 18
4.	Optimum Moisture Content %			13 - 21
5.	Absorbed Moisture % (Hygroscopic)	1.5	0.5	1.0
6.	Soil Classification			
	a) FAA	E-8	E-6	E-7
	b) Unified System	CL	ML	CL/ML
	c) AASHO	A-7	A-4	A-5 to A-7
7.	Specific Gravity	2.63	1.84	2.33
8.	Percent Passing No. 200 Sieve	100%	100%	100%
9.	Hydrogen Ion Conc. pH, dry clay at 20% solids, airfloated	3.5-5.0	—	—
10.	Clay Fraction	100%	0%	40,50,60%

In order to facilitate the acquisition and reduction of the CBR test data, a microcomputer-based automatic data collection system was used (Figure 1). CBR testing of the thermally cured clay-silt stabilized samples was done using the motorized and automated SOILTEST CBR testing equipment.

The data collection system consisted of (a) the motorized SOILTEST CBR testing equipment complete with a loading platform, plunger, proving rings, force and displacement dial indicators, and other attached accessories; (b) displacement transducers; (c) linear variable displacement transformer; (d) signal conditioner; (e) digital display; (f) screw terminal boards (panels); and (g) personal computer (see Figures 2 and 3).

The automated data collection system fabricated in-house was used to record and analyze in real time the displacement and resistance to deformation of clay-silt samples prepared and compacted to standard specifications after thermal soaking in a temperature-controlled chamber. Occasional manual checks on the collected data were made for correlation and validation purposes. The data collected are presented in Table 2.

ADDITIVE SELECTION

In considering possible materials for the stabilization of the clay-silt system, the use of traditional methods was reviewed but not considered. Most of the traditional materials will, in small quantities less than 5 percent by weight, not impart sufficient strength to the clay-silt system under study to meet FAA requirements. This property is caused by the poor clay-silt system particle size distribution and accompanying loss of frictional strength component, coupled with the degradation of cohesive strength that could quickly result with the infiltration of moisture.

Traditional methods of clay-silt stabilization currently in use are given by Yoder and Witczak (*3*).

The results of CBR tests on the untreated clay-silt system support the position that effort should not be placed solely on the effects of increased compaction and reduced plasticity enhancement as a means of soil stabilization of clay-silt systems. Equally vital to the task of clay-silt soil stabilization are the combined effects of additive application, effective construction practices, provision of adequate roadway drainage and ditches, in addition to good compaction and plasticity enhancement techniques.

The search for effective additives that could adequately meet flexible pavement design requirements for low-duty airport pavements was therefore focused on organic materials and polymers. Candidate materials were screened through a survey of chemical companies, materials testing laboratories, in-house materials testing, and personal contact.

EPOXY-RESIN HARDENER SELECTION

The final stabilization additive selected consisted of a two-part epoxy resin system. The first part is a bisphenol A/epichlorohydrin resin of the epoxy resin family. This resin has negligible solubility in water, is a very viscous liquid, very light yellow in color, with a specific gravity of 1.17. Though a stable material, in the presence of a strong mineral or Lewis acid or a strong oxidizing agent, the epoxy resin can react vigorously to release considerable heat, but hazardous polymerization will not occur. The heat release during the use of the resin in this research was minimal and generally unnoticeable at the ¼ to 4 percent threshold of additive application. Preliminary tests at higher concentrations of epoxy resin, say 10 percent and more, released a noticeable amount of heat.

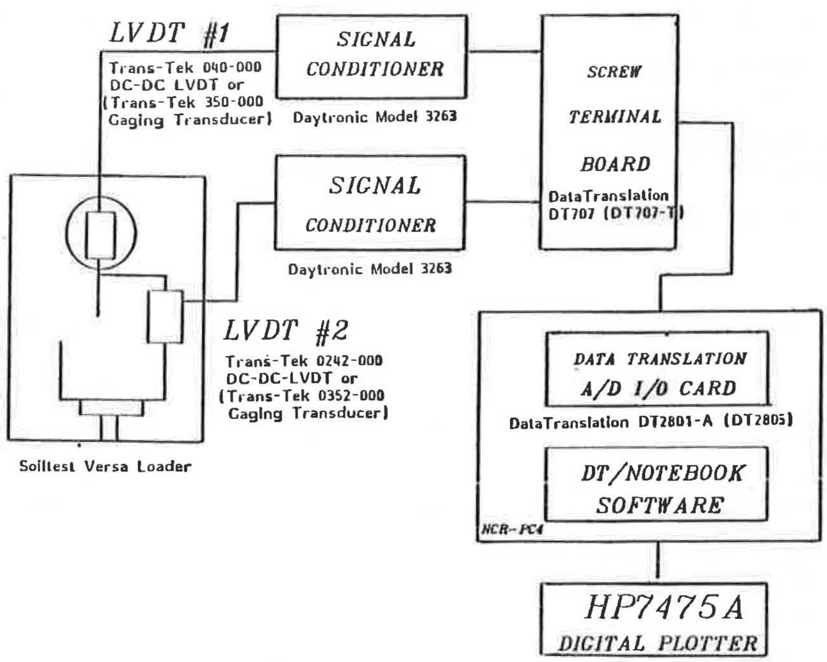

FIGURE 1 Schematic of automated data collection and display system.

