# Soil-Water Potential and Resilient Behavior of Subgrade Soils

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**The special significance water has for pavement systems is that such structures are generally associated with soils close to ground surface, are subject to large moisture content variations, and are strongly influenced by environmental conditions. The object of this study is to establish experimentally the relationship between the strength and deformation characteristics under highway loading conditions and the soil moisture regime in terms of the soil-water potential (or soil suction). To do this, laboratory specimens of a mixture of a typical Wisconsin subgrade soil and 25 percent sand were compacted at optimum and ±2 percent of optimum moisture content. These were subsequently equilibrated to a range of suction values up to 1500 kPa (217.4 lbf/in²) in a soil moisture extractor. The specimens were subjected to a repetitive uniaxial compression loading of 80 kPa (11.6 lbf/in²) at a frequency of 0.5 cycle/s up to 10 000 loading repetitions. After the computed values of resilient modulus and residual strain were studied as a function of the moisture parameters, it was concluded that soil suction is the fundamental parameter in characterizing the moisture state and its effects on the mechanical behavior of soils. For the silt loam soils (low-plasticity clays) considered, compaction at dry-of-optimum moisture content results in subgrades more susceptible to moisture changes. There appear to be significant advantages in taking suction-related improvements in the mechanical properties into account if the regional climatic conditions are to ensure a suitable range of moisture index. However, there seems to be a limit to the increases in resilient modulus with increasing soil suction because the resilient moduli decrease for suction values greater than a critical value.**

When a pavement is subjected to a wheel load, it undergoes both recoverable (resilient or elastic) and irrecoverable (permanent or plastic) deformations. The most significant factor influencing the design of a flexible pavement for given traffic and environmental conditions is subgrade soil support.

In recent years, the importance of resilient deformation, the major component of the total deformation for adequately designed pavements, has been studied extensively. Numerous field studies have established that pavement performance is controlled by the magnitude of resilient deformation responsible for fatigue failures in asphalt concrete surface courses (1). Several studies have shown that repetitive loading tests can be used to establish appropriate resilient properties for fine-grained subgrade soils (2, 3, 4), and, since then, the deformation characteristics of soils under repetitive action of compression loads have been studied extensively.

One very important parameter for cohesive soils is the moisture state of soil. In order to fully describe and control the mechanical behavior of subgrade soils, methods for predicting (a) moisture movement and equilibria in pavement systems and (b) influence of moisture on pavement behavior are needed (5). The emphasis in this investigation is on the latter aspect, and we expect the findings to be a complement to the research on moisture movement and equilibria by other investigators (6, 7).

Water has special significance in highway pavement systems because such structures are generally associated with the surficial boundaries of the terrain. Therefore, they are subject to large moisture content variations and are strongly influenced by environmental conditions. It is for this reason that the problems of controlling moisture changes and accumulation in soils under covered areas are of prime importance in relation to pavement design, construction, and performance. The recent advances in theoretical soil physics have provided researchers with a better understanding of the energy status of soil water (potential or suction). This has encouraged the application of the principles of soil suction to the mechanical response characterization (8).

The research reported here was further facilitated by the introduction of soil suction measuring devices that are practically applicable for all ranges of soil suction encountered (9).

The energy of a soil-water system can be expressed as a function of its characteristic water retention curve, or the relationship between water content and total soil-water potential or soil suction, where the latter is the difference between the free energy of water in the soil and that of pure water in a free surface condition. Total soil-water potential or soil suction is defined as the work required to remove an infinitesimal quantity of water from the soil and provides a measure of the combined effects of the forces holding the water in the soil. With the exception of cementation bonds, it implicitly includes the effects of the fundamental interaction forces that influence the deformation characteristics of the soil. The total soil-water potential of a soil varies with its water content, mineralogy, solutes present in the pore water, and soil fabric, among other parameters. This potential can be divided into several components.

Two of these components of primary interest are "matric potential", which arises from both capillarity and particle surface adsorption, and "solute potential", which arises from osmotic effects when water of a different solute content than pure water is extracted from the soil (9). In water retention curves, the data are usually presented in terms of equilibrium or steady-state values of water content, as related to some component of the soil-water potential. Expressed in terms of water content, sorption values are lower than desorption values; this is referred to as hysteresis. Soil-water extractors consisting of a pressure chamber containing a porous membrane of an appropriate bubbling pressure (for example, a ceramic plate) are commonly used for measuring or controlling matric suction. Solute suction can be evaluated by using freezing-point depression measurements and vapor-pressure depression measurements by thermocouple psychrometers (9).

The soil suction concept provides a fundamental soil parameter that reflects mechanical behavior (10). Another analytic advantage of soil-water potential over moisture content stems from the fact that a small error in moisture content may lead to a very serious error in the mechanical properties when the moisture content approaches saturation, whereas it takes correspondingly large values of suction to cause the same error. Furthermore, an indication of the effect of location and topography on soil suction values occurring under pavements can be obtained by correlating field suction

values with a climatic moisture index such as Thornthwaite moisture index (11). O'Reilly, Russam, and Williams (12) have shown a broad correlation between the average value of soil suction in the top 0.6 m (2 ft) of the subgrade under the pavement and the Thornthwaite moisture index for a number of soil groupings.

The few existing investigations that relate the mechanical response under repetitive loading conditions to soil suction (13, 14, 15, 16, 17, 18) indicate that soil suction is an important moisture variable for describing resilient behavior and relating it to the soil environment. Consequently, the study of soil suction is of ever-increasing importance to the design of pavements for arid areas, to the selection of placement conditions for base-course materials on expansive subgrades, and to the prediction of pavement performance. However, the resilient behavior of soils as a function of suction and other moisture parameters is not yet well understood, and only a very few investigations into it have been undertaken in this connection.

Therefore, the general objectives of this paper are to present experimental results concerning the resilient properties of selected fine-grained soils and to identify and quantify the effect of soil water in terms of soil suction and other pertinent parameters on the resilient and strength characteristics under typical pavement loading conditions.

## PROPERTIES OF SOILS USED

The basic material selected for the testing program is Fayette silt loam from Richland County, Wisconsin. It is typical of the soils adopted for subgrade construction by the Wisconsin Department of Transportation. The Fayette series of soils, which are available in several southwestern counties in Wisconsin, develop over clay residium from dolomite bedrock (19). These are moderately permeable soils with high available water. They have moderate frost heave potential and bearing value and are considered fair to good in compaction but poor as road subgrade.

