CHANGES IN SOIL SUCTION IN A SAND-CLAY SUBJECTED TO REPEATED TRIAXIAL LOADING

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This paper reports a laboratory investigation that examined whether soil suction values were dependent on the stress history experienced by a soil. Specifically, the effects of repeated triaxial compressive loading on the soil suctions of a kaolinite-sand mixture were studied. The variables examined included the effects of the initial and final dry densities and degrees of saturation and the magnitudes and numbers of the repetitively applied stresses. Both the matrix suctions and the suction-moisture content relations were studied. It was found that the suction values depended primarily on the degrees of saturation but were also slightly influenced by the dry densities. In most cases the effects of repeated loading were to reduce the soil suction corresponding to any given combination of density and saturation; the reduction was greatest at the highest saturations studied. An increase in the number of load applications also tended to reduce the matrix suctions. The work demonstrates the need to consider stress history effects in future investigations of soil suction.

•IT HAS long been recognized that the in-service performance of a pavement is controlled not merely by traffic loadings and initial properties of the pavement materials at placement but also by changes in the subgrade and pavement environments. In many regions of the world, including much of inland Australia and the arid areas of the United States, pavements function in conditions in which the subgrade and base course materials seldom, if ever, become fully saturated. Under those conditions, the effects of the soil environment can, for most practical purposes, be examined in terms of a single fundamental soil property: soil suction.

Many engineering properties of soils including the consistency limits (1, 2, 3), the undrained compressive and vane shear strengths (4, 5, 6), and the CBR's (5, 7, 26) can be related to the corresponding soil suctions. Moreover, limited evidence suggests that the stiffness of soils subjected to both single and repeated stress applications may be related to their suction values (4, 8, 9). Thus, it has been reported that the logarithm of the resilient moduli of repetitively stressed soils increases linearly with increase in the logarithm of their initial suctions (8, 9, 10). In addition, the rate at which residual strains accumulate has been shown to decrease as the initial soil suctions increase (9).

Because of the close interrelation of soil suction with other material characteristics, the observation of suction provides a convenient means of relating the engineering properties of pavement materials to their environment. Consequently, the study of soil suction is assuming an ever-increasing importance in the design of pavements for arid areas (8), the selection of placement conditions for base course materials on expansive subgrades (8, 10, 11), and the prediction of pavement performance (8, 9, 10).

To date most reported investigations of soil suction in pavement materials have ignored the possible influence of stress histories, similar to those experienced in actual pavements, in modifying the suction characteristics. Yet, it has been demonstrated (12) that the action of repetitive stressing on a soil produces complex changes in the soil structure and that the changes manifest themselves as marked alterations in

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properties such as stiffness and strength. It is, therefore, reasonable to expect that the suction values measured in a pavement might be modified from their placement values as a result of repeated traffic loadings.

The purpose of the work reported in this paper was to experimentally investigate the influence of repeated triaxial loading on the suction characteristics of a soil exhibiting both internal friction and cohesion. The investigation supplemented previously reported studies of stress-strain and energy dissipation under repeated loading (13, 14, 15, 16).

TEST METHODS

Soil and Specimen Characteristics

Most reported studies of repetitively stressed soils have been restricted to materials in which either the frictional or the cohesive component of shear strength has dominated the soil response. However, in the work reported here, a soil was selected that combined both frictional and cohesive components of shear strength in roughly equal proportions. A uniform sand from Botany, New South Wales, and a commercial air-floated china clay were chosen as the basic materials.

Although there is evidence that, for a given suction, the type of clay minerals present in a soil has little influence on the shear strength (6), the mineralogy of the clay phase nevertheless significantly affects many other engineering properties. The clay phase of the experimental soil was found, by X-ray diffraction and thermal balance analyses, to be a pure kaolinite with slight traces of quartz (less than 5 percent). The kaolinite contained more than 85 percent of particles smaller than 2 μm. Although it was recognized that soils containing kaolinite behave differently from soils containing other clay minerals, the effects of clay mineralogy and physicochemical properties on the soil response could not be studied because the investigation was restricted to just one particular soil.