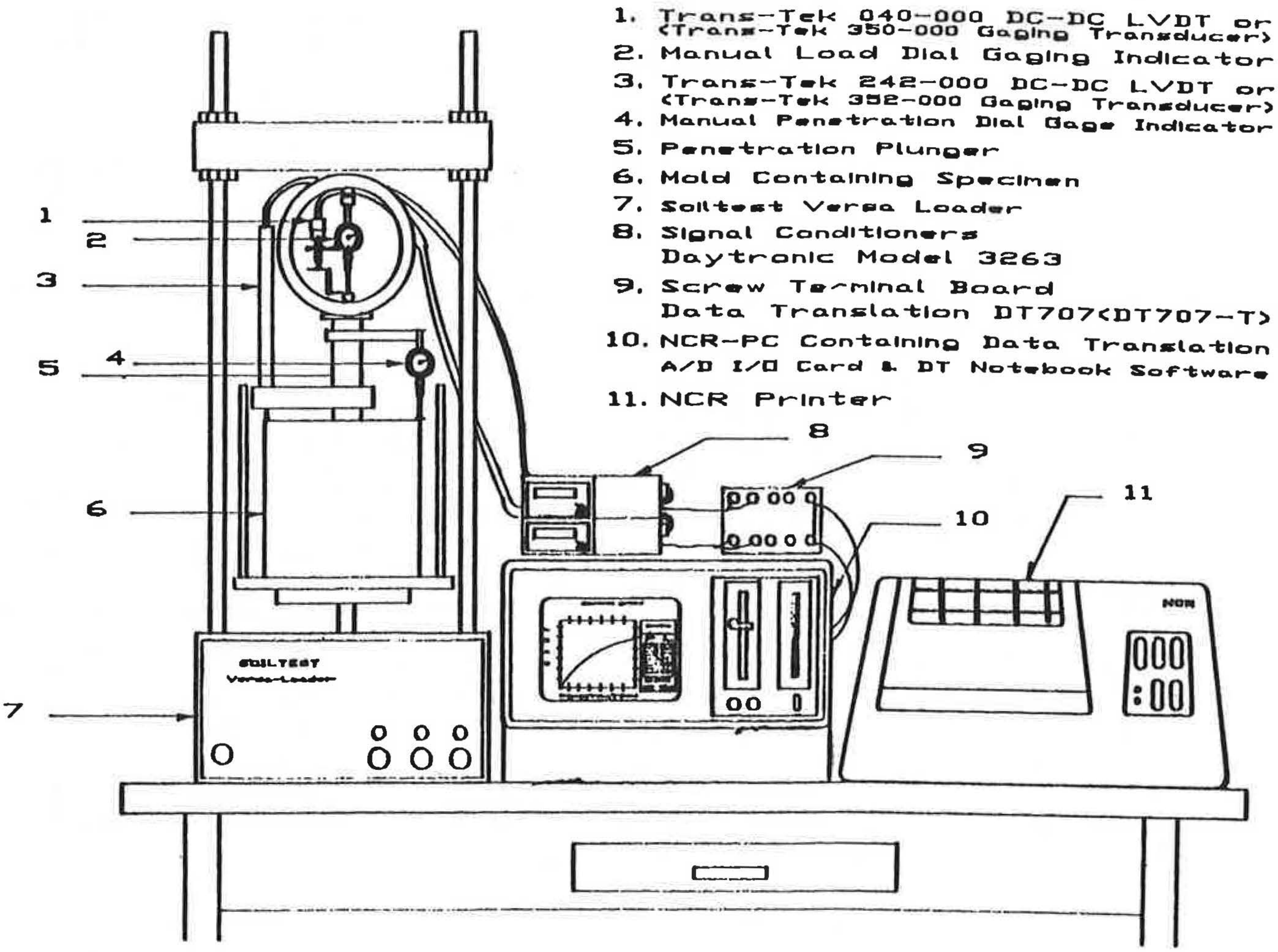

FIGURE 2 Automated data collection and display system.

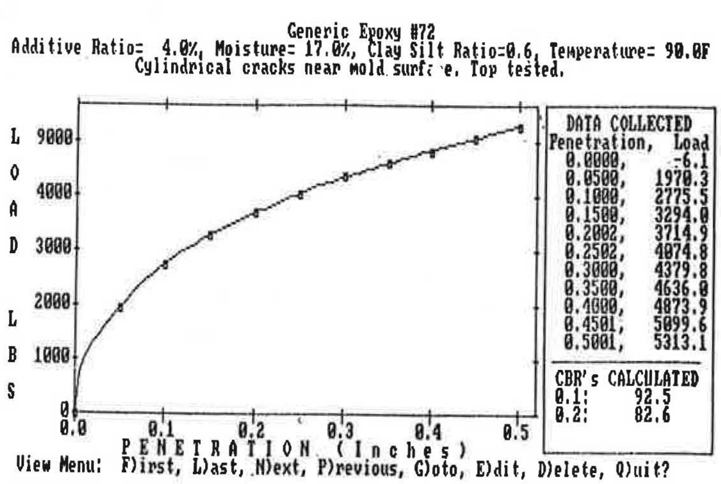

FIGURE 3 Screen output of automated data collection system.

TABLE 2 CBR VALUES FOR STABILIZED CLAY-SILT SYSTEM, FULL FACTORIAL EXPERIMENTAL DESIGN DATA MATRIX (EPOXY RESIN ADDITIVE, 3-DAY CURE PERIOD)

