ESTIMATIONS OF INDIRECT TENSILE STRENGTHS FOR LIME-TREATED MATERIALS

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Within the framework of a research effort concerned with the evaluation of tensile properties of stabilized subbase materials, it was desired to establish a means to predict indirect tensile strength from Texas Highway Department tests for lime-treated materials. Experiments were designed to develop a predictive equation in terms of factors involved with mix design, construction, and curing and to determine if acceptable correlations exist between the indirect tensile test and both the cohesiometer test and the unconfined compression test. These correlations were developed by using 2 approaches: The first varied 5 factors (compactive effort, molding water content, lime content, curing temperature, and clay content) at 3 levels each, and the second, based on Texas Highway Department testing procedures, varied only molding water content, lime content, and clay content because curing temperature and compactive effort are fixed by the test specifications. It was found that acceptable correlations for lime-treated materials exist for both approaches between the indirect tensile test and cohesiometer test, the indirect tensile test and unconfined compression test, and the indirect tensile test and the combined results of the cohesiometer and unconfined compressive test. These correlations provide the capability of estimating the indirect tensile strength from the cohesiometer or the unconfined compression test data or both for lime-treated materials used in pavements now in service.

•THE IMPORTANCE of the tensile characteristics in a rational design procedure for subbases can be demonstrated from both theoretical considerations and field observations. Nevertheless, until recently, little attention has been given to the tensile characteristics of stabilized materials and, therefore, little information was available. For this reason, the Center for Highway Research at the University of Texas at Austin began a research project to study the tensile properties of stabilized subbase materials for use in pavement design. On the basis of a review of existing methodology and laboratory tests, Kennedy and Hudson (1, 2) concluded that the indirect tensile test was the best test currently available for the evaluation of the tensile characteristics of stabilized materials.

In order to obtain information on the tensile strengths of lime-treated materials, 2 sequential experiments were conducted to determine the factors and the interactions among the factors that were important to tensile strength. A secondary objective was to develop a preliminary regression equation that could be used to estimate tensile strength in terms of the factors investigated. In addition, an attempt was made to determine whether correlations exist between the indirect tensile test and the tests used by the Texas Highway Department for evaluating lime-treated materials. Currently, the unconfined compression test and cohesiometer test are used by the Texas Highway Department.

The primary purpose of these correlation studies was to establish a means by which indirect tensile strengths could be estimated from unconfined compressive strengths or

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cohesiometer values because these tests were used to evaluate lime-treated materials used in pavements in Texas for which performance records have been maintained. Any subbase design procedure must consider performance, and these records can be used in conjunction with the correlations to estimate tensile strengths of the materials at the time of construction and, thus, to obtain performance information without waiting for test sections to be approved, funded, and constructed.

EXPERIMENT DESIGN

A central composite rotatable design was used to evaluate the effects produced by the 5 factors investigated and to develop predictive equations by a regression analyis. This design consisted of a 2^5 full factorial with 32 cells, 10 star points, and 6 center points (48 observations). The full factorial in this design allowed analysis of the main effects and of all interaction effects on the tensile strength of lime-treated materials for the factors and levels studied. The star points and center points allowed analysis of the curvilinear effects. The replicate center points also provided an estimate of experimental error. This basic design was utilized in the development of a regression equation capable of estimating indirect tensile strengths from the factors and conditions included in this experiment and for the conditions of the study. The factors and levels selected are given in Table 1.

The general correlation experiment consisted of a half fraction of a 2^5 factorial with 16 observations plus 3 center points for each of the 3 tests. The 5 factors were the same as those used in developing the regression equation. The factors and levels are given in Table 2.

Only 3 of the factors could be varied in the Texas Highway Department correlation because the Texas Highway Department standard procedures fixed the compactive effort and the curing temperature; thus, a design involving a 2^3 full factorial with 8 cells, 6 star points, and 6 center points was used. The factors and levels are given in Table 3.

In both correlation experiments, 3 companion specimens were prepared for each treatment combination: a 2-in. high by 6-in. diameter specimen to be tested in indirect tension, a 2-in. high by 6-in. diameter specimen to be tested in the cohesiometer, and an 8-in. high by 6-in. diameter specimen to be tested in unconfined compression.

