TENSILE PROPERTIES FOR DESIGN OF LIME-TREATED MATERIALS

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The design procedures for lime-treated materials have often been empirical in nature and are oriented for subgrade stabilization of modification. At the present time, design methods are based primarily on unconfined compressive strengths, plasticity characteristics of the soil or binder, or pH values. Design procedures for lime-treated subbase materials are very limited in scope, and the performance records of these materials used in in-service rigid pavements in Texas have generally been poor. This paper presents the results of a study that investigated factors affecting the indirect tensile strength of lime-treated materials. The factors studied were clay content, lime content, molding water content, compactive effort, and curing temperature. Significant effects produced by these factors and their interactions are discussed. A regression equation and a design table are presented for estimating indirect tensile strengths in terms of the factors investigated. The design table enables the engineer to estimate the tensile strengths for proposed lime-treated mixtures that are designed by using currently accepted design procedures.

•DURING the past 5 years, research has been conducted at the University of Texas at Austin to evaluate the tensile properties of subbases for use in rigid pavement design. A review of the literature indicated a lack of well-documented information concerning tensile properties of stabilized materials. Therefore, an experimental program was conducted to obtain such information. This paper summarizes the findings from laboratory studies on lime-treated subbase materials and discusses their application to mixture design.

A preliminary study (1) was designed to determine the important factors affecting the tensile strength of lime-treated materials and to determine the nature of the effects. Table 1 gives the 8 factors and their respective levels included in this initial study, which was made as a guide for future work. A second experiment (2) involved a more detailed analysis and evaluation of the effects of 5 of the original 8 factors on the tensile strength of lime-treated materials.

PROPERTIES OF MATERIALS

Lime used in the experiments was a hydrated calcitic lime manufactured by the Austin White Lime Company. The following chemical composition was determined by Texas Highway Department laboratories:

Chemical	Percent by Weight
$Ca(OH)_2$	93.67
CaO	0.0
Free water content, H_2O	1.38
$CaCO_3$	3.75
Inert mattter such as SiO_2	1.20
Residue retained on No. 30 (590-micron) sieve	0.0

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TABLE 1

FACTORS AND LEVELS SELECTED FOR PRELIMINARY STUDY

Factor	Level					Variable Type
	Low		Medium		High	
A, compactive effort[a]	Low				High	Quantitative
B, compaction type[a]	Impact				Gyratory shear	Qualitative
C, curing procedure	Air-dried				Sealed	Qualitative
D, molding water content, percent by weight	8	10	12	16	20	Quantitative
E, lime content, percent by weight	2		4		6	Quantitative
F, curing temperature, deg F	40		75		110	Quantitative
G, curing time, weeks	2		4		6	Quantitative
H, clay content, percent by weight	15		50		100	Quantitative

[a] Compactive effort for both types of compaction is given in Table 2.

The aggregate used in the experiments was a rounded, pit-run gravel known locally as Seguin gravel. It was quarried near Seguin, Texas, and is used in south central Texas as a base material. Its properties are

Unified classification	GM_d
Wet ball mill	37.2
Los Angeles abrasion	
100 revolutions	7.2
50 revolutions	27.3

The clay used in the experiments consists primarily of illite and montmorillonite. It is common to the central Texas area and is locally known as Taylor marl clay. Its plasticity and mineralogical characteristics are as follows:

Characteristic	Percent
Liquid limit	59
Plastic limit	18
Plastic index	41
Calcium montmorillonite	30 to 35
Illite	50 to 60
Kaolinite	10 to 15

EXPERIMENT DESIGN AND PROCEDURES

The 5-factor experiment was selected as the basis for the recommendations and conclusions in this paper because it was a more detailed study, founded on the results from the preliminary study. The factors and levels studied are given in Table 3.