Fayette silt loam and a mixture of it with Keweenaw sand were used in the testing program. For ease in identification, we shall call them Fayette and sandy mix.

Sandy mix, selected from a number of trial mixtures, was intended to produce a soil with textural characteristics different from those of Fayette silt loam. The sand used in preparing sandy mix was a reddish-brown loamy sand from Douglas County, Wisconsin. The final mixture used in the testing program contained 75 percent Fayette silt loam and 25 percent Keweenaw sand. Pertinent engineering properties of the soils used are listed in the table below (1 mm = 0.039 in; 1 N = 0.22 lbf; 1 KN/m$^3$ = 5.647 lb/ft$^3$).

| Item | Fayette Silt Loam | Sandy Mix |
|---|---|---|
| Liquid limit (%) | 39 | 33 |
| Plasticity index | 18 | 12 |
| Sand (0.074-4.76 mm) (%) | 2.4 | 21.6 |
| Silt (0.002-0.074 mm) (%) | 77.6 | 63.5 |
| Clay (<0.002 mm) (%) | 20.0 | 14.9 |
| AASHO soil classification | A-6(11) | A-6(9) |
| Unified soil classification | CL | CL |
| Optimum moisture content (%) | 18.2 | 15.8 |
| Maximum dry unit weight (kN/m$^3$) | 17.3 | 18.3 |
| Specific gravity | 2.69 | 2.71 |

The compaction characteristics of the two soils used were determined by using the Harvard miniature compactor following the procedure given by Wilson (20) and using a compressive force of 178 N (40 lbf). Based on the results of the compaction tests, specimens at approximately optimum moisture content and nominally 2 percent dry and wet of it were compacted to be used in the repetitive loading tests, again using the Harvard miniature compactor.

Addition of 25 percent sand to Fayette silt loam resulted in higher maximum dry density and lower optimum moisture content than found in the natural state. Preparation of nominally ± 2 percent of optimum moisture content specimens was successful in the natural Fayette; however, the wet-of-optimum specimens turned out to have molding moisture contents very close to the optimum in the case of sandy mix (a situation that could not be ascertained until after the termination of the testing program).

## EXPERIMENTAL PROCEDURES

The experimental phase of the investigation involved three stages: (a) preparation of soil samples, (b) equilibration of samples to various suction values, and (c) repetitive load testing and subsequent compression testing of samples.

### Sample Preparation

The test specimens were prepared from the two soil samples by compaction with controlled moisture content by using a miniature Harvard compactor in accordance with the procedures described by Wilson (20). Three sets of test specimens were compacted with molding moisture contents in the range of ±2 percent of optimum. Each set contained nine specimens to be equilibrated and load tested at suctions of 6.25, 12.50, 25, 50, 100, 200, 400, 800, and 1500 kPa (0.9, 1.8, 3.6, 7.3, 14.5, 29.0, 58.0, 116.0, 217.5 lbf/in$^2$).

During compaction the Harvard compactor was equipped with a 178-N (40-lbf) spring. Compacted specimens were allowed to equilibrate in sealed jars for about a week to ensure more uniform internal moisture distribution. The procedure described here results in reasonably homogeneous, reproducible specimens with controlled moisture contents. The compaction and subsequent moisture extraction resulted in moisture contents (weight basis) ranging from 12 to 25 percent. The dry density, once fixed during the compaction process, did not vary significantly during subsequent moisture extraction; therefore, no conclusive relationships between density and the observed behavioral patterns could be discerned.

Another important soil parameter, soil fabric, was not controlled or measured. During compaction of soils fabric is influenced primarily by the method of compaction and the compaction moisture content (21). Johnson and Sallberg (22) report that the kneading compaction method best represents the soil fabric obtained in the field. For this reason, among others, the Harvard method was used to prepare all specimens. The influence of compaction moisture content was included by preparing specimens at optimum as well as dry- and wet-of-optimum moisture contents.

### Equilibration of Specimens to Various Soil Suctions

The soil moisture extractors were used to equilibrate the soil samples to various matric (soil) suctions. One of the extractors, which contained a ceramic plate of 100 kPa (14.5 lbf/in$^2$) air-entry pressure, operated within the range of 6.25-50 kPa (0.91-7.25 lbf/in$^2$), whereas the other one, which contained a 1500 kPa (217.4 lbf/in$^2$) air-entry pressure plate, was used in the 100-1500 kPa (14.5-217.4 lbf/in$^2$) range. By

doing this, it was possible to substantially reduce the total equilibration time for the whole series.

After they were placed in the extractors, the samples were left to equilibrate with water under zero chamber pressure until no noticeable flow of water into the extractors' pressure plates was observed. Then chamber pressures of 6.25 kPa (0.91 lbf/in$^2$) and 100 kPa (14.5 lbf/in$^2$), respectively, were applied as the first increment; the pressures were doubled when equilibrium was reached under each incremental pressure. As soon as the air pressure inside the chamber is raised above the atmospheric pressure, the higher pressure inside the chamber forces excess water through microscopic pores in the porous membrane (ceramic plate). The high-pressure air, however, will not flow through the pores because they are filled with water and the surface tension of the menisci formed at the gas-liquid interface at each of the pores supports the pressure in much the same way as a flexible rubber diaphragm would. When the air pressure is increased inside the extractor, the radius of curvature of this interface decreases. However, the menisci will not break and let air pass throughout the whole pressure range of the extractor. At any given air pressure in the chamber, soil water will flow from around each of the soil particles and out through the porous membrane to the space under it, which is kept at atmospheric pressure by a tube connected to the atmosphere.

This process continues until such time as the effective curvature of the water films throughout the soil are the same as those in the pores of the porous membrane. When this occurs, equilibrium is reached and the flow of moisture ceases. At equilibrium the air pressure in the extractor and the soil suction are equal.

Each time the equilibrium between the chamber pressure and pore-water pressure in the samples was reached, three samples (with dry-of-optimum, optimum, and wet-of-optimum compaction moisture contents) were taken out, weighed, measured, trimmed (if necessary to provide parallel top and bottom surfaces for resilience testing), reweighed, and remeasured after trimming.