TABLE 1

FACTORS AND LEVELS FOR THE REGRESSION ANALYSIS

Factor	Level				
	-2	-1	0	+1	+2
A, compactive effort (4), psi	75	100	125	150	175
D, molding water content, percent	8.0	10.5	13.0	15.5	18.0
E, lime content, percent	0.0	1.5	3.0	4.5	6.0
F, curing temperature, deg F	50	75	100	125	150
H, clay content, percent	25.0	37.5	50.0	62.5	75.0

TABLE 2

FACTORS AND LEVELS IN THE GENERAL CORRELATION

Factor	Level		
	-1	0	+1
A, compactive effort (4), blows per layer	50.0	75.0	100.0
D, molding water content, percent	10.5	13.0	15.5
E, lime content, percent	1.5	3.0	4.5
F, curing temperature, deg F	75.0	100.0	125.0
H, clay content, percent	37.5	50.0	62.5

TABLE 3

FACTORS AND LEVELS IN THE TEXAS HIGHWAY DEPARTMENT CORRELATION

Factor	Level				
	-1.682	-1	0	+1	+1.682
D, molding water content, percent	8.8	10.5	13.0	15.5	17.2
E, lime content, percent	0.477	1.5	3.0	4.5	5.523
H, clay content, percent	29.0	37.5	50.0	62.5	71.0

PROPERTIES OF MATERIALS

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

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

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 as follows:

Unified classification	GM_d
Wet ball mill	37.2
Los Angeles abrasion	
100 revolutions	7.3
50 revolutions	27.3

The clay used in the experiments is common to central Texas and is known as Taylor marl clay. Its mineralogical and plasticity characteristics are as follows:

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

PREPARATION AND CURING OF SPECIMENS

For the tests, the aggregate was separated and recombined to meet the gradation requirement shown in Figure 1. However, Taylor marl clay was substituted for all material finer than the No. 40 sieve. The specimen preparation and curing for the 3 phases of the experiment are summarized in the following paragraphs.

Regression Analysis

All regression analysis specimens were compacted by Texas gyratory shear compaction. Although compactive efforts could not be calculated, relative compactive

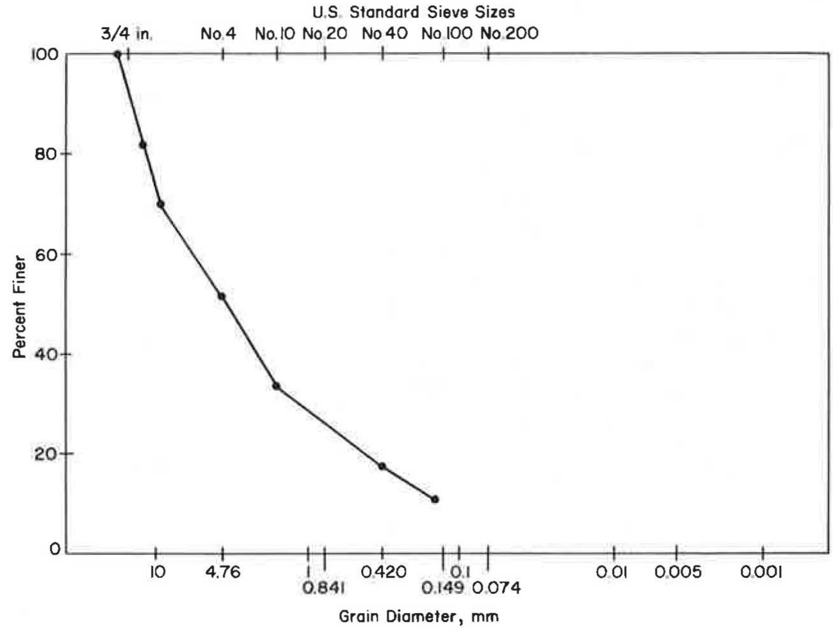

Figure 1. Grain size distribution for medium gradation.

efforts were specified in terms of the resistance the specimens produced on the hydraulic ram. High resistance pressures represented higher compactive efforts. Following compaction, the specimens were weighed and measured and were then wrapped in PVC film and cured 21 days at the specified curing temperatures given in Table 1.