A central composite rotatable experimental design (3) provided an economical and practical means of studying the effects produced by the 5 factors and their interactions with a minimum number of observations. This design consisted of a 2^5 full factorial with 32 cells, 10 star points, and 6 center points. The center points were replicate specimens that were produced by combining the middle or "zero" levels of all factors. The full factorial provided data for the analysis of the effects produced by the 5 factors and their

TABLE 2

TYPES OF COMPACTION

Compaction Type	Compactive Effort	
	Low	High
Impact, ft-lb/in.^{3}	21	45
Gyratory shear[a], psi	75	125

[a] Compaction procedure for the Texas gyratory shear compactor (9).

TABLE 3

FACTORS AND LEVELS FOR ADVANCED EXPERIMENT

Factor	Level					Variable Type
	-2	-1	0	1	2	
A, compactive effort[a], psi	75	100	125	150	175	Quantitative
B, compaction type			Gyratory shear			Qualitative
C, curing procedure			Sealed			Qualitative
D, molding water content, percent by weight	8	10.5	13	15.5	18	Quantitative
E, lime content, percent by weight	0.0	1.5	3.0	4.5	6.0	Quantitative
F, curing temperature, deg F	50	75	100	125	150	Quantitative
G, curing time, weeks			3			Quantitative
H, clay content, percent by weight	25.0	37.5	50.0	62.5	75.0	Quantitative

[a] Compaction procedure for the Texas gyratory shear compactor (9).

interactions; the star points and center points enabled the curvilinear effects to be evaluated.

The indirect tensile test (Fig. 1) consists of applying opposite compressive loads along the vertical diametral plane of a cylindrical specimen, resulting in a relatively uniform tensile stress perpendicular to and along the diametral plane containing the applied load. Failure usually occurs as splitting along this loaded plane when the tensile stress exceeds the tensile strength of the material.

The procedure followed for the indirect tension testing of lime-treated subbase specimens was that originally recommended by Hudson and Kennedy (4, 5) modified slightly (2).

TABLE 4

INDIRECT TENSILE STRENGTHS

Specimen	Level of Factor[a]					Indirect Tensile Strength (psi)
	A	E	H	D	F	
Full Factorial						
1	+1	+1	+1	+1	+1	42.7
2	+1	+1	+1	+1	-1	30.8
3	+1	+1	+1	-1	+1	35.2
4	+1	+1	+1	-1	-1	22.6
5	+1	+1	-1	+1	+1	33.3
6	+1	+1	-1	+1	-1	17.6
7	+1	+1	-1	-1	+1	53.8
8	+1	+1	-1	-1	-1	27.1
9	+1	-1	+1	+1	+1	22.8
10	+1	-1	+1	+1	-1	23.3
11	+1	-1	+1	-1	+1	24.6
12	+1	-1	+1	-1	-1	19.7
13	+1	-1	-1	+1	+1	17.5
14	+1	-1	-1	+1	-1	15.8
15	+1	-1	-1	-1	+1	40.5
16	+1	-1	-1	-1	-1	18.8
17	-1	+1	+1	+1	+1	26.9
18	-1	+1	+1	+1	-1	31.4
19	-1	+1	+1	-1	+1	27.4
20	-1	+1	+1	-1	-1	17.4
21	-1	+1	-1	+1	+1	37.1
22	-1	+1	-1	+1	-1	15.4
23	-1	+1	-1	-1	+1	53.7
24	-1	+1	-1	-1	-1	23.6
25	-1	-1	+1	+1	+1	20.1
26	-1	-1	+1	+1	-1	19.1
27	-1	-1	+1	-1	+1	22.0
28	-1	-1	+1	-1	-1	15.8
29	-1	-1	-1	+1	+1	12.5
30	-1	-1	-1	+1	-1	11.6
31	-1	-1	-1	-1	+1	27.7
32	-1	-1	-1	-1	-1	17.5
Star Points						
33	-2	0	0	0	0	24.2
34	+1	0	0	0	0	38.2
35	0	-2	0	0	0	22.6
36	0	+2	0	0	0	23.4
37	0	0	-2	0	0	18.7
38	0	0	+2	0	0	28.1
39	0	0	0	-2	0	23.2
40	0	0	0	+2	0	20.8
41	0	0	0	0	-2	25.6
42	0	0	0	0	+2	45.5
Center Points						
43	0	0	0	0	0	22.0
44	0	0	0	0	0	29.3
45	0	0	0	0	0	28.9
46	0	0	0	0	0	27.9
47	0	0	0	0	0	26.0
48	0	0	0	0	0	30.4

[a] Factors and levels are given in Table 3.