### Repetitive Load Testing

Cylindrical specimens [approximately 70 mm (2.76 in) high and 35 mm (1.38 in) in diameter] equilibrated to desired soil suctions were subjected to repetitive loading tests in an apparatus capable of applying repeated dynamic loads of controlled magnitude and duration with a choice of a number of loading functions. Repetitive loading tests were carried out under uniaxial loading conditions. Factors considered in adopting the unconfined compression procedure included

1. Simplicity and ease of testing,
2. The very small [normally less than 40 kPa (6.0 lbf/in$^2$)] magnitude of confining pressure that exists in the upper regions of the subgrade of a typical flexible pavement, and
3. Difficulty in assessing change in induced soil suctions as a result of the application of an all-around pressure, which introduces problems in correlating the resilient behavior with soil suction.

During repetitive load testing, an initial axial load of 20 N (4.5 lbf) was applied; this axial load was then varied between 20 and 100 N (4.5 and 22.5 lbf), which resulted in a repetitive axial stress of approximately 80 kPa (11.6 lbf/in$^2$). The load-time curve form chosen was haversine, and a series of pilot tests was performed with frequency of loading varying from 0.2 to 2 cycles/s and number of cycles running up to 10 000 repetitions.

Based on these tests, and the time constraints, a maximum of 5000 repetitions, a frequency of loading of 0.5 cycle/s, and a loading time of 0.3 s/repetition at a time interval of 2 s between two consecutive loadings were adopted as reasonable values in the main testing effort. Half of the Fayette series was carried to 10 000 repetitions.

Resilient deformation and the applied load were taken directly from a built-in recorder, and the resilient moduli were calculated. After the resilience testing, the unconfined compressive strength of each specimen was determined by a conventional unconfined compression testing apparatus following standard procedures (23).

## EXPERIMENTAL RESULTS

### Definition of Mechanical Parameters

The term "stress" refers to the average load per unit area, and "strain" is defined as the ratio of the average change in a dimension (deformation) to the original value of that dimension. Resilient or elastic strain is the ratio of that portion of the total deformation that is recovered after the repeated axial load is removed to the original specimen length. Residual or plastic strain is the ratio of that portion of the total deformation that is not recovered after the repeated axial load is removed to the original specimen length. Resilient modulus is the ratio of the repeated axial stress (or the repeated principal stress difference) to the resilient strain. And soil suction is the energy with which water is held in soil and is measured by the work required to move an infinitesimal quantity of water from the soil to a pressure-free and pure state.

Soil suction, when expressed as energy per unit volume, is a negative quantity with dimensions of pressure. However, in engineering use, its absolute value or positive magnitude is normally used for ease of discussion. This usage is also adopted in this study. Thus, a soil suction of -800 kPa (-116 lbf/in$^2$) is referred to as a suction of 800 kPa (116 lbf/in$^2$).

The influence of the moisture state variables on the resilient properties and post-repetitive loading strengths is demonstrated and discussed in the following sections.

### Water Retention Curves

After they were prepared, the cylindrical specimens were allowed to stand on the moisture extractor plate with access to free water. In response to the suction pressures induced during compaction, the specimens tended to absorb water, which they were allowed to do until there was no noticeable movement of water into the extractor. The specimens were then brought to equilibrium at various soil suctions, always following a fixed pressure schedule, i.e., always doubling the previous pressure. Only variations from the initially nearly saturated state were studied by means of a desorption schedule. Some of the specimens were taken out after equilibrium at various suctions to determine their equilibrium water contents and dry densities. They were tested in uniaxial repeated loading and static compression for resilient deformation and strength characteristics. The ceramic plate extractor primarily controlled the specimens' matric potential; the solute potential was not considered to be a significant component of the total potential for the materials and the conditions of this study.

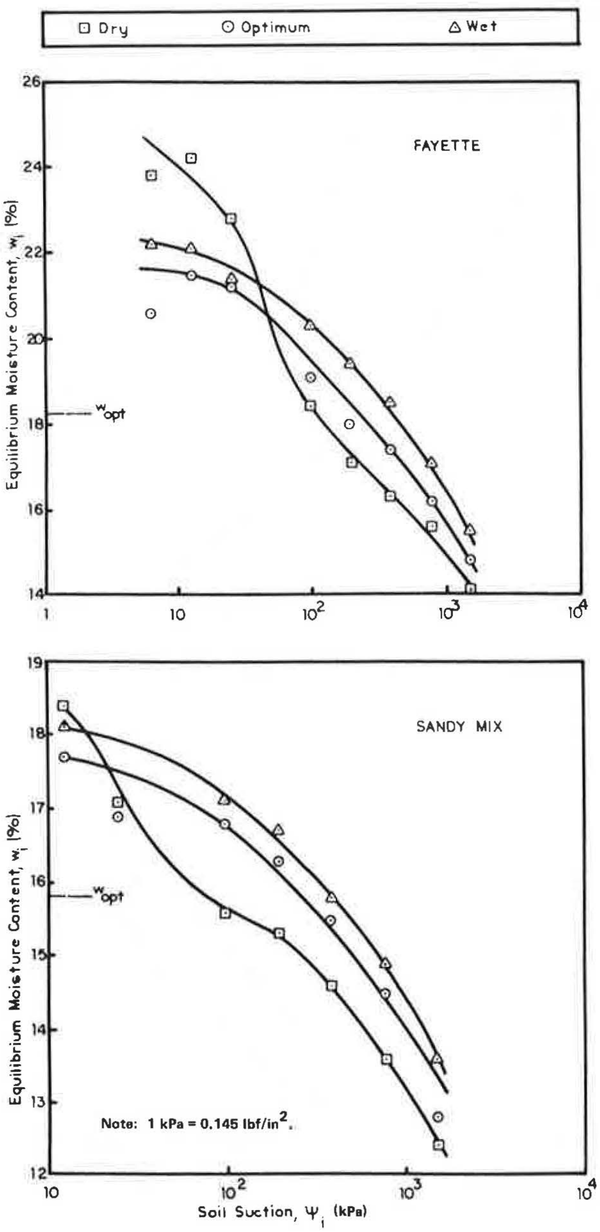
The characteristic water retention curves associated with the indicated desorption schedule are given in Figure 1 for the two soils tested. The gradual concave shape of the curves for the specimens molded

at the optimum and wet-of-optimum moisture contents (O to W specimens) indicates that, within the range tested, each of these specimens had a wide distribution of pore sizes, because the presence of a dominant pore size would have yielded a rapid decrease in water content at the value of the soil suction associated with the water-holding capacity of a pore of that given size. This was observed in the case of the specimens molded at dry-of-optimum moisture content (D specimens), particularly of Fayette and, to a degree, of sandy mix.