The work of Paduana (17) on sand-clay mixtures has indicated that, for clay contents between 30 and 50 percent, the relative contributions of the clay and sand fractions to the strength vary approximately with their respective proportions. Based on those findings, a mix showing a slight preponderance of frictional characteristics and composed of 60 percent sand and 40 percent clay, by weight, was selected for the experimental work. The properties of the soil are as follows:

Property	Amount
Liquid limit, percent	26.0
Plastic limit, percent	17.6
Shrinkage limit, percent	14.9
Dry density, lb/ft^3	
Max standard AASHO	112.0
Max modified AASHO	119.5
Optimum saturation, percent	86.5

Specimens of the soil, 4 in. in diameter and 4 in. high, were prepared to designated values of dry density and degree of saturation by the use of floating-mold compaction, a variant of static compaction giving specimens of exceptional uniformity (18). After compaction, each specimen was cured for 3 days at 20 C.

Repeated Load Tests

After being cured, the specimens were subjected to a variety of repeated loads by the use of special equipment described in detail earlier (19). The tests comprised unconsolidated undrained triaxial compression tests with as many as 10,000 repetitions of stress applied in such a manner that the confining stress σ_3 both increased and decreased in phase and in fixed proportion with the axial stress σ_1. This meant that the principal stress ratio σ_1/σ_3 remained constant at all times and that, consequently, the stress paths experienced by the specimens were similar (although not identical) to those observed in pavements under traffic loadings. The frequency of loading was 2 cpm, and the tests ran for as many as 84 hours, corresponding to 10,000 stress applications. The test temperature was maintained at 20 C.

Measurement of Soil Suction

At the conclusion of each repeated loading test, the soil specimens were broken down by hand into small pieces, each weighing about 10 grams. Representative samples, obtained by a quartering procedure, were used for the determinations of soil suction.

The various techniques for determining soil suctions in the laboratory have been described and critically evaluated elsewhere (1, 20, 21). Only one of those techniques was available to the author: the use of a pressure membrane apparatus of the type developed at the Road Research Laboratory (22). That method is usually considered to be of only moderate accuracy (21) but has the advantage of being relatively simple. That type of equipment is customarily used with null-point method of suction determination (20, 23). That involves the observation of the changes in specimen weight that accompany alterations in the applied air pressures. It then becomes possible to interpolate the pressure and, hence, the soil suction at which water neither enters nor leaves the soil. That procedure largely obviates errors arising from shrinkage and swelling.

In the work reported here it was desired to supplement measurements of the matrix suctions existing at the conclusion of the repeated load tests by observations of the suction-moisture content relations. That precluded the use of a null-point technique. The procedure adopted in the experimental work was, therefore, to first air-dry the soil at 20 C for several days and to subsequently remove the remaining moisture by drying at 45 C under a vacuum of 74 cm of mercury. The relations between suction and moisture content were then defined by measuring the moisture contents corresponding to 8 values of suction, usually ranging between -8 and -60 lb/in^2. Values of the matrix suction corresponding to particular values of moisture content could be interpolated from those relations. Thus, all the suction observations lay on the wetting branches of the suction-moisture content hysteresis loops.

For some soils, such as heavy clays, the effect of drying and rewetting the material may be to alter the suction-moisture content relations (5). Thus, the procedures adopted in the work described here carried the risk that they might result in appreciable disturbance of the soil structure. It was, therefore, decided to examine whether drying and rewetting the experimental soil would significantly change the suction values corresponding to various moisture contents. That was accomplished by compacting a number of specimens to a dry density of 115.8 lb/ft^3 at molding saturations ranging between 75 and 95 percent. The moisture contents corresponding to specified suctions ranging between -8 and -60 lb/in^2. were then determined for the moist samples. Those suction-moisture content determinations were then repeated after the soil was dried by the procedures detailed above.

The results of this experiment are shown in Figure 1. In general, drying and then rewetting the soil did not significantly alter the moisture contents corresponding to various designated values of suction. It was, therefore, concluded that the experimental procedures did not lead to a significant disturbance in the suctions of the sand-clay soil selected for study.

Control Specimens

Any changes in suction that might result from repeated loading were detected by comparisons of the suction values observed for the repetitively stressed specimens and the values obtained from unstressed duplicate control specimens. The duplicates were compacted, cured, and tested under the same conditions and at the same age as the specimens subjected to repetitive loading.

EXPERIMENTAL WORK

The experimental work comprised 3 interrelated investigations:

1. An examination of the effects of changes in the initial dry density and degree of saturation;
2. An investigation of the effects of load repetition; and
3. A study of the effects of stress history.