Testing was conducted at 75 F at a loading rate of 2 in./min. The specimens had nominal diameters of 4 or 6 in. and nominal heights of 2 in. A loading strip with a curved portion having a radius of either 3 in. or 2 in. was used to test the 6-in. diameter and 4-in. diameter specimens. The experimental results are given in Table 4.

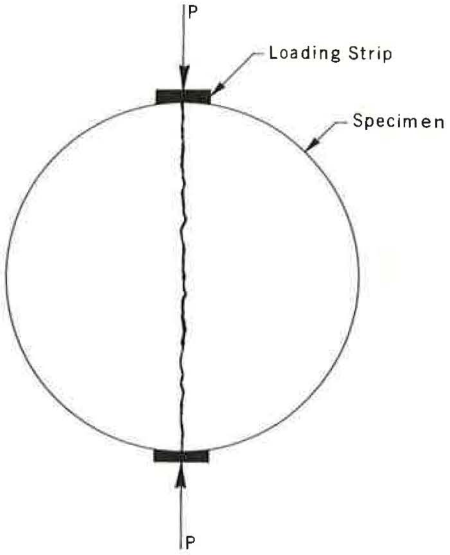

Figure 1. The indirect tensile test.

DISCUSSION OF RESULTS

In the following sections, effects produced by the various factors and their interactions and the curvilinear effects that were shown to be highly significant from both a statistical and engineering viewpoint are discussed. Although it is not possible from this experiment to explain definitely the observed effects, it is possible to postulate their probable causes.

Interactions

Many times the effect produced by varying the levels of a factor is dependent on the level of other factors. These interaction effects are very important and often reflect the complex interrelationships among factors affecting the behavior of a material. Four 2-factor interactions, which were statistically significant at the 5 percent confidence level, were judged to have engineering importance and are discussed in the following.

Curing Temperature and Clay Content—For a curing temperature of 75 F, a change in clay content from 37.5 to 62.5 percent caused a slight increase in indirect tensile strength. However, for a curing temperature of 125 F, the same change in clay content caused a considerable decrease in the indirect tensile strength. This loss was probably due to cracking of the high clay content specimens cured at elevated temperatures.

Molding Water Content and Clay Content—Figures 2, 3, and 4 show the trends predicted from the experimental strength data and the importance of this estimation. Estimated indirect tensile strengths were plotted against molding water content for lime percentages of 2, 4, and 6 percent. For the lower clay percentages, the majority of the specimens were on the wet side of an optimum strength. As the clay percentage increased, the observations centered around the optimum water content strength for the middle clay contents and fell on the dry side of the strength-water content curves for the high clay percentages. Therefore, as the lime content was increased, strength increased for the higher levels of clay content but decreased for small percentages of clay. Thus, an increase in lime content did not necessarily result in an increased strength after a given curing period.

Another interpretation of this interaction is that, when a low water content was combined with a low clay content, there was sufficient water to allow the strength-gaining reaction to take place. With a low water content and an increased clay content, however, there was an insufficient water content for the soil-lime reactions to take place because of absorption by the clay particles. Such a possibility is supported by the fact that, when the water content in combination with the high clay content was increased from 10.5 to 15.5 percent, there was an accompanying strength increase. However, when the water content in combination with the low clay content was increased from 10.5 to 15.5 percent, there was a sharp decrease in tensile strength because the molding water content was on the wet side of optimum.

