DIRECT-TENSILE STRESS AND STRAIN OF A CEMENT-STABILIZED SOIL

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A direct-tension test that permits determination of stress and strain is described. An equation for prediction of direct-tensile strength of a cement-stabilized silty soil compacted at standard AASHO optimum moisture content and cured at 70 F in a moist room is given as a function of cement content and curing time. Relations among the direct-tensile strength, unconfined compressive strength, and split-tensile strength for the conditions studied are established. Results show that the strain at failure in compression and tension respectively remains constant as long as dry density, molding moisture content, and curing conditions are the same. The cement-stabilized soil possesses different moduli in tension and compression; the modular ratio is proportional to the strength ratio. Both strength and strain at failure vary significantly with curing temperature; decreasing curing temperature decreases the strength but increases the strain at failure.

•BECAUSE of its inherent appreciable tensile strength, cement-stabilized soil has demonstrated itself as one of the most favorable materials for pavement construction. Development of a rational approach to the design of pavement requires establishment of both strength and failure strain criteria in tension and in compression so that stresses and strains developed in the pavement can be limited within a permissible range.

The importance of the property of stabilized soils under tension has provoked considerable study for years. Most studies (1, 2, 3, 4, 5), however, concentrate on the property of tensile strength determined by using the split-tension test; information on the deformation modulus and failure strain in tension is scarce.

A testing method that permits determination of both tensile stress and strain was developed. The developed testing method was used to study the stress-strain behavior of a cement-stabilized soil under uniaxial tension. This paper describes the test method and test results obtained to date.

TEST METHOD

Providence silt, a common glacial deposit in Rhode Island, was used for study. Classification test results of Providence silt are as follows:

Property	Value
Specific gravity	2.75
Atterberg limits, percent	
Liquid limit	28
Plastic limit	24
Plasticity index	4
Grain size, percent	
0.02 to 2.0 mm	9
0.002 to 0.02 mm	54
Finer than 0.002 mm	37
Classification	
Unified soil system	ML
AASHO system	A-4(8)

The test soil was treated with Type 1 portland cement. Tap water was used for mixing throughout.

The test samples were prepared at an optimum moisture content and a maximum dry density (14.5 percent and 106.5 lb/ft^3 respectively) determined prior to treatment by using the standard AASHO compaction effort. The test specimens were $1\frac{3}{4}$ in. wide over the central section and 3 in. wide at the ends with a thickness of approximately $1\frac{3}{4}$ in. (This thickness was chosen to make a square cross section at central portion of the test specimen.) The overall height of the test specimen was 7 in., including one 2-in. midsection, two 1-in. butted ends, and two $1\frac{1}{2}$-in. transition sections connecting the central portion and both ends. Detailed dimension is shown in Figure 1.

The necked-down test specimens were molded in 3 equal layers by using the static compaction method. Each end of the specimen was reinforced in each layer with a steel reinforcement to ensure a rupture at the central portion. The reinforcement was $\frac{1}{16}$ in. in diameter and was fabricated to a shape shown in Figure 1. The tip of the reinforcement was 2 in. off midpoint of the test specimen.

The test specimens were clamped on 2 acrylic jaws. The jaws are dimensioned to fit snugly to the ends of the test specimens. The test specimens could, therefore, slide into position very easily. The jaws were connected to the testing machine by using a spherical contact at each joint to provide a better alignment during loading.

Tests were conducted by using a Wykeham Farrance strain rate control machine. A strain rate of 0.050 in./min was used throughout the test. A diaphragm type of load cell was used for determination of applied load, and a pair of linear variable differential transformers (LVDT) was used for measurement of deformation over the central section of the test specimens. Both load and deformation were monitored by using an electronic recorder.

TEST RESULTS AND DISCUSSION

The mode of failure in tension is typical of brittle fracture, although appreciable strains develop before failure occurs (Fig. 2). The rupture plane, in general, is nearly perpendicular to the direction of loading. Figure 2 shows the typical stress-strain relationship in both tension and compression for the test soil treated with 3 percent cement and cured at approximately 70 F in a moist room.

Figure 2 also shows the difference in stress-strain behavior between tension and compression. The test specimens failed at considerably greater stress and strain in compression than in tension; however, the modulus of deformation was considerably higher in tension than in compression. Both tensile and compressive strengths increased significantly with increasing curing time and cement content of the test specimens. The test results accumulated to date suggest that the tensile strength of cement-treated Providence silt compacted and cured at the conditions mentioned can be predicted reasonably well by using the following expression:

$$\sigma = \left\{(1/2) + \left[60\,c^{4/3}/\left(32 + c^{4/3}\right)\right]\right\}\left\{1 + \left[2\,\log^{8/3} t/\left(2 + \log^{8/3} t\right)\right]\right\} \tag{1}$$

where

σ = direct tensile strength, psi,
c = cement content by weight of solid, percent, and
t = curing time, days.