Effects of Density and Saturation

The investigation of the effects of initial dry density and degree of saturation on the changes in suction that occurred under the action of repeated loading involved a simple fully randomized, factorial experiment without replication. Two factors, dry density and saturation, were each examined at 3 levels: 112, 115.8, and 119.5 lb/ft^3 (i.e., ranging between standard and maximum modified AASHO densities) for dry density and 75, 80, and 95 percent for saturation. Test specimens were manufactured for all 9 combinations of dry density and degree of saturation. These were supplemented by an additional specimen compacted at a dry density of 115.8 lb/ft^3 and a saturation of 86.5 percent, roughly lying on the "line of optimums." The specimens were then each subjected to 10,000 repetitions of octahedral shear stress τ_{oct} of 5.66 lb/in.^{2} at an octahedral stress ratio τ_{oct}/σ_{oct} of 0.82.

For each of the 10 combinations of density and saturation examined, the suction bore the following relation to the moisture content:

$$h_m = a - b \log_e w \qquad (1)$$

where

h_m = matrix suction, pF;
w = moisture content, percent; and
a and b = empirical constants.

That relation applied equally well to both the repetitively stressed samples and their unstressed duplicates. The empirical constants a and b were evaluated by regression analyses. Values of the correlation coefficient r ranged between 0.78 and 0.98.

Values of the suction parameters a and b, measured after compaction but before the application of any stress history, are shown as functions of the initial (molding) degrees of saturation and the compacted dry densities in Figure 2. By contrast, Figure 3 shows the changes in the suctions and the suction-moisture content relations that resulted from repetitive loading. In general, the effects of repeated loading were to reduce the matrix suctions, and that effect became more pronounced as the molding saturations were increased.

The work of Baver (24) and Russell and Mickle (2) has demonstrated that, in general, soil suction-moisture content relations plot as curves divided into 3 distinct regions by flex points at moisture contents corresponding to the plastic and liquid limits. In the work reported here, the molding moisture contents studied were all dry of the plastic limit. Thus, although the form of Eq. 1 is identical to that reported earlier by Livneh et al. (1), extrapolation of that relation beyond the domain of the experimental observations (or beyond the plastic limit) would not be valid. Consequently, Eq. 1 should be regarded only as a convenient engineering approximation to just part of the true suction-moisture relation, and it would be unwise to attempt to assign any fundamental physical meanings to suction parameters a and b.

In practice, most subgrade and pavement materials are compacted dry of the plastic limit; therefore, it can be argued that simple relations of the form given in Eq. 1 may prove useful in predicting suction-moisture changes. However, such an approach fails to recognize that changes in suction (or moisture content) are usually accompanied by changes in the soil volume (10). Thus, ideally, Eq. 1 should be expanded to include the effects of changes in the voids ratio or dry density.

Adopting that approach, we established that the matrix suction was a function of both the degree of saturation and the dry density and that the suction, density, and saturation relation could be represented as a curved surface. The techniques of multiple linear regression were used to determine that, for the range of densities and saturations examined, the surface could be closely approximated by a plane. That is shown in Figure 4. The relation for the unstressed soil is shown as plane ABCD. The regression equation describing that plane is

$$h_m = 0.099\ \gamma_d - 0.044\ S_r - 4.49 \qquad (2)$$

where

h_m = matrix suction, pF;
γ_d = dry density, lb/ft^3; and
S_r = degree of saturation, percent.

After repeated loading, the suction, density, and saturation relation could be approximated by plane A'B'C'D'(Fig. 4), which had the equation

$$h_m = 0.135\ \gamma_d - 0.067\ S_r - 7.060 \qquad (3)$$

Figures 3 and 4 show that the effects of repeated loading on the matrix suctions became increasingly more pronounced as the molding saturations increased or as the initial dry densities decreased. However, for both the repetitively stressed specimens and the unstressed control specimens, the multiple regression analyses revealed that the degree of saturation S_r was statistically more significant than the dry density γ_d in controlling the matrix suctions. That is consistent with experimental data published earlier (11, 23, 25).