Molding Water Content and Curing Temperature—At the molding water content of 10.5 percent, an increase in curing temperature from 75 to 125 F caused a marked increase in indirect tensile strength. However, for the specimens compacted at a water content

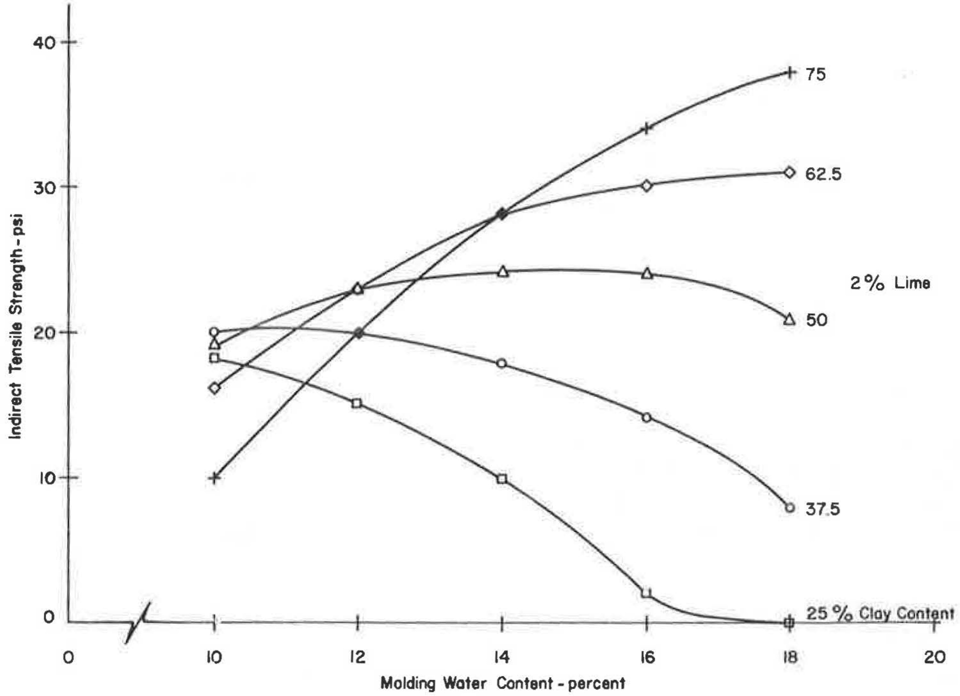

Figure 2. Effect of molding water content and clay content on indirect tensile strength of soil-aggregate mixtures containing 2 percent lime.