General Correlation Analysis

The general correlation was an attempt to relate cohesiometer and unconfined test results with indirect tensile strengths obtained from specimens selected from the full factorial design. All specimens were impact compacted with a Rainhart compactor. The compactive efforts, given in Table 2, were specified as a number of blows per layer struck by a 10-lb hammer falling 18 in. After compaction, the specimens were weighed, and the height and the diameter or circumference were measured. The specimens were then wrapped with a layer of PVC film, placed in the appropriate temperature environment, and cured for 3 weeks prior to testing.

Texas Highway Department Correlation Analysis

The Texas Highway Department specifies that impact compaction be done by using a 10-lb ram with an 18-in. drop and subjecting each layer of lime-treated material to 50 blows. The curing procedure specified for lime-treated materials (5) is as follows: (a) The test specimens are extruded from the mold with the top and bottom porous stones in place, immediately covered with a triaxial cell, and then stored at room temperature for 7 days; (b) after the moist-curing period, they are removed from the cells and dried at a temperature not exceeding 140 F for about 6 hours or until one-third to one-half of the molding moisture is removed; and (c) they are cooled for at least 8 hours, weighed, measured, and then placed in triaxial cells and subjected to capillarity for 10 days with a constant lateral pressure of 1 psi and a surcharge weight of 15 lb.

TEST PROCEDURE

The procedure followed for the indirect tensile testing of soil-lime specimens was the same as that originally recommended by Kennedy and Hudson (1, 2) and the same as that reported by Tullock et al. (4). Essentially, the test consists of the application of compressive loads along a diametrical plane (Fig. 2). These loads result in a tensile stress distribution that is perpendicular to and along the plane containing the applied lime loads and that causes failure by splitting along this plane.

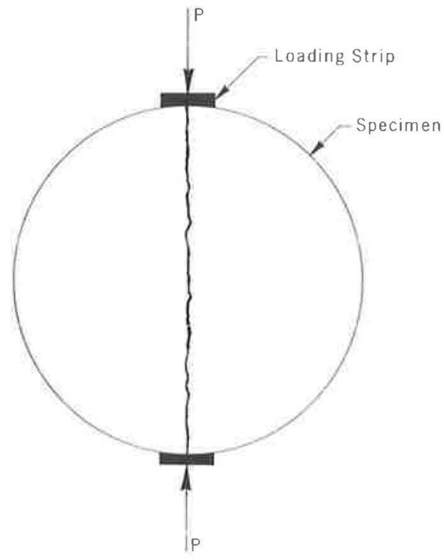

Figure 2. Indirect tensile test.

Testing was conducted at 75 F at a loading rate of 2 in./min. Each specimen had a nominal diameter of 4 or 6 in. and a nominal height of 2 in. A loading strip with a curved portion having a radius of 3 in. was used to test the 6-in. diameter specimens, and one with a curved portion having a radius of 2 in. was used to test the 4-in. diameter specimens. More detailed descriptions of the test are given in other reports (1, 2, 4).

The unconfined compression tests and the cohesiometer tests were conducted according to Texas Highway Department standard procedures (5). The cohesiometer specimens were tested at the laboratories of the Texas Highway Department. The unconfined compression test specimens had a nominal diameter of 6 in. and a nominal height of 8 in., and the cohesiometer specimens had a nominal diameter of 6 in. and a nominal height of 2 in. The test temperature for all specimens was 75 F. The loading rate for the unconfined compression test was 0.05 in./min, and the cohesiometer loading rate was 1,800 ± 20 grams/min of shot.