The multiple F values for Eqs. 2 and 3 were 223.7 and 86.97 respectively, with 2 and 7 degrees of freedom. Inspection of tables of critical F shows that, for P(F) = 0.005, there was no significant lack of fit between the regression equations and the experimental data. That does not, of course, imply that the models represented by Eqs. 2 and 3 were fundamentally correct or that they were necessarily the best fits to the experimental data. Nevertheless, the models provided useful predictions of the alterations in suction that resulted from changes in density or saturation as long as those changes did not fall outside the domain of the experimental observations.

Figure 4 shows that the effect of repetitive loading was to substantially alter the suction-density-saturation relation. Thus, a soil, whose initial condition can be represented by point p in plane ABCD, may, as the result of cyclic loading, adopt the state represented by point p″ in plane A'B'C'D'. However, changes in suction need not be accompanied by changes in either density or saturation; i.e., the suction may change along path pq (Fig. 4). That suggests that the observed changes in matrix suction probably arose from alterations in the soil structure caused by repeated loading.

A study of the relations between strength and suction provided further evidence of changes in soil structure. For the control samples, which were not subjected to repeated loading, compressive strengths C were determined to be linearly related to the suctions. That is shown in Figure 5. The regression equation was

$$C = 51.74\ h_m - 97.97 \qquad (4)$$

That relation appeared to be independent of both the density and the saturation. However, for specimens that had been subjected to 10,000 load cycles, it was found that the simple relation given in Eq. 4 was no longer valid. Although, as in the case of the unstressed specimens, increases in suction were accompanied by increases in strength, it was not possible to fit a single curve relating strength and suction to the data. Instead it was necessary to plot separate curves for each of the levels of dry density studied (Fig. 5). The suctions and compressive strengths were affected to quite different degrees by repeated loading; therefore, the mechanisms causing strength changes were probably different from those associated with alterations in the matrix suctions. The changes in strength that resulted from repetitive loading have been considered in greater detail elsewhere (12).

As noted earlier, some evidence suggests that the stiffness of repetitively stressed soils may be related to the soil suctions. It was, therefore, decided to investigate whether it would be possible to relate the strains caused by cyclic loading to the cor-

Figure 1. Comparison of suction measurements on moist and dried samples.

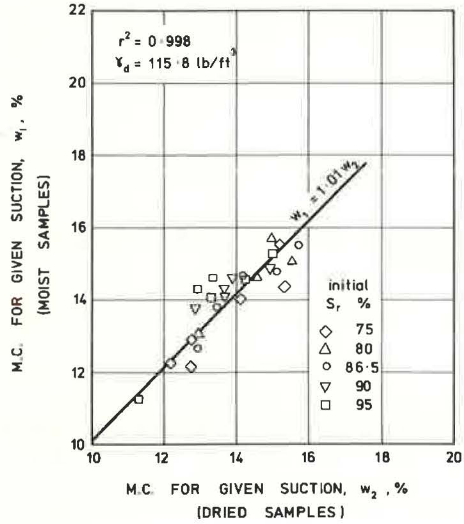


Figure 2. Suction parameters for unstressed control specimens.

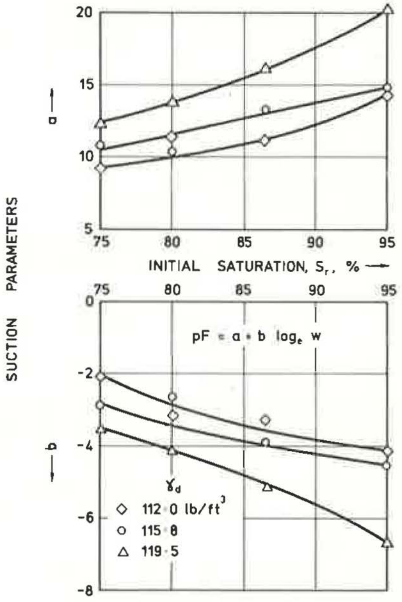


Figure 3. Changes in soil suction resulting from repetitive loading.