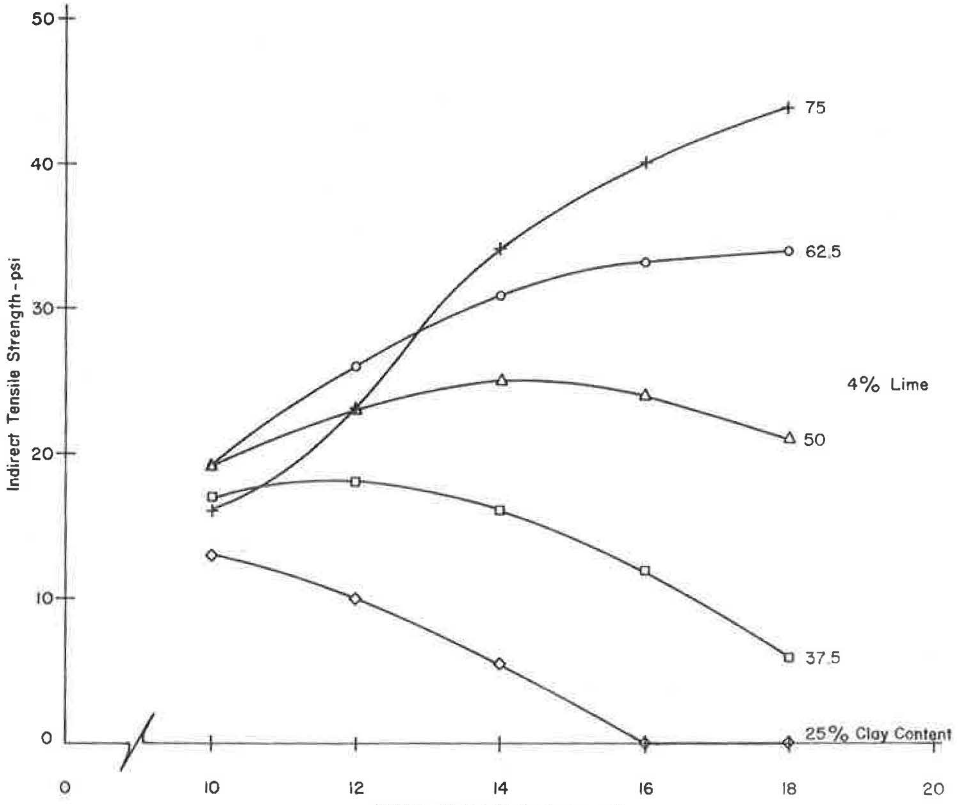

Figure 3. Effect of molding water content and clay content on indirect tensile strength of soil-aggregate mixtures containing 4 percent lime.

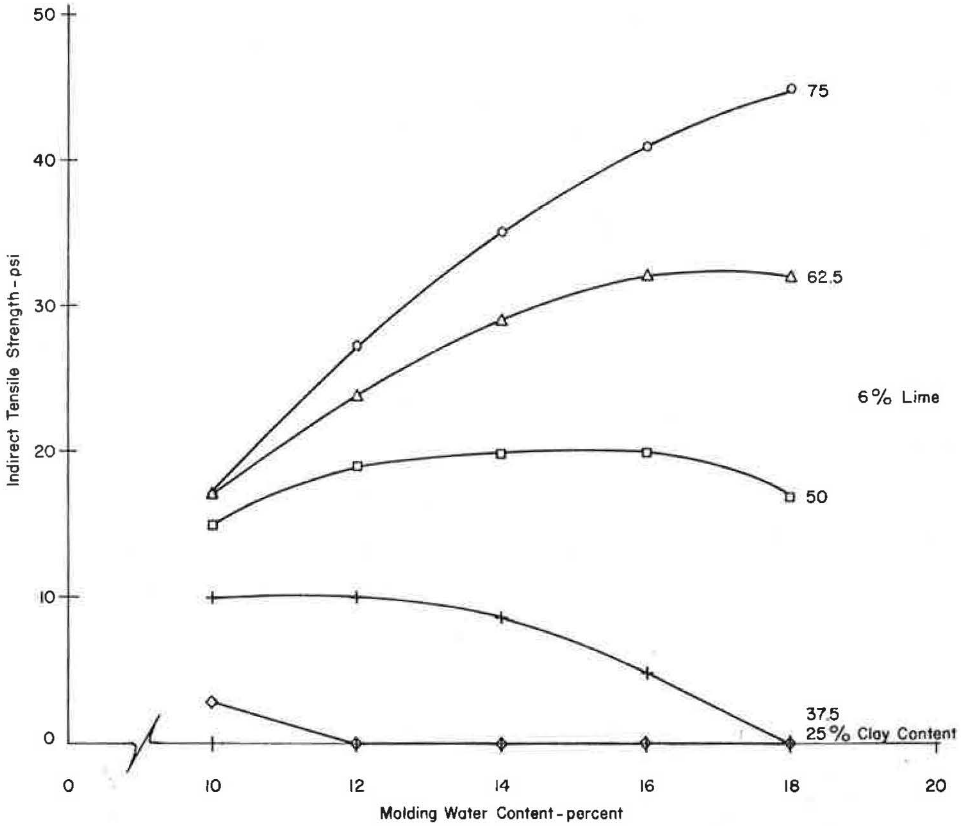

Figure 4. Effect of molding water content and clay content on indirect tensile strength of soil-aggregate mixtures containing 6 percent lime.

of 15.5 percent, the strength increase was much less for the same increase in curing temperature. Because 15.5 percent was on the wet side of optimum and excessive water caused a reduction in the strength of the clay matrix of the specimens, the strength increase due to an increase in curing temperature was less apparent than it was in the low water content specimens, which were relatively dry and hard.