%M	C/S = 0.4 %A 0	C/S = 0.4 %A .25	C/S = 0.4 %A 1	C/S = 0.4 %A 4	C/S = 0.5 %A 0	C/S = 0.5 %A .25	C/S = 0.5 %A 1	C/S = 0.5 %A 4	C/S = 0.6 %A 0	C/S = 0.6 %A .25	C/S = 0.6 %A 1	C/S = 0.6 %A 4	T (°F)
13	(2)* 61.2	(2) 55.8	(1) 71.0	(2) 86.2	(1)* 68.3	(2) 50.15	(2) 62.9	(1) 84.2	(3)* 37.7	(2) 44.9	(2) 48.8	(1) 89.6	40
17	(1) 3.9	(1) 16.2	(1) 19.1	(1) 42.5	(2) 19.9	(1) 37.4	(2) 31.45	(1) 44.3	(2) 35.0	(1) 60.6	(2) 53.86	(1) 66.4	40
21	(1) 0.8	(1) 4.2	(3) 14.5	(3) 47.0	(1) 1.5	(1) 8.2	(1) 9.3	(3) 23.2	(1) 3.9	(2) 11.3	(1) 18.6	(2) 25.0	40
13	(1) 39.6	(1) 44.6	(1) 68.3	(1) 103.7	(1) 24.6	(1) 41.2	(1) 71.9	(1) 100.6	(1) 22.7	(1) 38.0	(1) 52.0	(1) 96.2	65
17	(1) 4.4	(1) 10.0	(1) 24.8	(1) 47.0	(1) 21.7	(1) 36.0	(1) 42.6	(2) 60.5	(1) 34.2	(1) 55.7	(1) 62.0	(1) 93.4	65
21	(1) 1.2	(1) 4.4	(1) 20.9	(1) 64.0	(1) 2.4	(1) 7.1	(1) 14.7	(1) 40.0	(1) 5.0	(1) 17.8	(1) 31.7	(1) 39.3	65
13	(2) 82.0	(2) 89.5	(1) 45.6	(1) 135.4	(2) 67.2	(2) 52.3	(1) 86.4	(2) 134.2	(2) 26.9	(1) 33.9	(1) 51.3	(2) 115.9	90
17	(2) 3.5	(2) 6.8	(1) 28.5	(1) 47.38	(2) 13.7	(2) 26.6	(2) 36.6	(1) 70.05	(1) 45.7	(1) 59.0	(1) 64.15	(1) 93.52	90
21	(1) 0.7	(1) 9.5	(1) 27.2	(5) 87.1	(1) 1.4	(1) 14.1	(3) 20.0	(3) 48.7	(1) 6.1	(1) 6.7	(1) 44.7	(1) 33.8	90

* Denotes number of CBR values averaged to obtain indicated CBR

The second part of the two-part epoxy resin system, a curing agent, is a viscous, water-insoluble polyamide, tan in color, with a specific gravity of 0.97. In the presence of a strong oxidizing agent, it could react to form nitrogen oxides and carbon monoxide or to release free polyamides that are also deleterious to health. The likelihood of this reaction occurring in the field is low because of protective surface treatment. The polyamide, however, could be replaced without loss of strength with amidoamines (*13*).

Epoxy resin is an organic chemical group composed of polymerized molecules consisting of split oxygen molecules bonded with two carbon atoms already united in some way. Epoxy resin is an amorphous, natural organic substance that could be of plant extraction or synthesized by, for example, the dehydrohalogenation of the chlorohydrin prepared by the reaction of epichlorohydrin with a suitable di- or polyhydroxyl substance or other molecule containing active hydrogen (*13*). Numerous (over 20) types of epoxy resin are possible and resin formulation to suit a particular application is almost always necessary. For the achievement of high strength, the use of a hardener or setting or curing agent is always essential for cross-linking between the epoxy resin and hardener molecule. The mix of epoxy resin and curing agent used in all the tests was 1:1 by weight.

Though epoxy resins harden through exothermic reactions, the quantities needed for stabilization, generally 4 percent or less, would not generate heat and stress that could lead to cracks and other imperfections. The addition of clay and silt as fillers for the epoxy resin system provides heat sinks, and the release of the heat generated can be controlled through choice of hardeners or variation of hardener concentration to control the duration the hardening requires. Though epoxy resins can set in as short a time as 20 min, they can be designed to set in 3 hr, thereby easing and making flexible the time required for construction procedures preparatory to stabilization and subsequent construction equipment cleanup.

An important strength delivery factor in epoxy resin application is the mixing quality. Thorough mixing of the two-part system for a definite length of time until mixing resistance drops off noticeably is imperative for effective cross-linking and strength development.

EPOXY RESIN COST VERSUS EFFECTIVENESS TRADE-OFF

The cost of epoxy (bisphenol A/epichlorohydrin) resin and polyamide hardener varies depending on the type and application. At an average cost of \$1.76/lb, the cost of the epoxy system is much higher than those associated with traditionally used additives such as lime, cement, or fly ash, which cost about \$0.04/lb. However, with an effective dispensing mechanism, the fractional weight application level of an epoxy system for achievement of the same effectiveness as judged by CBR strength delivery may range between ⅙ and 1/25, or less, of that required using stabilization agents such as cement or fly ash.

With the advent of high-technology epoxy application techniques since the 1970s, the gap in the total cost advantages of using conventional materials such as lime, cement, or even fly ash rather than epoxy resins in engineering construction is beginning to narrow when such factors as high strength delivery, lower unit weight of epoxy system required, and total cost, including labor, materials, and other indirect cost factors are all considered (*13*). The advantages of epoxy resin include

1. Reduction in direct cost of repairs by substituting high-technology application techniques for costly manual labor.
2. Introduction of improved consistency and quality leading to savings in terms of reduced deterioration because of the strength and durability of epoxy-treated materials.
3. Accelerated strength attainment within a few hours because of the formation of a solid, dense material capable of withstanding inclement weather, heavy traffic, and chemical attack. The strength of epoxies is borne out by the fact that broken chunks of concrete bonded together by epoxy resin become stronger than before disintegration (*13*).
4. Reduction in indirect cost of repairs, such as delayed air traffic, can be substantial in addition to the reduction in the frustration of aircraft and vehicular operators caused by these unwelcome delays.