A correlation between the direct-tensile strength and the unconfined compressive strength of the test soil is shown in Figure 3. The unconfined compressive strength was determined from 1.4-in. diameter specimens. The tensile-to-compressive strength ratio varies approximately from 10 to 20 percent increasing with an increase in the compressive strength for the conditions studied.

Tensile strength of the test soil was also determined by using the split-tension test. The split-tension test specimens had a diameter of 3 in. and a height of 2 in. and were tested at a rate of loading equal to that of the direct-tension test. Figure 4 shows a comparison between direct- and split-tensile strengths. The direct-tensile strength is approximately 15 percent higher than the split-tensile strength.

Figure 1. Test setup.

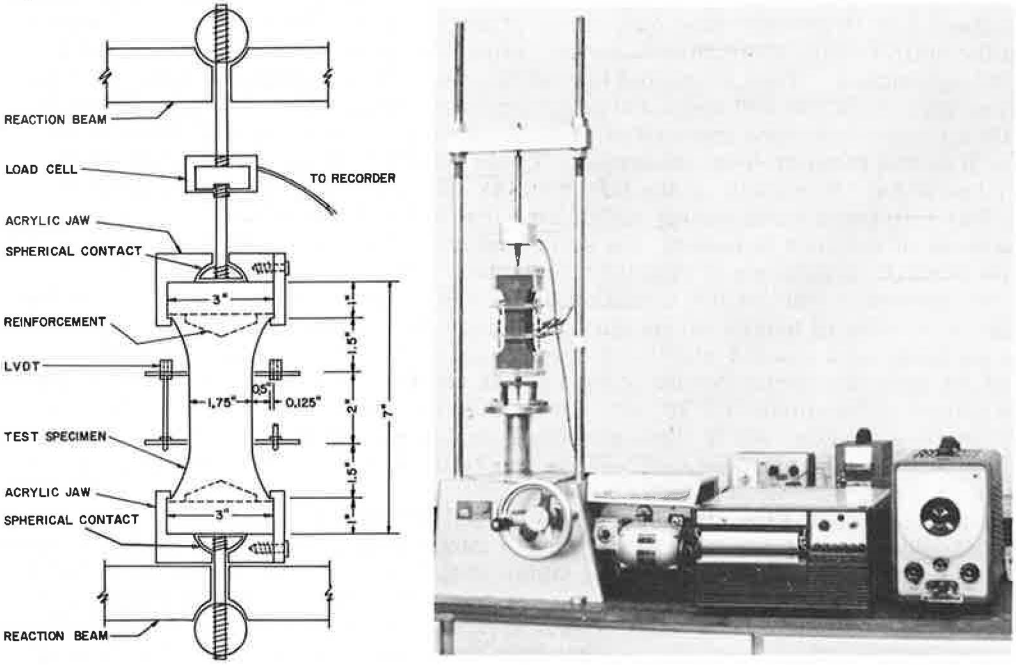


Figure 2. Stress-strain relation of 3 percent cement-treated Providence silt.

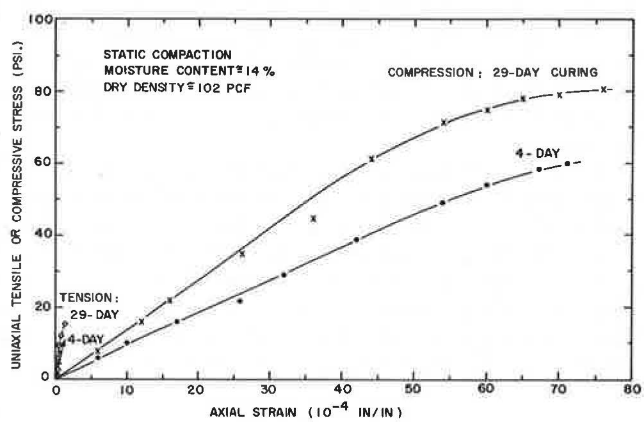
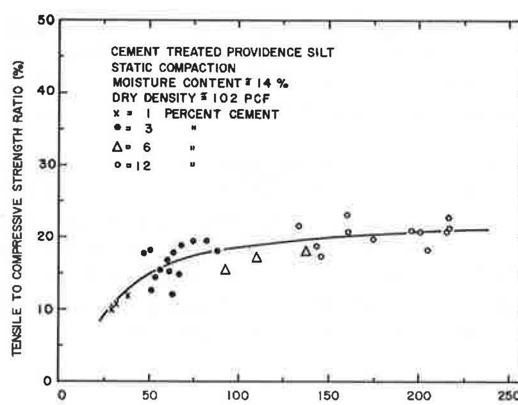


Figure 3. Relation of direct-tensile strength and unconfined compressive strength.