Lime Content and Curing Temperature—For specimens with a lime content of 1.5 percent, an increase in curing temperature from 75 to 125 F caused an increase in the indirect tensile strength of the specimens; but for specimens with a lime content of 4.5 percent, the same increase in curing temperature caused a much greater increase in specimen strength. It is probable that at the low lime content there was insufficient lime for the increased curing temperature to have much effect.

Main Effects

The analysis of variance showed that 4 of the factors produced significant effects at the 5 percent probability level and that 3 factors were significant at the 1 percent level. In addition, it was found that 2 of these main effects were curvilinear. Clay content was the only factor that did not appear to be important. It was found that the average indirect tensile strength was increased by increasing the compactive effort, increasing the lime content, decreasing the molding water content, and increasing the curing temperature. The latter 2 factors, curing temperature and molding water content, produced significant curvilinear or quadratic effects.

Curing Temperature—Tensile strength increased with an increased curing temperature; the increase associated with raising the temperature from 100 to 150 F was much greater than that associated with raising the temperature from 50 to 100 F. This observation is supported by Ruff and Ho (5), who reported a greater rate of strength increase associated with a temperature increase in the higher temperature ranges.

Molding Water Content—The average indirect tensile strength increased when the molding water content was increased from 8 to 13 percent but decreased when it was raised from 13 to 18 percent. Thus, there was an average optimum water content for the materials tested and conditions of the tests.

Prediction Equation

A regression analysis was conducted in order to obtain an equation with which the indirect tensile strength of the lime-treated materials in this study could be estimated. The use of this prediction equation is valid only for the range of levels of the factors considered and the conditions in this experiment. The prediction equation derived from the experiment is

$$\begin{aligned} S_t = {} & 228.18 - 1.647A + 3.100D - 86.375E - 2.218F - 5.234H + 0.017AF \\ & + 0.035AH + 581AE + 0.043FH + 0.137DH + 1.727EH - 0.037DF \\ & + 0.929EF - 0.261D^2 - 0.611E^2 + 0.0028F^2 - 0.008H^2 - 0.0116AEH \\ & - 0.0058AEF - 0.00348AFH - 0.0173EFH + 0.000116AEFH \end{aligned} \tag{1}$$

where

S_t = predicted value of indirect tensile strength, in psi, and
A, D, E, F, H = factors considered (Table 2).

The coefficient of determination R^2 for the predictive equation was 0.88, and the standard error of estimate was ±4.03 psi.

The regression equation utilizes the uncoded factor levels given in Table 3 and not the coded levels, i. e., -2, -1, 0, +1, and +2. Because this regression is given for the uncoded data, the equation is valid only for predictive purposes and cannot be interpreted term by term.

APPLICATION TO DESIGN

At present there are few definite design procedures for lime-treated materials and no method of designing lime-treated mixtures for a specified or desired strength. Eades (6), McDowell (7), and Thompson (8) have formulated guidelines for the determination of the percentage of lime required for lime-treated materials.

Eades based his procedure on the pH of the lime-soil mixture, which is a measure of the amount of lime consumed by the soil. Nevertheless, it was noted that strength gains vary with the mineralogical components of a soil and that a strength test is necessary to determine the percentage of increase.

McDowell, on the other hand, developed a chart based on performance and field measurements that expresses the percentage of lime required if the percentage of binder in the soil-aggregate mixture and the plasticity index of the binder are known. McDowell stated that use of the chart did not eliminate the need for materials tests and recommended that strength tests be conducted to verify the acceptability of the lime percentages obtained from the chart. It was also recommended that a soil-aggregate mixture treated with lime should have a minimum unconfined compressive strength of 50 psi when used as a subbase or subgrade.