The variety of complex interactions between clay particles and water made it virtually impossible to calculate theoretically the water-retaining characteristics of a given soil. However, the measurement of water retention can be made without regard to the individual forces holding the water in the clay, and a qualitative interpretation of the different possible mechanisms can be advanced.

Two factors affecting the matric potential of a soil at equilibrium to a large degree are the pore size and number and the adsorptive forces associated with the

**Figure 1. Water retention curves for Fayette and sandy mix.**




particles' surfaces. Accordingly, soil fabric strongly influences the pore-size distribution and consequently the shape of the characteristic water retention curves, especially in the low suction range.

The individual points on a given water retention curve were obtained by testing different specimens with hypothetically the same initial fabric and dry density. Specimens compacted wet and dry of optimum as well as at optimum moisture content follow distinct curves throughout the moisture-extracting process. These water retention curves do not tend to merge at higher suctions, which reflects the dominant influence of the initial fabric characteristics (i. e., pore sizes and shapes) on the water retention rather than the role of the surface adsorptive forces holding water in the soil for the range of soil suctions used.

This rationalization is based on the premise that, as the soil suction increases, the larger pores empty and shrink, and the role of surface adsorptive forces is increased. Therefore, water-retaining characteristics tend to be increasingly governed by the specific surface area of the particles rather than by the fabric. Since specific surface area is expected to be the same for specimens of compositionally the same soil, the retention curves can be expected to merge at sufficiently high suctions.

The D specimens seem to have a fabric distinctly different from that of the O or W specimens. This is reflected in the shape of their respective water retention curves. It appears that the D specimens contain a large portion of relatively large pores of roughly equal size when compared to the O and W specimens at approximately the same void ratio (average molding void ratios were 0.55 and 0.48 for Fayette and sandy mix, respectively).

This observation conforms with the reported open, flocculant fabric of specimens compacted dry of optimum versus the oriented, dispersed fabric of specimens compacted wet of optimum (21). Furthermore, the stress-strain curves obtained in the unconfined compression testing of the compacted specimens indicated a peak for the D specimen, whereas smooth curves were obtained for the O and W specimens. This again reflects the variation in the fabrics of these specimens.

In order to demonstrate these inferences, a more direct approach was adopted, and the fabric of specimens wet, dry, and optimum were observed under a scanning electron microscope (SEM). A difference between the fabric of the D specimen and O or W specimens was discernible on the micrographs, and the preponderance of voids in the micrograms was compared in a qualitative manner. There appeared to be hardly any discernible difference between O and W specimens, and the fabric differences of sandy mix specimens were much more subtle.

The soil suctions corresponding to the as-compacted state of the wet, dry, and optimum specimens can be estimated indirectly by reading the suction values corresponding to the molding moisture contents from the respective retention curves. The average compaction suction values in kilopascals (kPa = 0.145 lbf/in²) of the specimens prepared are given below.

| | Suction (kPa) | | |
|---|---|---|---|
| Soil Sample | Dry of Optimum | Optimum | Wet of Optimum |
| Fayette | 530 | 250 | 130 |
| Sandy mix | 280 | 200 | 25 |

These values could differ from the actual as-compacted suctions; nevertheless, the specimens compacted dry of optimum indicate much higher suction values and a more

open fabric than the wetter specimens. When allowed access to water, as in this study in the extractor before the desorption cycle, they absorb much more water than the wetter specimens (Figure 1).

For instance, the dry Fayette and sandy mix specimens gained 7.8 percent and 2.5 percent in moisture content, respectively, when allowed access to water in the extractor under a small suction pressure [6.25 kPa (0.91 lbf/in$^2$) and 14 kPa (2.03 lbf/in$^2$), respectively], whereas the optimum and wet-of-optimum Fayette and sandy mix specimens gained, under the same conditions, on the order of 2.1 and 1.2 percent in moisture content, respectively.

Practical implications are important in that certain soils when compacted to the same density, if the compaction moisture content is dry of optimum, will be more susceptible to moisture changes. In the presence of moisture they may equilibrate to higher moisture contents than the corresponding soils compacted wetter. Since structural properties have a general dependency on moisture content, this would result in inferior performance.

All the observations made above were more distinct for Fayette than for sandy mix. This was probably because sandy mix packed better with its 25 percent sand and less clay.

## Repetitive Loading Test Results

Uniaxial repetitive loading tests were performed on more than 60 specimens from the two soil samples. The results were analyzed in terms of the resilient modulus ($E_r$) and the residual strain ($\epsilon_p$). These two parameters define the behavior of subgrade soils and are useful in the design of highway and airfield pavements.

Figure 2 shows the variation of $E_r$ and $\epsilon_p$ as a function of the number of loading cycles (N). Both $E_r$ and $\epsilon_p$ steadily increase with increasing N, and the soil be-