Through use of the rapid setting properties of epoxy resins, runway closure resulting in delay and disruption of air traffic operations could be reduced from a time span of months to hours because of the significant engineering properties of epoxy resins.

Large-scale applications based on epoxy resin have been gaining considerable acceptance in the construction industry. In Philadelphia, for example, a successful use of over 10,000 gal of epoxy resin was reported in the construction and structural repair of the city's Schuylkill Expressway (*14*).

SOIL STABILIZATION COST ANALYSIS

An analysis of the cost of an actual laboratory soil stabilization validation experiment conducted at Wright-Patterson Air Force Base in Dayton, Ohio, is presented. The analysis allows a comparison of the cost of epoxy resin application with that of conventional stabilization materials such as cement, as presented in Table 3 using the following data:

Item	*Cost ($ per indicated unit)*
Additives	
Epoxy resin	1.62/lb
Polyamide hardener (V–40)	1.89/lb
Reference additive (cement)	2.78 per 80-lb bag
Aggregates	
Clay soil	6.00/ton
Silt soil	6.00/ton
Labor	15.00/hr-person

In the validation study, a time base of 1 hr was assumed for stabilizing 6.25 ft^3 of material using the productive capacity of one worker.

Overhead costs are specified at 50 percent of the total labor and material costs.

Clay-silt stabilization requires 20 to 30 percent of cement by weight for effectiveness (*3*). In the foregoing analysis, 25 percent was used. Clay-silt specific gravity was 2.67; and water specific gravity was 1.00.

Total weight of 6.25 ft^3 of stabilized material used in the validation experiment is approximately 1,043 lb.

REGRESSION ANALYSIS

The results of the $3^3 \times 4$ factorial design experiments in temperature (TEMP), clay-silt ratio (CS), moisture percentage (PM), and additive percentage (PA), respectively, were subjected to descriptive and inferential statistical analyses. These analyses yielded estimates of the effects of the various independent variables on CBR, the dependent variable. These regression analyses were performed to determine the form of the statistical models suitable for predicting the CBR of a clay-silt system when stabilized at various levels of the independent variables. The comprehensive second-order, stepwise, multiple linear regression analysis was performed. The key feature of this procedure is that a number of intermediate regression models are obtained adding one variable at a time. The variable added at each step is the one that makes the greatest improvement in the goodness-of-fit. The significance level for staying in the model was set at 0.05, and that for exiting at 0.10. These values correspond to confidence levels of 0.95 and 0.90, respectively.

A graphical display of the CBR data in Table 2 is provided in Figures 4–6. The figures all show a striking and similar CBR response of the clay-silt system to additive treatment at the temperatures of 40°F, 65°F, and 90°F. The CBR-degrading influence of moisture in the clay-silt soil system is generally emphasized by all the plots and particularly by the evenly split clay-silt mixture (C/S = 0.5).

The main regression model postulated for the prediction of clay-silt system soil strength was obtained by pooling all of the experimental data. The result obtained using the stepwise regression procedure involving first-order terms only is

$$\text{CBR} = 91.69 + 11.07(\text{PA}) - 5.62(\text{PM}) + 44.97(\text{CS}) + 0.14(\text{TEMP})$$

$$(R^2 = 0.76) \quad (1)$$

where

PA = epoxy resin additive level (percent),
PM = moisture content level (percent),
CS = clay-silt ratio (decimal), and
TEMP = temperature of curing (°F).

All the regression coefficients were significant at the 3 percent level. The model therefore supports the hypothesis that moisture content increase leads to a degradation of CBR values by its reduction of the cohesive and frictional strength of the soil particles. The CBR test measures the shear resistance of a soil to deformation under applied loads. Because a clay-silt system is being tested, increases in the clay content of a

TABLE 3 SOIL STABILIZATION COST ANALYSIS [IN DOLLARS PER TOTAL WEIGHT OF STABILIZATION (1,043 lb)]

COST ELEMENTS	CONTROL CASE		EPOXY ADDITIVE CASE		CEMENT CASE	
	Weight	Cost*	Weight	Cost*	Weight	Cost*
MATERIAL COST ANALYSIS						
CLAY*	530	0.0	519	0.0	519	0.0
SILT*	357	0.0	346	0.0	346	0.0
WATER (MOISTURE)	132	0.0	143	0.0	143	0.0
ADDITIVE	0	0.0	33	58.1	216	7.5
TOTAL MATERIAL COST PER 6.25 CU. FT.		0		58.10		7.50
LABOR COST ANALYSIS						
1 Pers. @ $15.0/Hr. for 1 Hr .		15.00		15.00		15.00
OVERHEAD COST						
50% OF LABOR + MATL COST		7.50		36.50		11.25
TOTAL COST		22.50		109.60		33.75
COST RATIOS		1.00		4.87		1.50

(Labor Rate : 1 person @ $15.00/hr. for 1 hr.)