Thompson suggested that unconfined compression tests samples be made by using the natural soil and the soil treated with lime. It was recommended that the lime-treated soil be allowed to cure for 48 hours at 120 F. Then, if the strength increase of the lime-treated soil is less than 50 psi compared with the untreated soil, the soil is considered to be nonreactive; if the strength difference between the natural soil and the lime-treated soil is greater than 50 psi, the soil is termed reactive. The nonreactive soil is then treated to obtain a minimum plasticity index, and the reactive soil is reevaluated to obtain a lime content that produces a maximum unconfined compressive strength.

With the exception of these references to strength, there is little additional information available regarding the design of lime-treated materials in terms of strength or load-deformation characteristics. Thus, it would be desirable to develop information that would allow a lime-treated mixture to be designed to provide a given level of strength or that would allow an estimate of its strength to be made. Such information would supplement these procedures and would provide a basis for the development of a rational mixture design procedure. Such a procedure is desirable for the design of pavements to achieve an optimum pavement section in terms of strength and economic requirements.

It is, therefore, proposed that the predictive equation previously discussed be used as a means of estimating tensile strengths of lime-treated mixtures similar to the mixtures used in this study and possibly as a basis for the development of a design procedure. Although the equation can be solved directly, a table of tensile strengths has been generated in terms of clay content, moisture content, curing temperature, and lime content (Table 5). The purpose of the data given in Table 5 is to expedite the estimation of tensile strengths without the need for extensive manual calculations or the use of the computer.

The dry densities of the lime-treated specimens ranged between 110 and 125 pcf for all the treatment combinations tested. Within this density range, no correlation was

TABLE 5

INDIRECT TENSILE STRENGTH, PSI, BASED ON TEMPERATURE AND CLAY, LIME, AND MOISTURE CONTENTS

Lime (percent)	Moisture (percent)	25 Percent Clay			37.5 Percent Clay			50 Percent Clay			62.5 Percent Clay			75 Percent Clay		
		40 F	60 F	80 F	40 F	60 F	80 F	40 F	60 F	80 F	40 F	60 F	80 F	40 F	60 F	80 F
0	10	21	18	18	20	17	16	17	14	13	11	8	7	2	0	0
	12	20	15	13	22	18	15	22	17	15	19	14	12	14	9	7
	14	16	10	6	22	16	12	25	19	15	26	19	16	24	17	13
	16	10	3	0	19	12	6	26	18	13	30	22	17	31	24	18
	18	2	0	0	15	6	0	25	16	9	32	23	16	37	28	21
1	10	19	19	21	20	19	20	19	17	17	15	12	12	8	5	4
	12	17	16	16	22	19	19	24	21	20	23	19	17	20	15	13
	14	14	10	10	22	18	16	27	22	20	30	24	21	30	24	19
	16	8	3	1	19	14	10	28	22	18	34	27	22	37	30	24
	18	0	0	0	15	8	3	27	19	13	36	28	21	43	34	26
2	10	16	18	23	19	20	23	20	19	21	18	16	16	13	10	9
	12	14	15	18	20	20	22	25	23	23	26	23	21	25	20	17
	14	10	10	12	20	18	18	28	24	23	32	28	25	35	28	24
	16	4	2	3	18	14	13	28	24	21	37	30	26	42	34	29
	18	0	0	0	13	8	6	27	21	17	39	31	25	48	38	31
3	10	11	16	24	16	19	24	19	20	23	19	18	19	17	13	12
	12	9	13	19	18	20	23	24	23	25	28	25	24	29	24	21
	14	6	8	12	18	18	20	27	25	25	34	30	28	38	32	28
	16	0	1	4	15	14	14	28	24	13	38	32	29	46	38	32
	18	0	0	0	11	8	7	27	22	19	40	33	28	52	42	35
4	10	5	13	23	12	17	25	17	19	24	20	19	20	19	16	14
	12	4	10	18	24	18	23	22	23	26	28	26	26	31	26	23
	14	0	5	12	14	16	20	25	25	25	34	31	29	41	34	30
	16	0	0	3	12	12	15	26	24	24	39	33	30	48	40	34
	18	0	0	0	7	6	7	25	21	20	41	34	30	54	44	37
5	10	0	8	21	8	14	24	14	18	24	19	19	21	20	17	15
	12	0	6	17	9	15	22	20	21	26	27	26	26	32	27	24
	14	0	0	10	9	13	19	22	23	26	34	30	30	42	35	31
	16	0	0	1	6	9	14	23	22	24	38	33	31	50	42	35
	18	0	0	0	2	3	6	22	20	19	40	34	30	55	46	38
6	10	0	3	8	1	10	21	10	15	22	17	17	20	20	17	15
	12	0	0	14	3	10	20	15	19	24	25	24	25	32	27	24
	14	0	0	7	3	9	17	18	20	24	32	29	29	42	35	31
	16	0	0	0	0	5	12	19	20	22	36	32	30	50	41	35
	18	0	0	0	0	0	4	18	17	18	38	32	29	55	45	38