**Figure 2. Resilient modulus and residual strain versus number of loading cycles.**

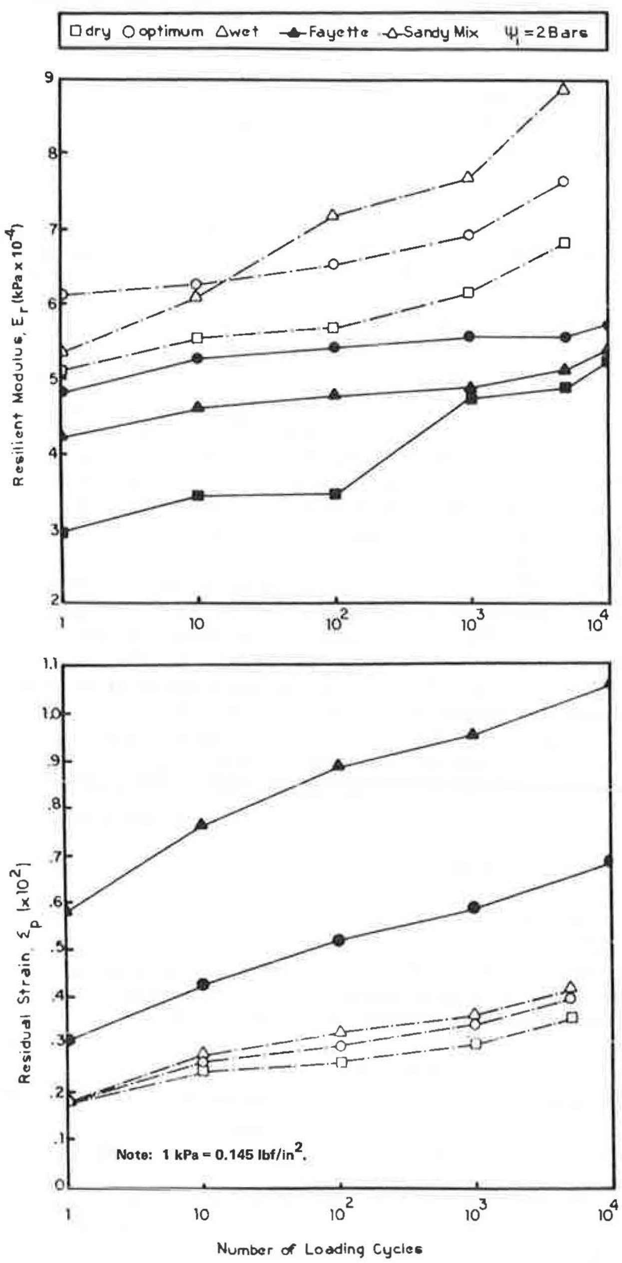
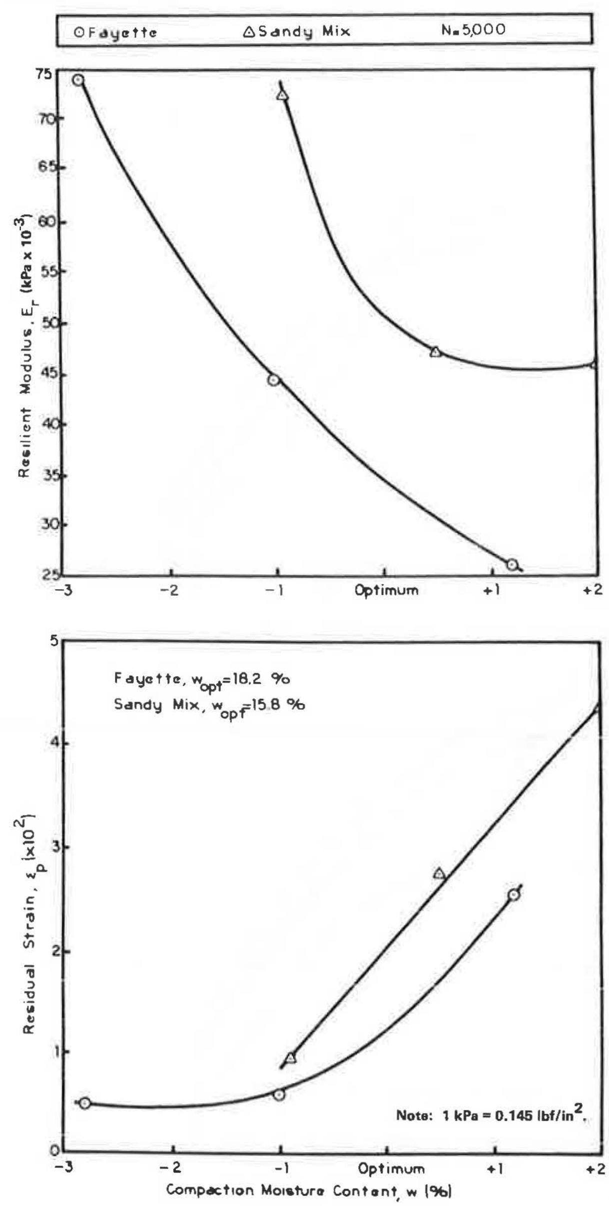



**Figure 3. Resilient modulus and residual strain versus compaction moisture content.**



comes less elastic. This behavior was usually observed for all the specimens at all suctions. $E_r$ increases approximately 1.4-fold for both soils over a range of 1000-5000 N (225-1125 lbf), and $\epsilon_p$ increases approximately 2- and 3-fold for sandy mix and Fayette, respectively, over the same range.