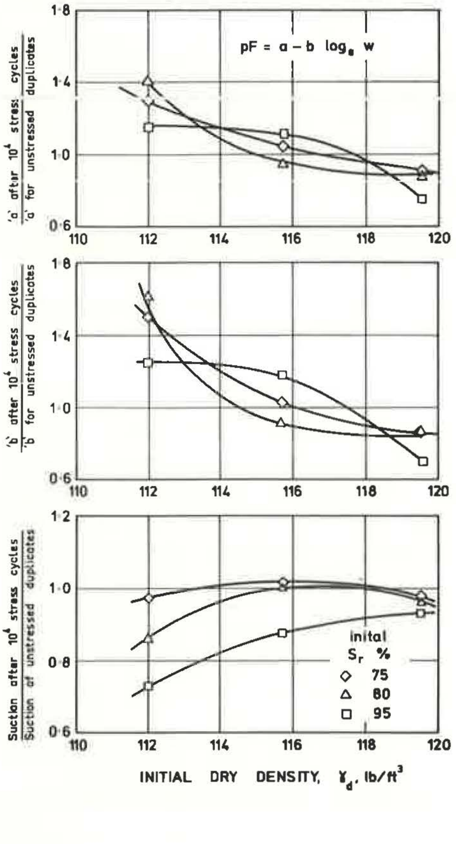
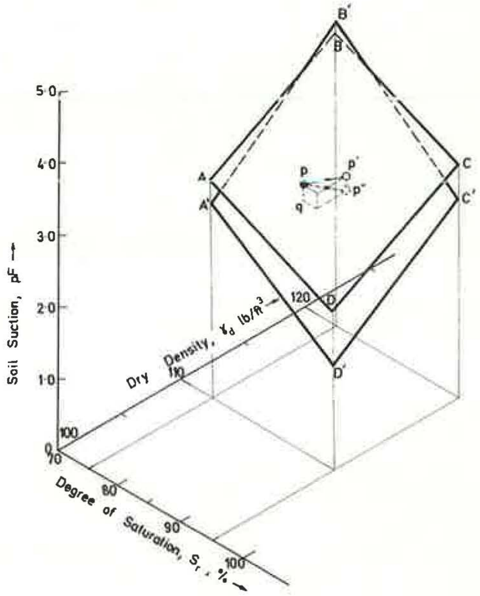


Figure 4. Regression models used to approximate the suction-saturation-density relations.



responding matrix suctions. Two axial strain components were examined: resilient strain ϵ_r and cumulative nonrecoverable (plastic) strain ϵ_f.

The relations between resilient axial strains ϵ_r and suctions are shown in Figure 6 for the first and last load cycles. As shown in the figure, it was established that the relations between the resilient strains and the suctions were dependent on the molding saturations and the initial dry densities. The techniques of multiple regression were used to determine the following arbitrary relations among ϵ_r, the suctions, and the degrees of saturation.

For N = 1,

$$\epsilon_r = -75\ h_m - 19.94\ S_r + 4{,}714 \text{ (microstrain)} \qquad (5)$$

and F = 3.02 with 2 and 6 degrees of freedom; and for $N = 10^4$,

$$\epsilon_r = -778.3\ h_m - 40.8\ S_r + 6{,}649 \text{ (microstrain)} \qquad (6)$$

and F = 9.74 with 2 and 5 degrees of freedom.

Previous stiffness-suction relations (8, 9, 10) have been reported in terms of the suctions measured prior to repeated loading. By contrast the simple models represented by Eqs. 5 and 6 relate the suctions resulting from a given stress history to the corresponding strains. However, the regression models are based on only a limited amount of experimental data. Consequently, although the models are useful in delineating possible stiffness-suction relations, they must nevertheless be treated with caution until their validity can be tested against more comprehensive data than those available to the author.

The relation between cumulative nonrecoverable strains ϵ_f and suctions is shown in Figure 7. Each point represents a different combination of initial dry density and molding saturation. The residual strains resulting from the designated stress history decreased rapidly as the suctions increased. The form of that relation and the form reported earlier by Sauer and Monismith (9) are similar in that the coefficients of residual deformation are related to the initial suctions.

Effects of Load Repetition

The effects of various numbers of load applications were examined in a series of 5 repeated load tests, each terminating at a different number of applications. Five replicate specimens were compacted to a nominal dry density γ_d of 115.8 lb/ft^3 at a degree of saturation S_r of 80 percent. They were then respectively subjected to 1, 10, 100, 1,000, and 10,000 applications of an octahedral shear stress τ_{oct} of 5.66 lb/in^2 at an octahedral stress ratio τ_{oct}/σ_{oct} of 0.82.

At the conclusions of the repeated load tests, measurements were made of suction parameters a and b and matrix suctions h_m. Those observations are shown in Figure 8. At low numbers of load applications, the suction parameters measured for the repetitively stressed specimens were significantly higher than the corresponding values measured for the duplicate control specimens. Moreover, the maximum increase in suction occurred during the first load application. Subsequently, however, the suctions tended to decrease with increasing numbers of load applications.