*Material is not Imported

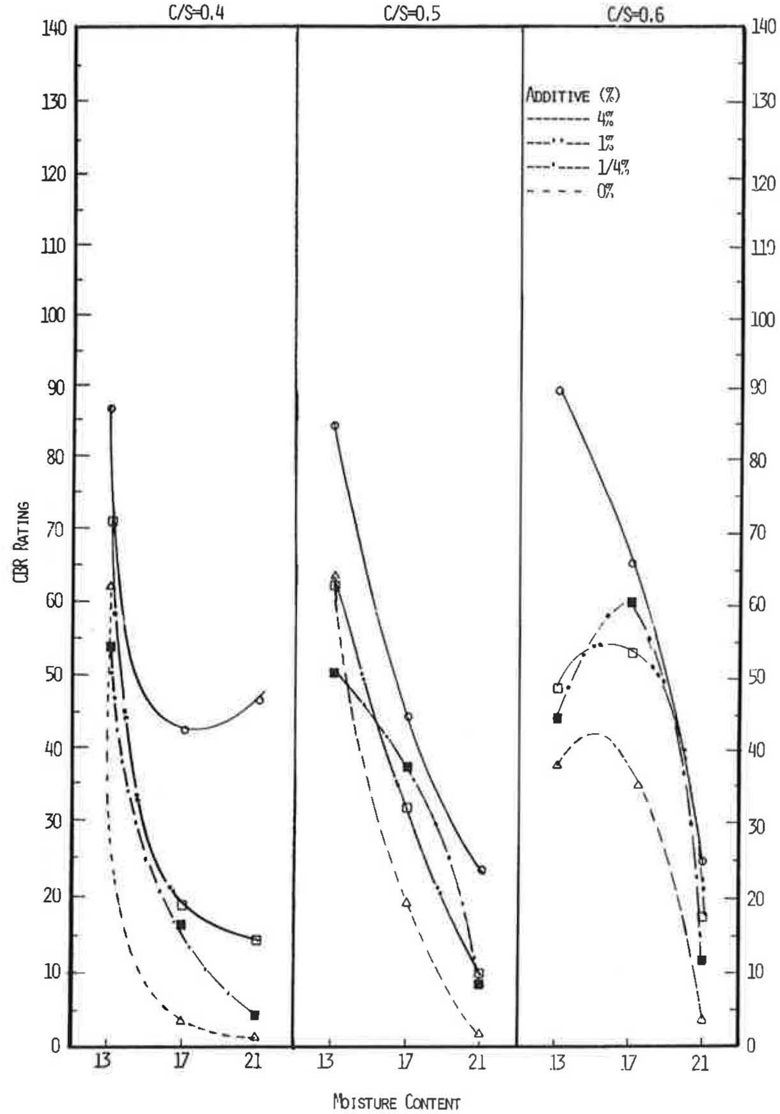

FIGURE 4 CBR versus moisture content by additive at three levels of clay-silt ratio (curing: 3 days at 40°F).

clay-silt soil lead to increased cohesive strength and an overall increase in the shear strength and consequently the CBR. This result is consistent with Coulomb's law of shear resistance.

The marginal increase in the clay-silt CBR values caused by a 1 percent increase in additive content was 11.07 units. The temperature component of the CBR model has a positive coefficient that supports the hypothesis that increased temperature leads to increased strength formation with the use of the epoxy resin.

A nomograph for clay-silt soil system CBR prediction using epoxy resin as the stabilizing agent is shown in Figure 7. The chart is used by first connecting the molding temperature and clay-silt ratio scale values with a straight line that cuts the auxiliary line F1. The intersection with F1 is next connected by a straight line to the molding (optimum) moisture content scale values to yield an intersection of F2 that is finally connected to the additive percentage scale value to yield the predicted CBR.

An alternative model was specified using a two-step regression method as suggested by Edris and Lytton (*9*). In the first step, a linear multiple regression analysis of the logarithms of the dependent and independent variables is obtained. Taking the antilog of the coefficients specifies the best unbiased linear estimator of the powers of the independent variables. For the second step, a linear multiple regression of the independent variables raised to the powers determined in the first step is performed. The appeal of this approach is that there is no predetermined polynomial form, rational function, or power law expression for the model, and it is reported that this method produces a consistently higher coefficient of determination (R^2) (*7*).

The results obtained from the two-step procedure follow.

Step 1:

$$\text{Ln CBR} = 16.102 + 0.040 \text{ Ln PA} - 4.257 \text{ Ln PM} + 1.511 \text{ Ln CS} + 0.139 \text{ Ln TEMP}$$