ANALYSIS

Regression Equation

A regression analysis was conducted in order to obtain an equation with which to estimate the indirect tensile strengths of lime-treated materials for the conditions of the experiment. The levels of the factors used in the experiment are given in Table 1. The resulting predictive equation was

$$\begin{aligned}\hat{S}_t = {} & 228.18 - 1.647A + 3.100D - 86.375E - 2.218F - 5.234H + 0.017AF \\ & + 0.035AH + 0.581AE + 0.043FH + 0.137DH + 1.727EH - 0.037DF \\ & + 0.929EF - 0.261D^2 - 0.611E^2 + 0.0028F^2 - 0.008H^2 - 0.0116AEH \\ & - 0.0058AEF - 0.000348AFH - 0.0173EFH + 0.000116AEFH \qquad (1)\end{aligned}$$

where

$\hat{S}_t$ = predicted value of indirect tensile strength, psi; and
A, D, E, F, H = factors considered for prediction (Table 1).

The multiple correlation coefficient for the predictive equation was 0.94, and the standard error of estimate was ±4.03 psi.

The regression equation utilizes the uncoded factor levels given in Table 1. The coded levels, i.e., -2, -1, 0, +1, and +2, should not be used in the calculation of estimated indirect tensile strengths. Because this regression is based on the uncoded levels, the equation is valid only for predictive purposes and cannot be interpreted term by term. It should also be noted that the predictive capabilities of the regression are valid only for the conditions of this study and the factors and levels included in the study. The use of any levels outside of this factor space is not recommended and caution is required for intermediate levels within the experiments.

Correlation Analysis

The ultimate objective of the correlation analysis was the development of relationships with which to estimate indirect tensile strengths of lime-treated materials when the unconfined compressive strengths or cohesiometer values are known.

General Correlation—Plots of indirect tensile strengths versus unconfined compressive strengths and cohesiometer values are shown in Figures 3 and 4 respectively. A regression analysis was run on the data, and the following equations were obtained:

$$\hat{S}_t = 16.46 + 36.7q_u \quad (2)$$

for which the multiple correlation coefficient was 0.89 and the standard error of estimate was ±5.9 psi;

$$\hat{S}_t = 7.46 + 2.19\ (C/100) \quad (3)$$

for which the multiple correlation coefficient was 0.93 and the standard error of estimate was ±4.8 psi; and

$$\hat{S}_t = 9.27 + 14.8q_u + 1.46\ (C/100) \quad (4)$$

for which the multiple correlation coefficient was 0.94 and the standard error of estimate was ±4.4 psi,

where

$\hat{S}_t$ = predicted value of indirect tensile strength, psi;
q_u = measured value of unconfined compressive strength, ksi; and
C = measured cohesiometer value, in grams/in. of width corrected to a 3-in. height.

Texas Highway Department Correlation—Plots of indirect tensile strengths versus unconfined compressive strengths and cohesiometer values are shown in Figures 5 and 6 respectively. A regression analysis was conducted, and the following prediction equations were obtained:

$$\hat{S}_t = -1.43 + 96.5q_u \quad (5)$$

for which the multiple correlation coefficient was 0.85 and the standard error of estimate was ±2.4 psi;

$$\hat{S}_t = 1.52 + 4.59\ (C/100) \quad (6)$$

for which the multiple correlation coefficient was 0.75 and the standard error of estimate was ±3.0 psi; and

$$\hat{S}_t = -1.68 + 74.4q_u + 1.6\ (C/100) \quad (7)$$

for which the multiple correlation coefficient was 0.87 and the standard error of estimate was ±2.3 psi,