The ratio of split-tensile to unconfined compressive strength (Figs. 3 and 4) ranges from about 9 to 18 percent depending on the strength level. Kennedy et al. (5) correlated the split-tensile strength with the unconfined compressive strength of cement-treated aggregates. They suggested that within the range of conditions studied, viz., between approximately 500 and 2,000 psi unconfined compressive strength, the split-tensile strength increased from about 14 to 16 percent of the unconfined compressive strength as the strength level increased. These results are reasonably close to the upper boundary, 18 percent, of the test results. The materials studied by Kennedy et al. had a strength considerably higher than that of the material used in this study.

Because of the ease in testing, the split-tension test is often used for evaluating the tensile strength properties of stabilized materials. However, the split-tension test does not provide a test-loading condition to resemble that in the field, nor does it permit determination of tensile strain during loading. In addition, Adepegba (6) concluded, from his study on a cement-stabilized laterite and a cement-stabilized sand, that the stabilized soils can easily deform at load points and that such deformations are usually large enough to invalidate $\sigma = 2P/\pi dt$, the formula normally used for calculating the split-tensile strength. All of these constitute disadvantages and, therefore, restrict the application of the split-tension test for determination of tensile-strength property of stabilized soils.

Figure 5 shows that the strain at failure ranged between 0.9 and 1.5×10^{-4} in./in. in tension and between 60 and 90×10^{-4} in./in. in compression. Cement content and curing time had essentially no influence on the strain at failure. The tensile strain at failure is approximately 1.0 to 2.5 percent of compressive strain for all cement contents and all curing times studied. The compressive strain at failure for cement-treated silty clay, reported by Wang et al. (7), ranged from 80 to 100×10^{-4} in./in. regardless of change in cement content (from 3 to 6 percent), curing age, and effect of repeated loading and a 1.3-hour delay in compaction. They also reported that the flexural strain at failure for the same material ranged between 3 and 5×10^{-4} in./in. independent of the factors studied. The compressive strain at failure coincides surprisingly well. It appears that the strain at failure in tension and compression respectively remains constant as long as the dry density, molding moisture content, and curing conditions are the same.

Although the strain at failure remains constant with respect to the curing time and cement content, the increase in strength with increasing curing time and cement content would cause an increase in the initial tangent modulus of deformation. Figure 6 shows the variation of initial tangent modulus with the strength in both tension and compression. The test results suggest that the modulus is directly proportional to the strength with a proportional factor approximately 12,000 and 185 respectively for tension and compression. Based on these 2 factors, the modular ratio can be expressed in terms of the strength ratio as follows:

$$\frac{\text{tensile modulus}}{\text{compressive modulus}} \cong 65 \times \frac{\text{direct-tensile strength}}{\text{unconfined compressive strength}} \qquad (2)$$

where the strength ratio is a function of strength level as shown in Figure 3.

The modulus of deformation is one of the basic factors required in pavement stress and strain analysis. Figures 3 and 6 provide data sufficient for evaluation of both tensile and compressive moduli from the unconfined compressive strength for the soil studied.

Equation 2 indicates that the cement-stabilized soil possesses different moduli in tension and compression, except when the tensile strength equals approximately 1.5 percent of the compressive strength. According to data shown in Figure 4, the strength ratio varies from 10 to 20 percent and, therefore, the tensile modulus ranges between 650 and 1,300 percent of the compressive modulus. It would appear, therefore, necessary to treat the cement-stabilized soil as a material with moduli that are different in tension and compression in the analysis of stress and strain in cement-stabilized soil pavements.

Figure 4. Relation of direct-tensile strength and split-tensile strength.

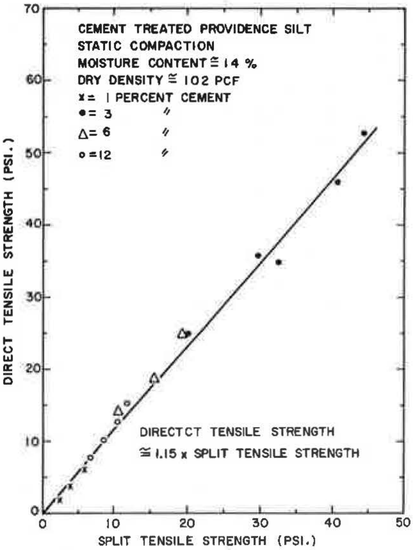


Figure 5. Strain at failure as a function of curing time.