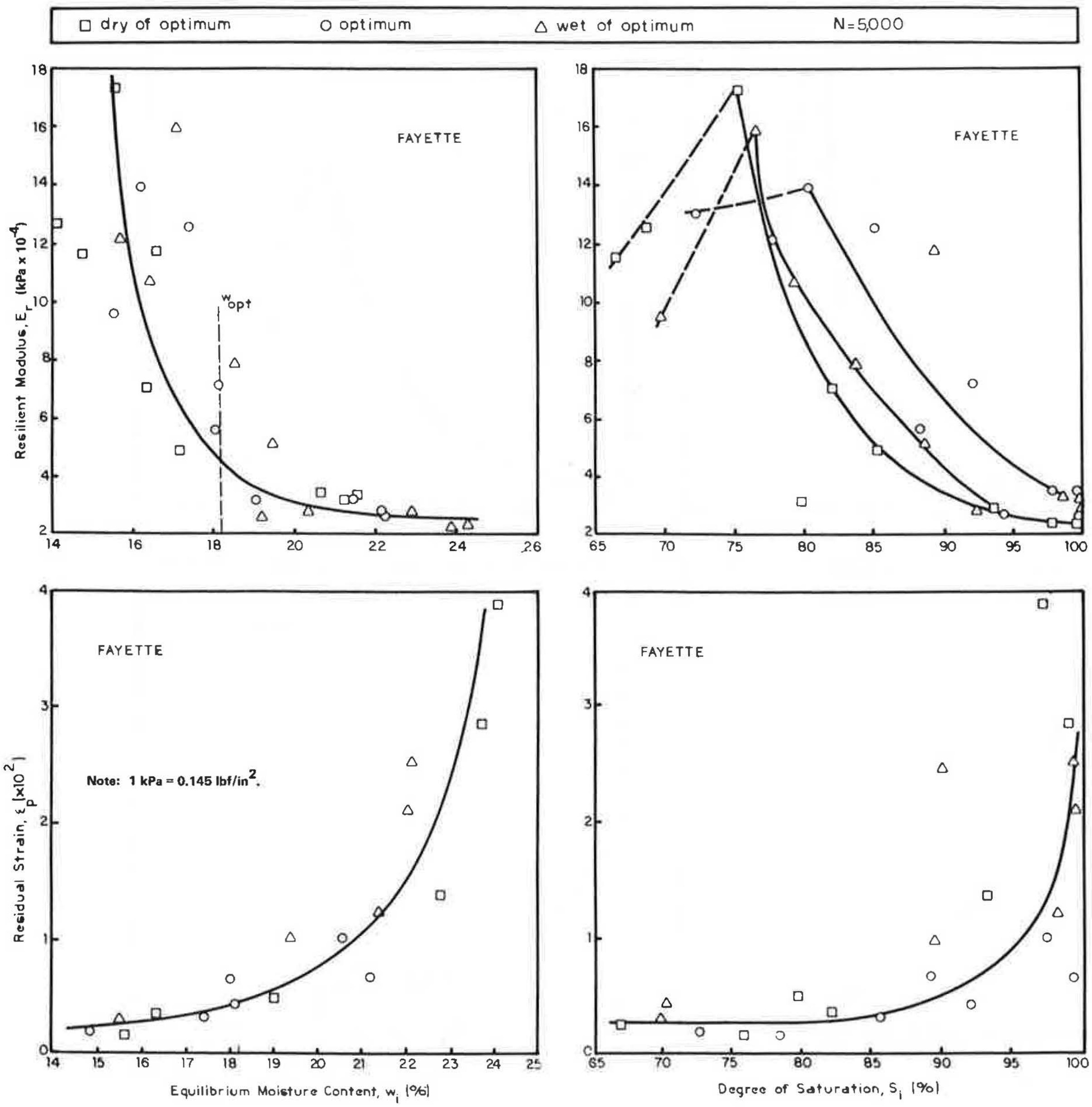
The general influence of compaction moisture content on $E_r$ and $\epsilon_p$ is shown in Figure 3. Variations in compaction moisture content on the dry side of optimum result in more significant changes in $E_r$ than similar variations on the wet side of optimum. In the case of $\epsilon_p$, the opposite of the resilient modulus response is observed.

Permanent strains increase rapidly for the specimens compacted wet of optimum. However, one must remember that moisture content of the soil may change after compaction in response to environmental conditions. In order to investigate this response, compacted specimens were equilibrated to a range of moisture regimes in the laboratory and tested.

Figure 4 gives the resilient modulus and residual strain at 5000 load repetitions as a function of the equilibrium moisture content and the degree of saturation for Fayette silt loam. The data indicate a general tendency for $E_r$ to decrease as $w_i$ increases. Changes in $E_r$ for moisture contents greater than the optimum are relatively small, whereas significant changes occur with moisture content in the dry-of-optimum range. Small variations occur in $\epsilon_p$ for moisture contents equal to or less than optimum. However, for states wetter than optimum, residual strains rapidly increase with moisture content. The data points are not scattered much, which indicates a strong dependency on equilibrium moisture content.

The moisture-density relations for soils can also be considered in terms of degree of saturation. In Figure 4 a trend is noted between $E_r$ and $\epsilon_p$ and the degree of saturation ($S_i$). Resilient modulus decreases at saturations less than 75 percent for the range of $S_i$. The specimens tested at a suction of 1500 kPa (217.4 lbf/in$^2$) had consistently lower moduli than the ones tested at 800 kPa (116 lbf/in$^2$).

**Figure 4. Resilient modulus and residual strain versus moisture content and degree of saturation.**



This change in behavior trends at a suction roughly corresponding to 800 kPa is responsible for the lower moduli for degrees of saturation less than the critical value of $S_i$ (75 percent for Fayette silt loam). Residual strains remain relatively constant for $S_i$ equal to or greater than 95 percent. Significant changes in $\epsilon_p$ take place when the soil is nearly saturated ($S_i$ is smaller than 95 percent). Residual strains are apparently more strongly dependent on moisture content than on degree of saturation.

A volume measurement is required to determine degree of saturation, and this introduces significant inaccuracies. Consequently, the data points were quite scattered (especially for sandy mix). It is noted from Figure 4 that the use of moisture content or degree of saturation alone to characterize moisture regime of a soil is, in general, inadequate.

Figure 5 shows the range of values for the resilient modulus and residual strain as a function of the initial soil suction ($\psi_i$) for the two soils. $E_r$ does not change appreciably up to $\psi_i$ = 100 kPa (14.5 lbf/in²). Thereafter, there is generally a sharp increase in $E_r$ with increasing $\psi_i$ except at $\psi_i$ = 1500 kPa (217.4 lbf/in²). The drop in $E_r$ at $\psi_i$ = 1500 kPa was observed for both soils and was verified with duplicate specimens prepared and tested in the same manner. It is therefore believed to be an intrinsic behavioral characteristic rather than an experimental error.