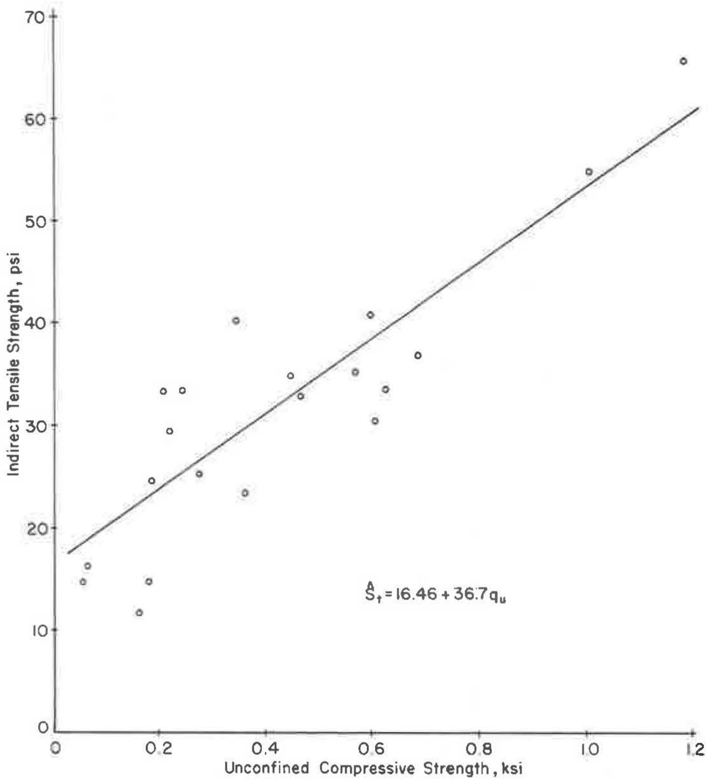

Figure 3. **Relationship of indirect tensile strength and unconfined compressive strength for general correlation.**

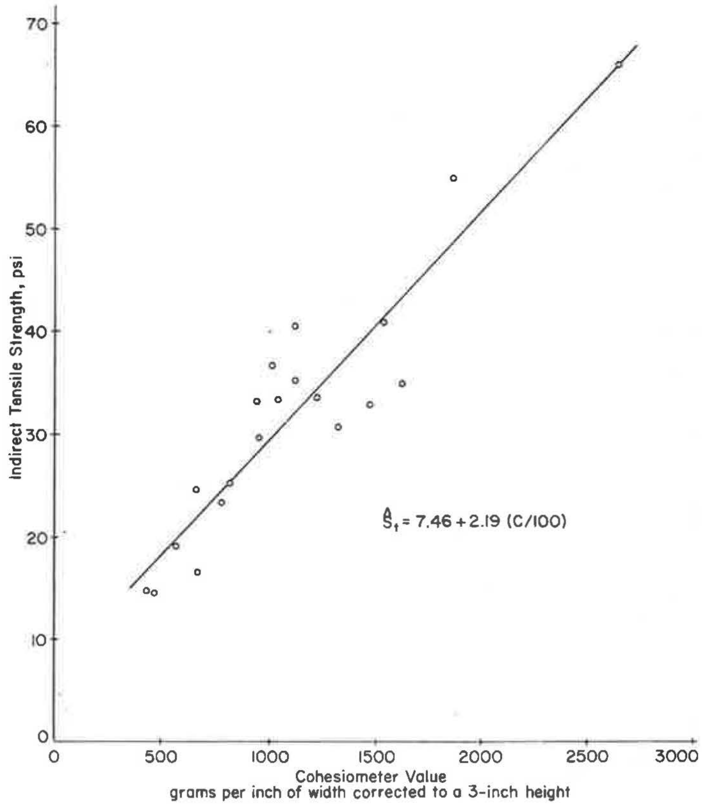

Figure 4. **Relationship of indirect tensile strength and cohesiometer value for general correlation.**