Effects of Stress History

The effects of stress history were examined in an incomplete factorial experiment. The factors investigated were octahedral normal stress σ_{oct} and octahedral stress ratio τ_{oct}/σ_{oct}. Three levels of τ_{oct}/σ_{oct} ranging from 0.82 to 1.07 were studied. Values of octahedral shear stress τ_{oct} ranged between 5.7 and 22.6 lb/in^2. The test specimens were each compacted to a dry density of 115.8 lb/ft^3 at a saturation of 80 percent.

The results of that experiment are shown in Figure 9. Varying the stress regime produced complex changes (usually decreases) in the matrix suctions. Those changes were generally smaller than those that accompanied alterations in the density, saturation, or number of load applications. Although for each level of τ_{oct}/σ_{oct} examined the suctions were a minimum at some particular value of σ_{oct}, the author was unable to

Figure 5. Relation between unconfined compressive strength and matrix suction before and after repeated loading.

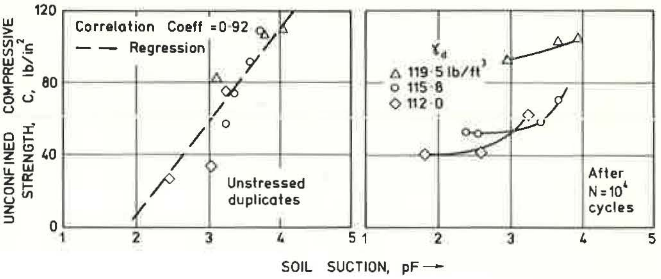


Figure 6. Relation between resilient axial strains and matrix suctions.

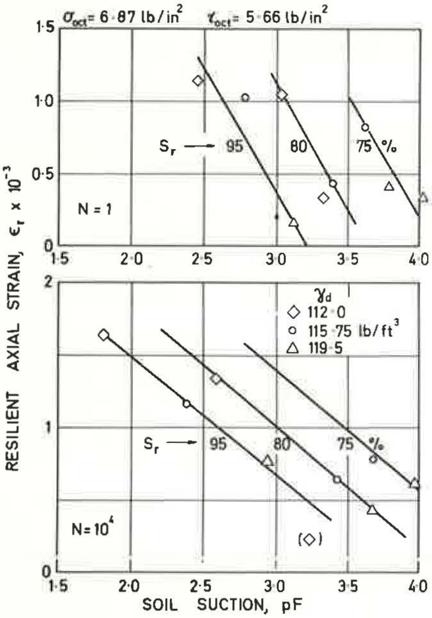


Figure 7. Relation between the nonrecoverable strains and final matrix suctions.

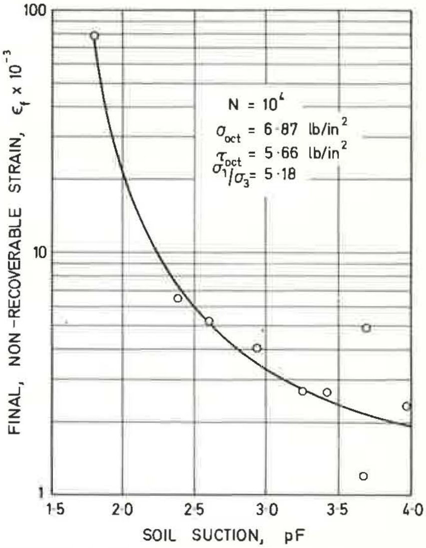


Figure 8. Effects of load repetition on soil suctions.