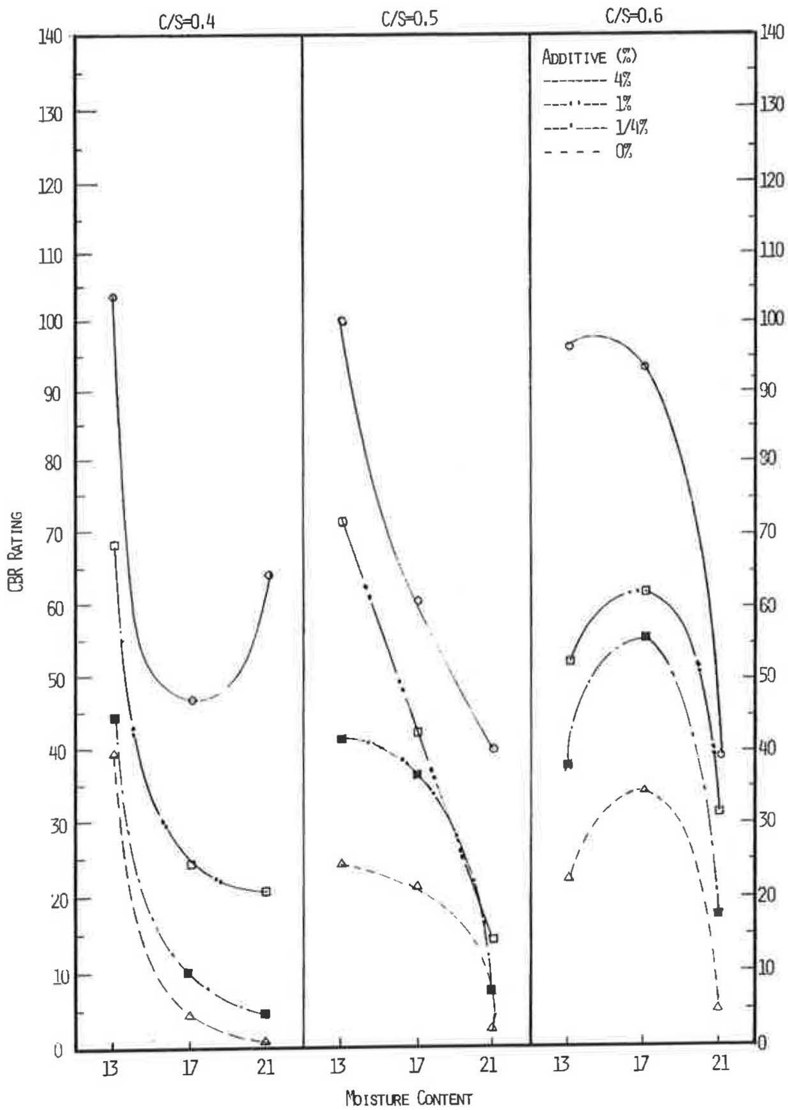

FIGURE 5 CBR versus moisture content by additive at three levels of clay-silt ratio (curing: 3 days at 65°F).

$(R^2 = 0.71)$ (2)

Step 2:

$$CBR = 6708.25 + 10.58(PA)^{1.041} - 6431.74(PM)^{0.0142} + 106.80(CS)^{4.532} + 0.06(TEMP)^{1.149}$$

$(R^2 = 0.77)$ (3)

A casewise multiple linear regression analysis of the data at fixed levels of selected independent variables was performed. The results for fixed levels of additive, clay-silt ratio, and temperature are as follows:

Fixed additive level:

- Additive level = 4 percent:

$$CBR = 160.87 - 7.47(PM) + 0.57(TEMP)$$

$(R^2 = 0.75)$ (4)

- Additive level = 1 percent:

$CBR = 125.78 - 4.95(PM)$ $(R^2 = 0.61)$ (5)

- Additive level = ¼ percent:

$CBR = 117.85 - 5.10(PM)$ $(R^2 = 0.56)$ (6)

- Additive level = 0 percent:

$$CBR = 90.50 - 5.43(PM) + 56.00(CS)$$

$(R^2 = 0.70)$ (7)

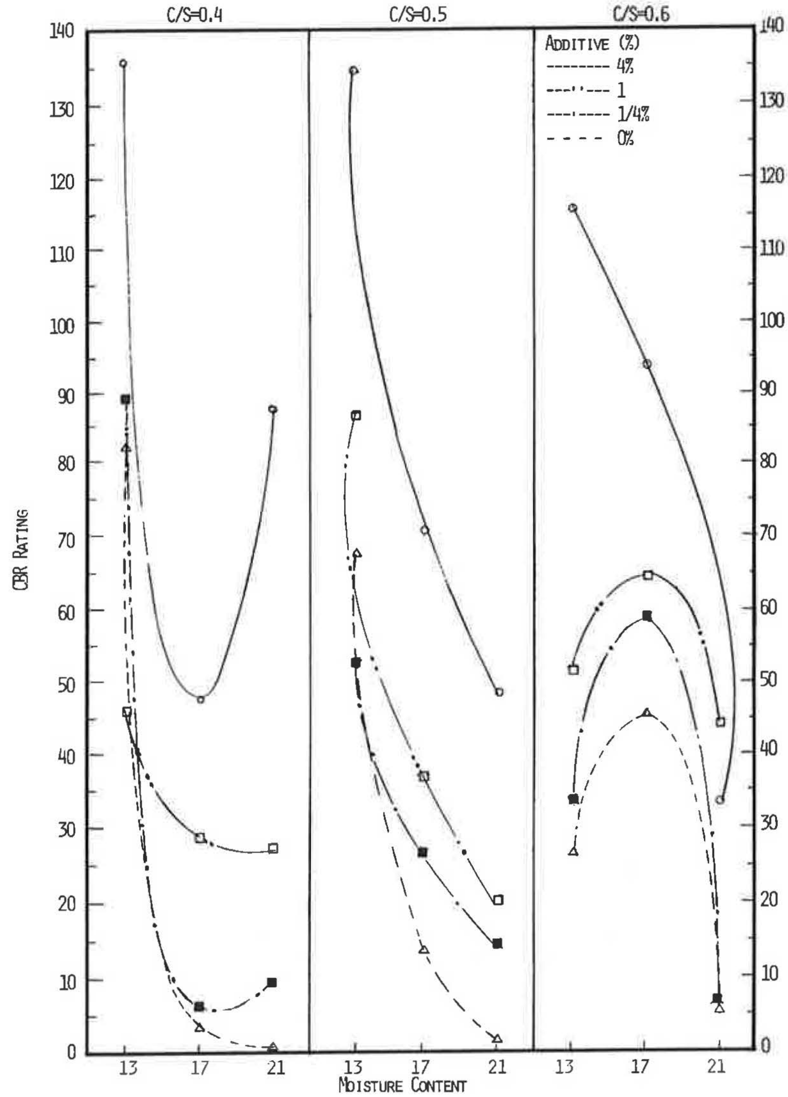

FIGURE 6 CBR versus moisture content by additive at three levels of clay-silt ratio (curing: 3 days at 90°F).