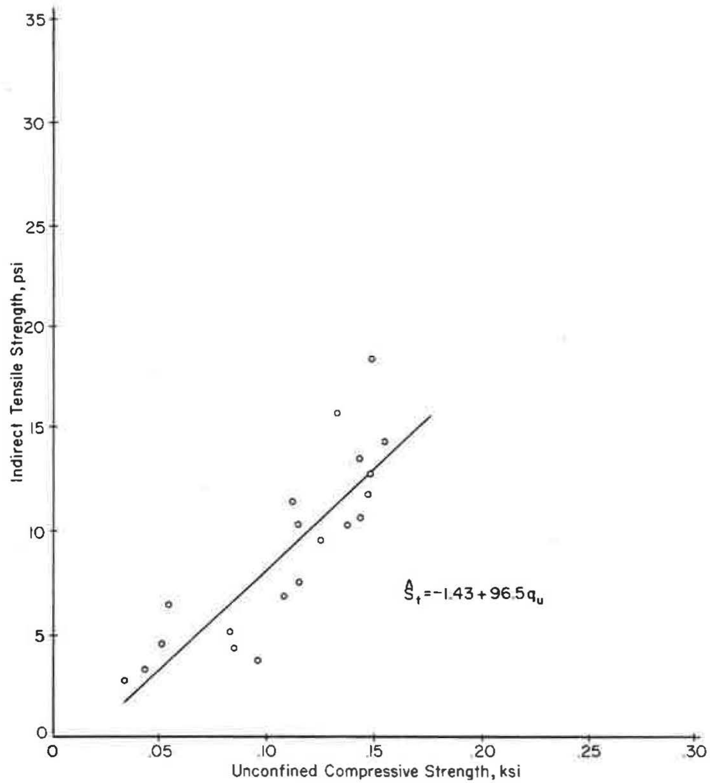

Figure 5. Relationship of indirect tensile strength and unconfined compressive strength for Texas Highway Department correlation.

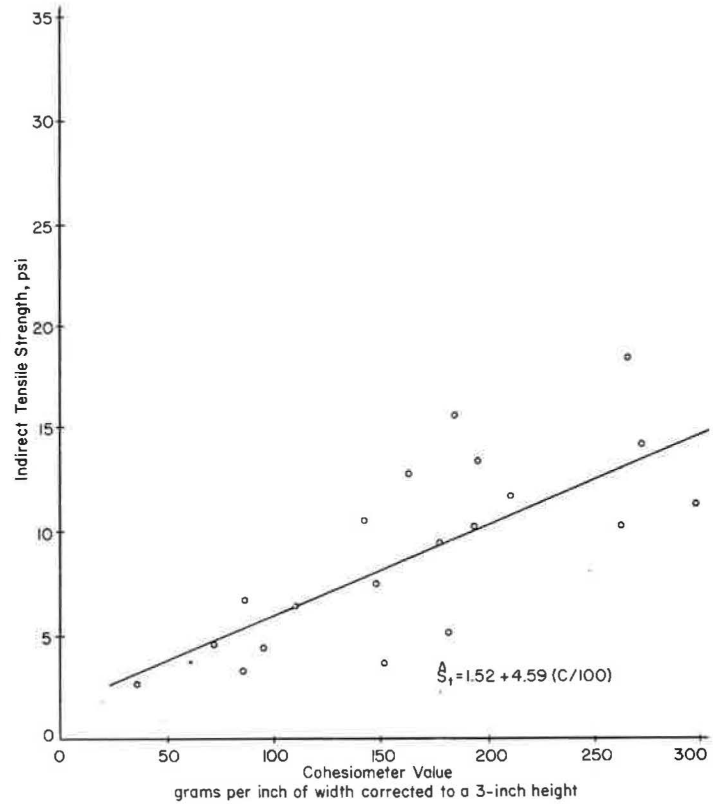

Figure 6. Relationship of indirect tensile strength and cohesiometer value for Texas Highway Department correlation.

where

$\hat{S}_t$ = predicted value of indirect tensile strength, psi;
q_u = measured value of unconfined compressive strength, ksi; and
C = measured cohesiometer value, in grams/in. of width corrected to a 3-in. height.

Combined Correlation—The strengths of the specimens tested for the Texas Highway Department correlation were generally less than the strengths of those tested for the general correlation. The Texas Highway Department correlation specimens were cured in capillarity for 10 days prior to testing, which probably accounts for their lower strengths. Because the ranges of strength of the 2 correlations were quite different, the data from the experiments were combined to check for a relationship between indirect test results of the unconfined compression test and the cohesiometer test over the entire range of strengths. Figures 7 and 8 show the combined data. A regression analysis was run on these combined data, and the following prediction equations were obtained:

$$\hat{S}_t = 6.89 + 50.6q_u \quad (8)$$

for which the multiple correlation coefficient was 0.91 and the standard error of estimate was ±6.4 psi;