The critical suction value at which the change in behavior occurs cannot be precisely determined; however, it probably has a value slightly in excess of 800 kPa. This critical suction corresponds to a moisture content approximately 2 percent dry of optimum. Similar observations with regard to the changes in mechanical behavior at certain critical suctions have been reported. Krizek and Edil (24) reported a change in the static compression behavior of kaolinitic soil samples at a suction of 500-600 kPa (72.5-86.9 lbf/in²). Edris and Lytton (16) refer to a change in resilient modulus response of certain Texas soil samples from

**Figure 5. Resilient modulus and residual strain versus soil suction.**

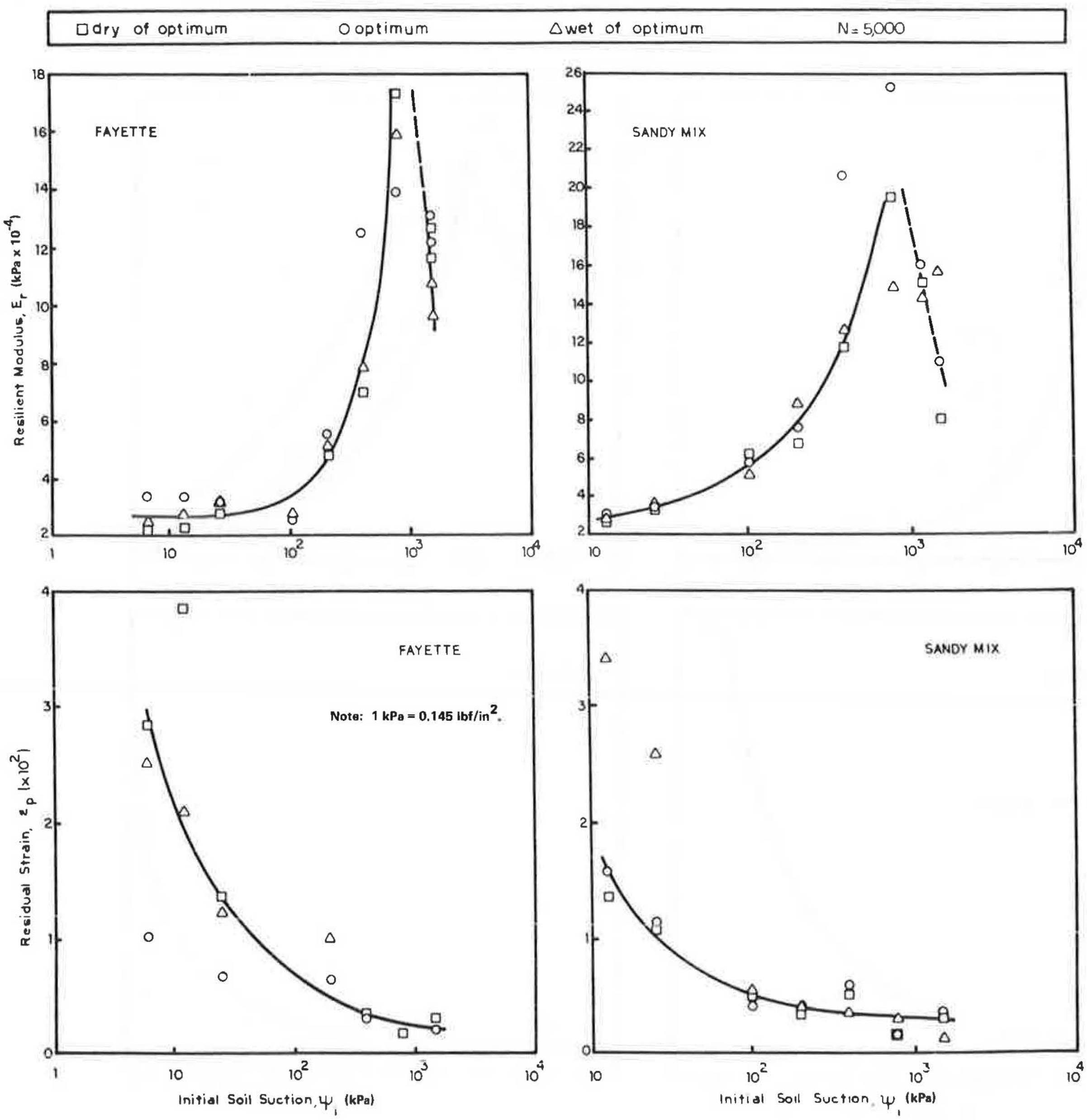


**Figure 6. Effect of repetitive loading on unconfined compressive strength.**

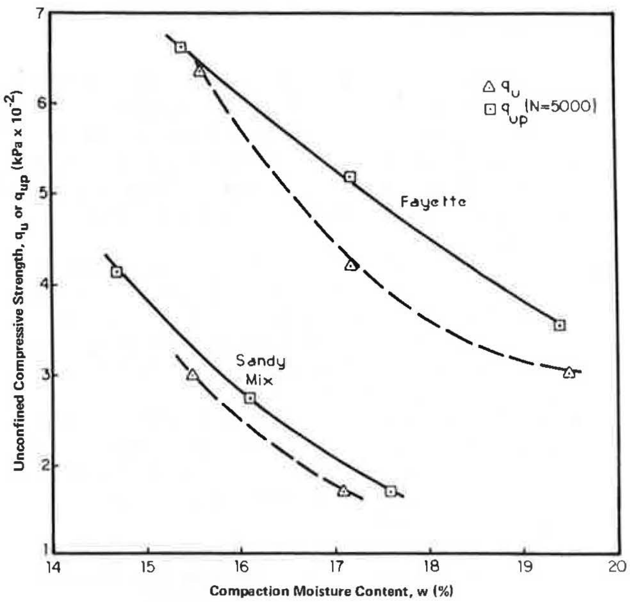
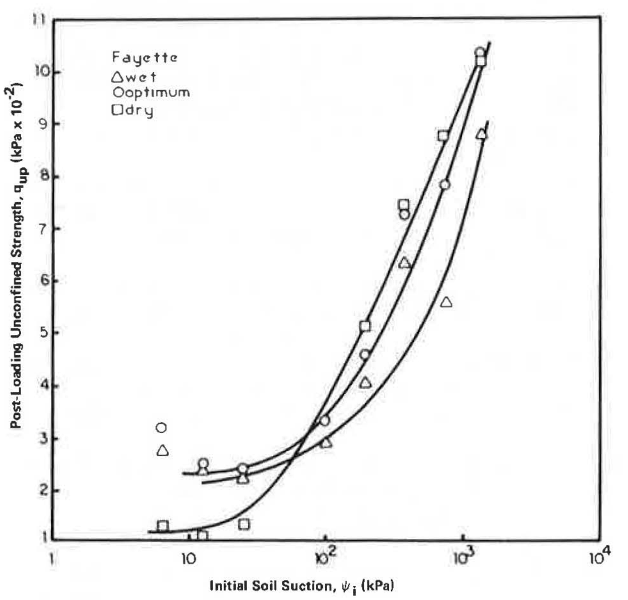