found to exist between tensile strength and dry density. However, it is stressed that a lime-treated mixture must be well compacted for the lime reaction to occur and for the development of strength.

The design table has treatment combinations that have estimated "zero" tensile strength. Because these mixtures have low clay contents and the aggregate is nonreactive to lime stabilization, this lack of tensile strength would be expected. Although lime does not produce strength improvements with these mixtures, it does favorably modify the plasticity characteristics of the clay binder to greatly decrease its swelling potential. Often this benefit can be substaintial.

CONCLUSION

The information on the interaction effects among the factors studied indicates that the mechanisms of lime stabilization are complex in nature and cannot be modeled adequately in simple terms. The documentation of these effects gives greater understanding of the tensile behavior of lime-treated materials.

In addition, information is provided in the form of a predictive equation that can be used to estimate tensile strength or to begin to provide preliminary mixture designs for materials similar to those studied. As additional tests are conducted on similar and different materials stabilized with either lime or another additive, the equation can be modified and expanded. Thus, by incorporating strength requirements, cost of the additive and the placement of the treated materials, and estimates of tensile strength either from a direct test or possibly a predictive equation such as the regression equation given here, the designer will be able to make a better decision as to the type of additive and the amounts needed to sufficiently upgrade a substandard construction material.

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REFERENCES

1. Miller, S. P., Kennedy, T. W., and Hudson, W. R. An Evaluation of Factors Affecting the Tensile Properties of Lime-Treated Materials. Center for Highway Research, Univ. of Texas at Austin, Research Rept. 98-4, March 1970.
2. Tulloch, W. S., Hudson, W. R., and Kennedy, T. W. Evaluation and Prediction of the Tensile Properties of Lime-Treated Materials. Center for Highway Research, Univ. of Texas at Austin, Research Rept. 98-5, June 1970.
3. Cochran, W. G., and Cox, G. M. Experimental Design. John Wiley and Sons, New York, 1968.
4. Hudson, W. R., and Kennedy, T. W. An Indirect Tensile Test for Stabilized Materials. Center for Highway Research, Univ. of Texas at Austin, Research Rept. 98-1, Jan. 1969.
5. Kennedy, T. W., and Hudson, W. R. Application of Indirect Tensile Test to Stabilized Materials. Highway Research Record 235, 1968, pp. 36-48.
6. Eades, J. L., and Grim, R. E. A Quick Test to Determine Lime Requirements for Lime Stabilization. Highway Research Record 139, 1966, pp. 61-72.
7. McDowell, C. H. Evaluation of Soil-Lime Stabilization Mixtures. Highway Research Record 139, 1966, pp. 15-24.
8. Thompson, M. R. Mixture Design for Lime-Treated Soils. Highway Research Laboratory, Univ. of Illinois, Urbana, Highway Eng. Series 26, Jan. 1969.
9. Manual of Testing Procedures. Texas Highway Department, Vol. 1, Test Method TEX-206-F, Sept. 1966.