$$\hat{S}_t = 5.52 + 2.33\ (C/100) \quad (9)$$

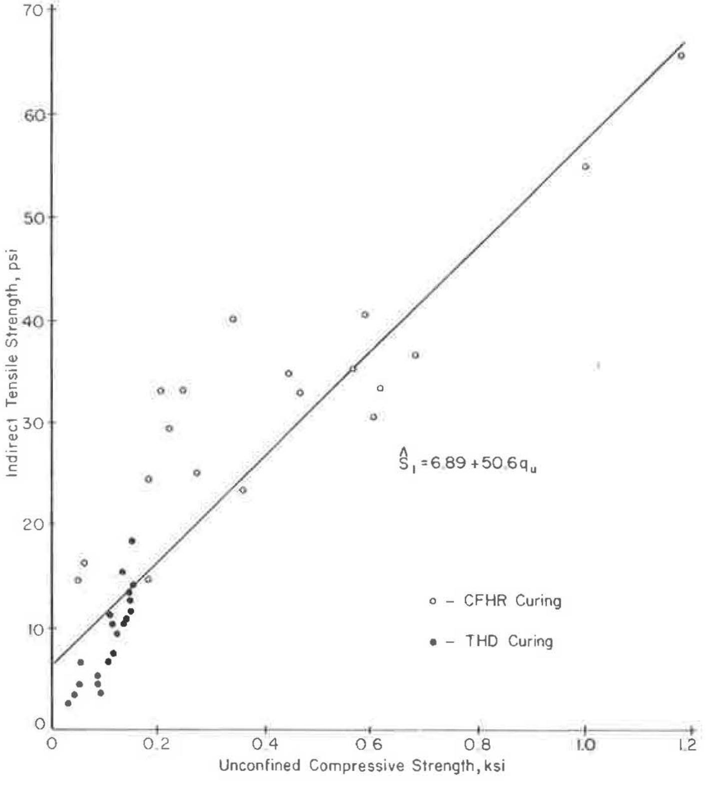

Figure 7. Relationship of indirect tensile strength and unconfined compressive strength for combined correlation data.

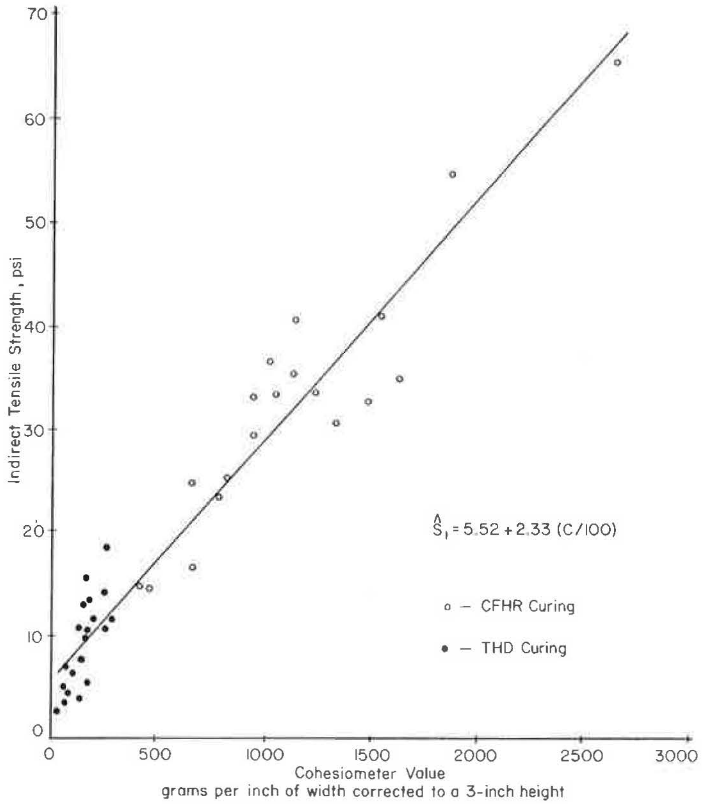

Figure 8. Relationship of indirect tensile strength and cohesiometer value for combined correlation data.

for which the multiple correlation coefficient was 0.96 and the standard error of estimate was ±4.1 psi; and

$$\hat{S}_t = 3.61 + 16.5q_u + 2.3\ (C/100) - 0.03\ (C/100)^2 \qquad (10)$$

for which the multiple correlation coefficient was 0.97 and the standard error of estimate was ±3.7 psi,

where

$\hat{S}_t$ = predicted value of indirect tensile strength, psi;
q_u = measured value of unconfined compressive strength, ksi; and
C = measured cohesiometer value, in grams/in. of width corrected to a 3-in. height.