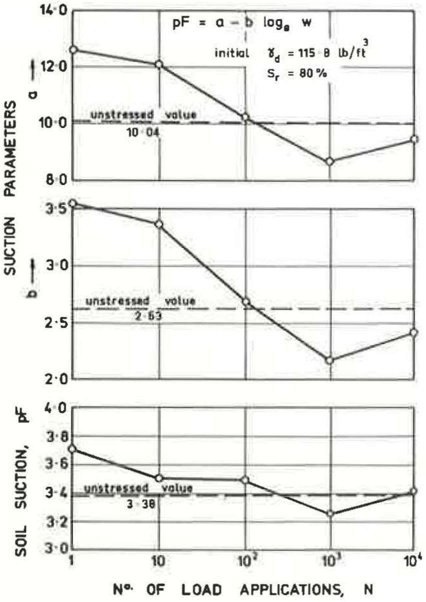
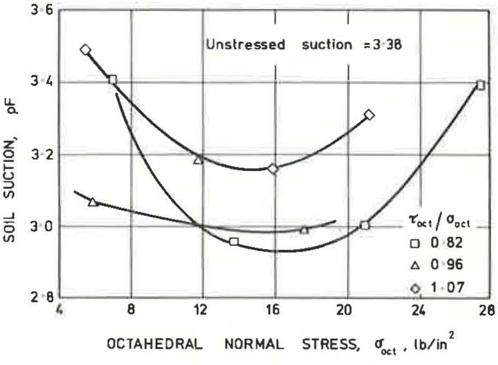


Figure 9. Influence of stress history on final matrix suctions.



determine whether it was possible to relate the suctions measured after repeated loading to the magnitude of the repetitive stresses. Moreover, there did not appear to be any obvious relation between the suctions and the corresponding strains or compressive strengths.

SUMMARY AND CONCLUSIONS

The work reported here demonstrated that the suctions exhibited by a compacted soil were functions not merely of the moisture content and dry density at compaction but also of the stress history experienced by the soil. A summary of the principal conclusions of the experimental investigation follows.

1. The matrix suctions h_m of both the repetitively stressed samples and the unstressed control specimens were primarily a function of the degree of saturation but also slightly depended on the dry density. In general, the suctions increased with increase in density or with reduction in saturation.
2. The effects of repeated triaxial loading were usually to decrease the suction corresponding to any given combination of dry density and degree of saturation. The decreases in suction could largely be attributed to changes in the soil structure.
3. For both the repetitively stressed samples and the control specimens, the matrix suctions could, for the range of densities and saturations studied, be related to changes in the moisture content by expressions of the form

$$h_m = a - b \log_e w$$

The effects of repeated loading were to alter the coefficients a and b.

4. The magnitude of the changes in soil suction resulting from repetitive loading tended to increase as the initial (molding) saturations were increased.
5. As the numbers of stress applications applied to a sample were increased, the final suctions tended to decrease.
6. Alterations in the stress regime produced slight alterations in the final suction values; however, those changes were smaller than those associated with alterations in density or degree of saturation.
7. For a particular molding saturation, the resilient axial strains decreased linearly with increase in the suctions, expressed in pF units.
8. The cumulative, nonrecoverable (residual) axial strains decreased rapidly as the suctions increased.

Elsewhere, Richards (26) has drawn attention to the fact that soil suction measurements are, in effect, measurements of potential that obey hydrodynamic and thermodynamic laws. It is of interest, therefore, to examine whether there are any relations between the changes in soil suction resulting from some given stress history and the corresponding expenditures in strain energy. The author has already reported some of the changes in the input and damping strain energies that occurred in the experimental soil during the various repeated load tests (13, 27); it has been found possible to qualitatively relate those changes to the alterations in soil suction.

It was determined that, with increasing dissipation of the loaded input strain energy, the suctions tended to decrease. Moreover, it was observed that both resilient and residual strains occurring in any cycle of loading and unloading often tended to decrease as the damping energies decreased. Because soils continue to dissipate part of the input strain energy even when the deformations are completely recoverable, it would be expected that, in general, the suctions would tend to steadily decrease with increase in the numbers of stress repetitions. Except for a few tests in which the suctions increased slightly, that type of behavior was observed throughout the experimental work, and conclusions 5 to 8 can, at least in part, be explained in terms of energy changes. However, to derive valid, quantitative, thermodynamic soil relations that include both suction and strain energy parameters has not yet proved to be possible.

Dry densities and saturations of the soil specimens and stress paths and stress levels used in the repeated load tests were all carefully chosen to be as nearly representative of actual pavements as could be conveniently achieved in the laboratory. Therefore, real pavement materials probably would exhibit changes in soil suction similar to those observed in this study. However, it is important to recognize that the changes in soil suction reported here were produced in a test lasting only $3\frac{1}{2}$ days. By contrast, similar changes in a pavement might take several months or even years to complete. The significance of the suction changes observed under laboratory conditions may, therefore, be different from those occurring in situ, and further research is needed on that aspect of the problem.

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