Fixed clay-silt ratio:

- Clay-silt ratio = 40 percent:

$$CBR = -423.20 + 13.38(PA) + 516.62(PM) + 0.39(PM)^2 + 0.19(TEMP)$$

$(R^2 = 0.88)$ (8)

- Clay-silt ratio = 50 percent:

$$CBR = -75.7 + 10.10(PA) + 1693.44(PM)$$

$(R^2 = 0.85)$ (9)

- Clay-silt ratio = 60 percent:

$$CBR = 233.09 + 10.16(PA) - 1785.80(PM) - 0.30(PM)^2$$

$(R^2 = 0.79)$ (10)

Fixed temperature:

- Temperature = 40°F:

$$CBR = -101.37 + 7.10(PA) + 1684.45(PM) + 0.54(CS)$$

$(R^2 = 0.83)$ (11)

- Temperature = 65°F:

$$CBR = -81.33 + 12.33(PA) + 1330.43(PM) + 0.48(CS)$$

$(R^2 = 0.81)$ (12)

- Temperature = 90°F:

$$CBR = -74.60 + 14.37(PA) + 1683.76(PM)$$

$(R^2 = 0.76)$ (13)

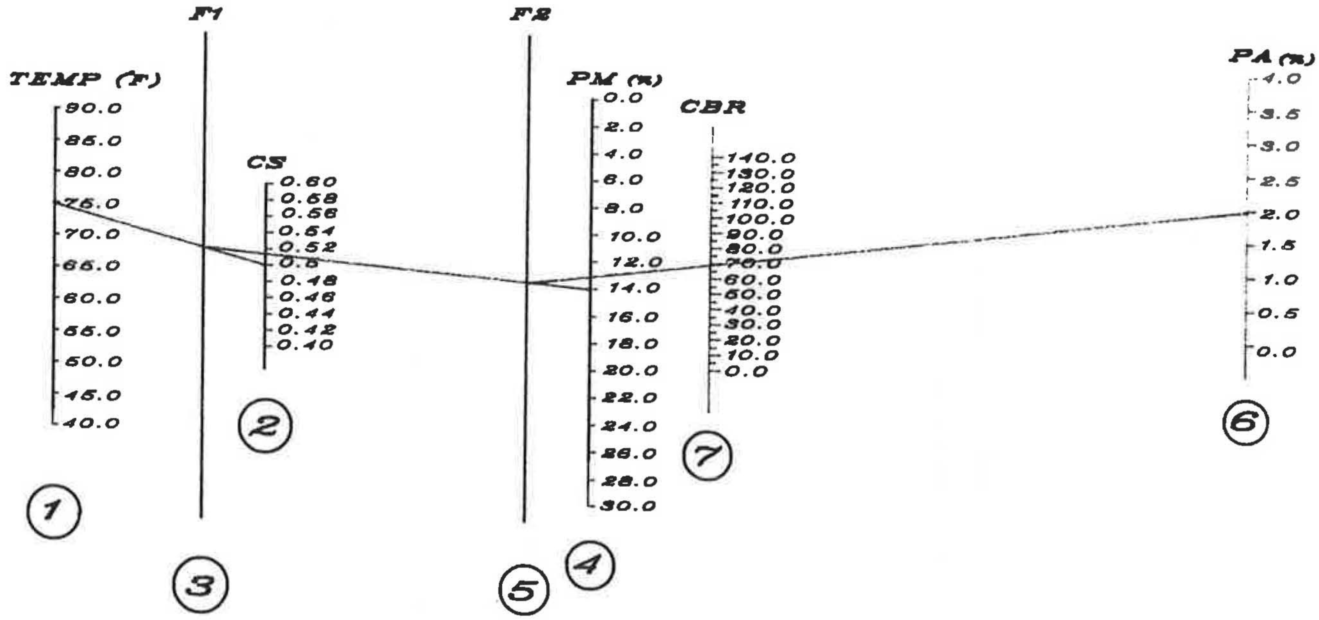

FIGURE 7 Nomograph for clay-silt system CBR prediction using epoxy-resin stabilizing agent (see Equation 1).

DISCUSSION OF RESULTS

In problem airport sites where an exclusive preponderance of clay and silt exists, the use of epoxy resin as a stabilizing agent has been demonstrated as a viable method of improving the bearing strength of clay-silt mixtures. This assertion is based on the analysis of experimental data obtained through the stabilization of a clay and silt mixture using a two-part epoxy system. The first part is a bisphenol A/epichlorohydrin resin and the other a polyamide hardener.

The CBR values obtained from the experimental test runs were either at 1 or 3 days after thermal soaking in a test chamber regulated to 40°F, 65°F, or 90°F.

STABILIZED CLAY-SILT SYSTEM RESULTS

The design of airport pavements depends on several important inputs, one of which is the strength of the subgrade. This parameter, in turn, depends both on the native moisture content and soil density, and, in cases involving chemical stabilization, the additive properties. Usually, the soaked CBR test is used in determining the subgrade strength. This represhents the worst-possible field condition; however, in cases where factors such as ambient moisture content and compaction characteristics are known with certainty, use of the unsoaked CBR strength is justified and was used in this study.

Plots of CBR value versus moisture content by clay-silt ratio stratification are shown in Figures 4–6 for all tested temperatures. The general similarity of the plots attests to the internal validity of the generated data. The variations in the graphs indicate the effects on the CBR of the variables whose changes are being stdied. In particular, the plots in Figures 4–6 indicate that in the presence of epoxy resin as additive for the clay-silt system the CBR value increases with temperature from 40°F to 90°F.

The increase in CBR value with temperature is explained partly by the increased physical bonding between the clay-silt particles made possible by the epoxy resin. The strength gain is also explained by the accelerated curing of the stabilized clay-silt mixture in response to increased curing temperatures. The implication is that temperature loss will cause a decrease in CBR value.