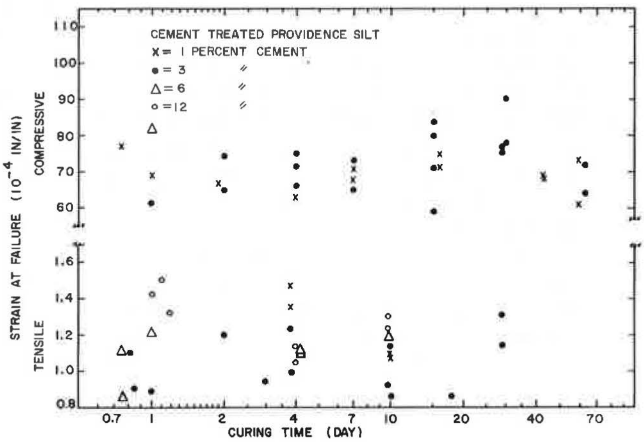


Figure 6. Initial tangent modulus as a function of strength in both tension and compression.

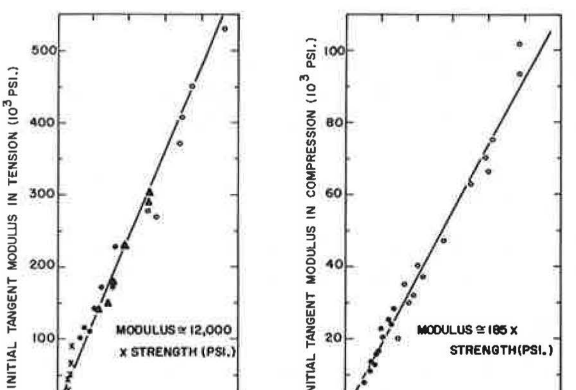
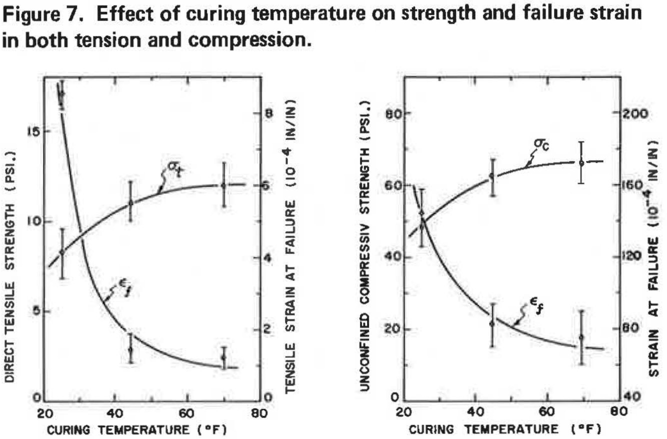


Figure 7. Effect of curing temperature on strength and failure strain in both tension and compression.



All preceding test results were established for the test specimens wrapped and cured at approximately 70 F in a moist room. The influence of curing temperature on the tensile strength property was studied by wrapping the soil specimens compacted to identical conditions and curing them at temperatures of 25 and 45 F. The test results (Fig. 7) indicate that decreasing curing temperature decreases the strength but increases the strain at failure probably because of the retardation of cement hydration at low temperature. The same effect of curing temperature on the compressive and tensile strength of lime-treated material was obtained respectively by Ruff and Ho (8) and Moore et al. (4).

Test results would imply that, if a representative field-strength property of cement-stabilized soils is obtained, the test specimens used in the laboratory study should be cured at the same temperature as that which occurs in the field. Furthermore, selection of strength and failure strain criteria for a design of cement-stabilized soil pavements requires consideration of the effect of ambient temperature.

SUMMARY AND CONCLUSIONS

A testing method that permits determination of both stress and strain during the course of uniaxial tension was described. A study of the direct-tensile stress and strain behavior of cement-stabilized Providence silt leads to the following conclusions:

1. The mode of failure in tension is typical of brittle fracture although appreciable strains develop before failure;
2. Both strength and failure strain in tension are considerably smaller than those in compression (for the conditions outlined, the direct-tensile strength of the test soil ranges approximately from 10 to 20 percent of the unconfined compressive strength, and the failure strain in tension ranges between 1.0 and 2.5 percent of that in compression for all cement contents and curing times studied);
3. The cement-stabilized soil possesses different moduli in tension and in compression, and the modular ratio is directly proportional to the strength ratio; and
4. Decreasing curing temperature decreases the strength but increases the failure strain in both tension and compression.

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