DISCUSSION OF RESULTS

A summary of the correlation studies is given in Table 4. Whenever an experiment is designed for studying the possible correlation between 2 materials tests, criteria are required for judging the acceptability of the results from both a statistical and engineering viewpoint.

The first test used to determine whether there were correlations was based on the multiple correlation coefficients. A minimum value for R^2 of 0.25 was selected. At

TABLE 4

CORRELATION SUMMARY

Correlation Variables	Multiple Correlation Coefficient	Does Correlation Exist?	Standard Error of Estimate (psi)	Coefficient of Variation	Is Correlation Acceptable?
Tensile strength versus unconfined compressive strength					
General	0.89	Yes	±5.9	0.18	Yes
Texas Highway Department	0.85	Yes	±2.4	0.26	Yes
Combined	0.91	Yes	±6.4	0.31	Yes
Tensile strength versus cohesiometer					
General	0.93	Yes	±4.8	0.15	Yes
Texas Highway Department	0.75	Yes	±3.0	0.33	Yes
Combined	0.96	Yes	±4.1	0.20	Yes
Tensile strength versus cohesiometer and unconfined compressive strength					
General	0.94	Yes	±4.4	0.14	Yes
Texas Highway Department	0.87	Yes	±2.3	0.25	Yes
Combined	0.97	Yes	±3.7	0.18	Yes

this level, as outlined in Snedecor and Cochran (6), the correlation coefficient R for all the correlations presented is significant at a probability level of 95 percent. In fact, they are all significant at the 99 percent probability level, and it is believed with confidence, therefore, that all the correlations presented do exist.

The second test used to determine the acceptability of the correlation data considered the standard error of estimate. A large standard error is unacceptable because the tensile strengths of lime-treated materials are relatively low, but the decision as to whether the standard error is too large must be left to the judgment of the user. The largest standard error obtained for the various correlations was ±6.4 psi, which was considered to be within tolerable limits because the indirect tensile test for the lime-treated materials used in the experiments had a standard error of ±3.05 psi for duplicated specimens (4).

It is interesting to note (Figs. 7 and 8) that the restrictions of the Texas Highway Department procedures provided results that were confined to a specific range, an outcome which might result from any test procedure that severely restricts the manner in which the material can be varied. Most materials tests attempt to reproduce the most severe conditions under which the materials will have to perform satisfactorily in the field in order to provide conservative results. However, doing so may require procedures that result in an inference space so narrow that results are completely unrealistic. This indicates that materials testing concepts, practices, and theories must be changed if maximum information is to be obtained for design purposes.

SUMMARY AND CONCLUSIONS

This paper presents a predictive equation that, for the factors and levels of factors investigated, predicts indirect tensile strength reasonably well for the conditions of this experiment. In addition, correlations relating indirect tensile strength with both cohesiometer and unconfined compressive test results were developed and evaluated. It was shown that correlations exist for these tests and that tensile strengths may be estimated from cohesiometer and unconfined compressive strength data within some given level of error.

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REFERENCES

1. 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.
2. Kennedy, T. W., and Hudson, W. R. Application of the Indirect Tensile Test to Stabilized Materials. Highway Research Record 235, 1968, pp. 36-48.
3. Miller, S. P., Kennedy, T. W., and Hudson, W. R. 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.
4. 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.
5. Manual of Testing Procedures. Texas Highway Department, Vol. 1.
6. Snedecor, G. W., and Cochran, W. G. Statistical Methods. Iowa State Univ. Press, Ames, 1968.