Figures 4–6 indicate that for a 4 percent epoxy resin application at 40°F the range of CBR improvement over the unstabilized clay-silt soil case varies approximately from 10 to 60 units. At 90°F, the strength increase obtained over the unstabilized cause from application of 4 percent epoxy varies from approximately 27 to 90 CBR units. At lower percentages of epoxy application, proportionately lower CBR increases are obtained. The plots reveal that at lower clay-silt ratios, the greater relative improvements in CBR are generally possible at higher moisture contents, whereas at higher clay-silt ratios, greater relative improvements occur at lower moisture content ranges.

Superimposing the effect of pore water pressure caused by increased moisture content on the preceding hypothesis explains the effectiveness of the epoxy resin both at higher moisture contents for low clay-silt ratios and at lower moisture contents for higher clay-silt ratios. The adsorption of water by the flat, clay particles of high surface area is smaller for samples with lower clay-silt ratios; consequently, the effect of pore water pressures on the molded samples is smaller, and relatively greater CBR improvements are possible. For samples with higher clay-silt ratios (0.6), the pronounced effect of pore water pressure leads to a further degradation of CBR over and above that resulting from the deemphasizing of stronger resin-silt particle bonds caused by an increased proportion of clay particles. The clay-silt ratio of 0.5 represents roughly the onset of the threshold of CBR improvement caused by varying levels of clay particles in the stabilized clay-silt mixture.

Explanation for the relatively better performance of CBR values at a lower clay-silt ratio (0.4) is that, because increases in clay content increases the clay skin around the larger silt particles leading to increased specific surface of the mixture, avenues for effective bonding between the silt particles and epoxy resin additive become increasingly limited in favor of the clay-silt physical bond enhanced by compaction. The relatively weaker clay-silt physical bond fails quickly under shearing forces imposed by the CBR plunger, leading to lower CBR test results compared to the situation in which a lower clay-silt ratio allows for the formation of only a lower degree of clay-silt bonds in favor of stronger bonds that lead to higher CBR values.

The use of multivariate analysis of variance technique (MANOVA) on the full factorial data in Table 2 supports the hypothesis that the increases in CBR values caused by epoxy-based treatment compared to the untreated soil CBR values are significant. These increases are statistically explained by the variables, additive percentage, and temperature and their interactions.

CONCLUSIONS

1. The effectiveness of a two-part epoxy system, bisphenol A/epichlorohydrin resin plus a polyamide hardener, in enhancing the soil bearing strength of clay-silt systems has been demonstrated against a baseline of an unstabilized clay-silt system (Table 2). The dry CBR test served as an evaluation tool for appraising the effectiveness of additive application. The dry test was chosen to enable the estimation of the effects of moisture content on the relative soil strength of a stabilized clay-silt system.

2. Within the ranges of the experimental variables and the data obtained in this research, the two-part epoxy system studied is effective for additive applications between ¼ and 4 percent at the least. The largest unsoaked CBR value obtained was 135 at the 4 percent level of epoxy application.

3. The nomograph for dry CBR value prediction developed from this research effort allows a quick estimate of the expected CBR for specified levels of soil stabilization parameters incorporated into the model. The marginal increases in CBR values caused by a 1 percent increase in epoxy resin application level, clay-silt ratio, temperature (°F), and moisture level are 11.1, 0.45, 0.14, and −5.6, respectively. The degradation of dry CBR value with increasing moisture content is consistent with engineering experience.

4. In this study, the influence of moisture content in degrading the CBR value has been found to depend on the curing condition, the ratio of clay to silt, and temperature. At the 4 percent level of resin application, a waterproofed stabilized soil system is not obtained; therefore, a limited number of wet CBR tests have been performed. These wet CBR tests confirmed that soaked CBR values ranging from 27 to 63 can be obtained even under 3 or 7 days of soaked test conditions. Above the 10 percent level of epoxy resin application, a waterproof system of stabilized clay-silt soil was obtained. Under unsoaked testing conditions, the onset of CBR degradation occurs at moisture levels of about 14, 17, and 18 percent for clay-silt ratos of 0.4, 0.5, and 0.6, respectively, on the basis of a cutoff dry CBR value of 40. In addition, the combined effects of clay-silt ratio and temperature were found to be significant in influencing dry density, and consequently CBR values. This result is confirmed by the work of Carpenter and Lytton (*8*) that explains the internal forces at work in clay-silt systems and the contraction and heave behavior of such samples under different temperature conditions.

5. On the basis of the cost of a laboratory validation experiment successfully conducted to verify the effectiveness of the chemical stabilization method outlined in this study, the cost of epoxy resin chemical stabilization may vary between one and one-half to about four times the cost (of material, labor, and overhead) per cubic yard of conventional stabilization (using materials such as cement). This cost does not take into account the pavement failure costs associated with construction on an unstabilized terrain. The higher estimate of relative cost factor, specified as four-fold, would probably be lower as the labor cost of construction increases, other factors remaining constant. Other factors that could conceivably affect the parameter include the prevailing clay-silt soil condition, equipment sophistication, labor efficiency, volume or scale of epoxy resin stabilization, epoxy resin demand and production economics, and other market forces.

ACKNOWLEDGMENTS

This study was supported by the FAA's Aircraft, Interfacility, and Safety Branch.

The authors are grateful to Aston L. McLaughlin for his invaluable assistance, which was vital to the execution of this research.

The contributions of Mahmoud A. Abd-Allah and other faculty members; Carl White, Research Associate; and the research assistance of the students in the Manufacturing Engineering Department, Central State University, Wilberforce, Ohio, are appreciated.

Dorothy Coates and Michelle Harris provided secretarial assistance and diligent efforts.

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The views expressed in this study are solely the opinions and responsibilities of the authors. They do not necessarily, in part or in whole, command the endorsement of the FAA.

Publication of this paper sponsored by Committee on Chemical Stabilization of Soil and Rock.