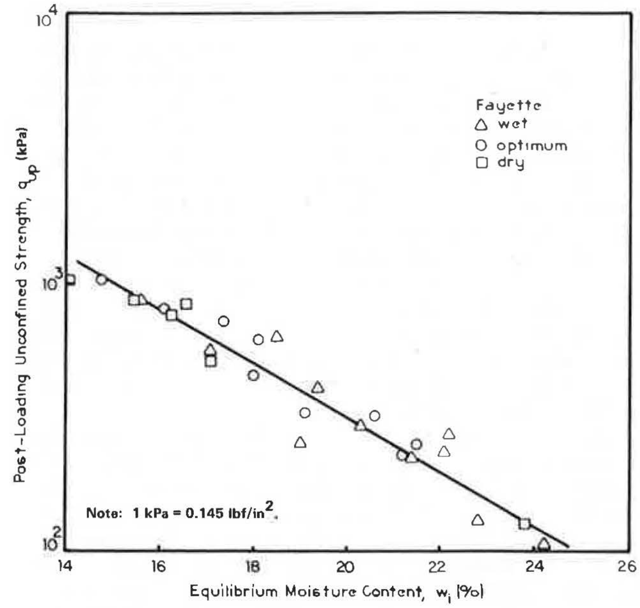

**Figure 7. Post-loading unconfined strength versus soil suction.**




"effectively saturated" to "effectively unsaturated" at a suction corresponding to 2 percent dry-of-optimum moisture content. The reasons for this change in behavior have not yet been identified. The dependency of $E_r$ on $\psi_i$ for dry, wet, and optimum samples appears similar; however, there are no distinguishable trends with respect to the compaction moisture content and the resultant fabric.

Major changes in $\epsilon_p$ take place for the suction range less than 100 kPa (14.5 lbf/in$^2$), beyond which irrecoverable strain stabilizes and remains, in general, equal to or less than $5 \times 10^{-3}$. As suction increases from 6.25 to 100 kPa (0.91-14.5 lbf/in$^2$), $\epsilon_p$ decreases 2.5- to 7-fold, depending on the specimen's compaction condition (i.e., wet, dry, or optimum).

**Figure 8. Post-loading unconfined strength versus water content.**




## Compressive Strength After Repetitive Loading

The specimens that were used in the repetitive loading tests were subsequently subjected to unconfined compression tests. This strength is referred to as the "post-loading unconfined compressive strength" and is designated $q_{up}$. The $q_{up}$ value represents the soil's strength after 5000-10 000 cycles of repetitive loading to a stress level only a fraction of its strength.

As a result of the repetitive loading, the initial characteristics of the specimens are expected to change somewhat. The post-loading strength of compacted specimens are compared in Figure 6 with those of the specimens not subjected to repetitive loading. The specific repetitive loading level used causes a slight increase in unconfined strength. No attempt was made to measure the final suction at the end of the repetitive loading. Based on the data presented by Edris and Lytton (16), the ratio of final to initial suction is very nearly one for the soils tested in this program. Consequently, the variation of $q_{up}$ values with the known initial suction ($\psi_i$) is considered and presented in Figure 7 for Fayette soil. As shown in this figure, $q_{up}$ increases with increasing values of $\psi_i$.

Similar behavior by kaolinite samples prepared by consolidation from a slurry has been reported by Edil and Krizek (10). At each suction value, there is a range of $q_{up}$ values that results from the difference in water contents of dry, wet, or optimum specimens equilibrated to the same soil suction. In order to demonstrate the effect of water content, log $q_{up}$ is plotted versus $w_i$ in Figure 8; there is a distinct dependency on water content and $q_{up}$ varies with $w_i$ in approximately an exponential manner.

## SUMMARY AND CONCLUSIONS

A study of the relationship between the resilient modulus, residual strain, post-repetitive loading strength and the moisture regime of two fine-grained soils has been made. Based on the behavior of the silt loam soils investigated here, the following conclusions can be drawn. The application of these conclusions to similar soils may be possible in a qualitative manner;

however, for quantitative comparisons caution must be exercised.

1. Characteristic water retention curves are useful for reflecting the susceptibility of compacted soils to moisture changes. The silt loam soils compacted dry of optimum are found to be more susceptible to moisture content changes than are the ones compacted at optimum or wet-of-optimum moisture contents at comparable compaction densities. For example, the specimens compacted dry of optimum equilibrated to higher moisture contents than the optimum and the wet-of-optimum specimens at low soil suctions. Since most mechanical properties are adversely affected by increasing moisture content, the necessity of specifying the compaction moisture content in addition to the compaction density becomes apparent in field compaction of fine-grained soils.

2. The resilient modulus and strength strongly depend on compaction moisture content on the dry side of optimum with insignificant dependency on the wet side (within the range of ±2 percent of optimum), whereas the residual strain exhibits the opposite behavior.

3. The moisture regime subsequent to compaction can be expressed most suitably in terms of soil suction. It is an intrinsic parameter of the moisture equilibrium and reflects the effects of soil type and fabric, climate, and position of groundwater table on the mechanical response better than moisture content or degree of saturation alone.

4. Resilient modulus and post-repetitive loading strength are primarily related to soil suction. For silt loam soils investigated, variations in these properties were small for suction values less than 100 kPa (14.5 $lbf/in^2$). This suction corresponds roughly to 2 percent dry-of-optimum moisture content. For suctions greater than this, however, significant increases in mechanical properties (on the order of three- to sixfold) are obtained.

5. The opposite of this behavior is obtained in the case of residual strain. Major decreases in residual strain take place up to a suction of 100 kPa. However, for suctions greater than this, residual strain remains virtually constant.

6. Resilient modulus increases monotonically for soil suctions from 100 kPa to a critical suction beyond which it decreases. This critical suction appears to be about 800 kPa (116 $lbf/in^2$) (corresponding moisture content is 2 percent dry of optimum) for the soils tested. This anomaly in behavior was not observed in the case of residual strain or strength.

7. The significant range of soil suctions is from 100-800 kPa for the soils considered. This corresponds to a range of Thornthwaite moisture index of from -15 to +15 for the soils tested. In the regions where the climatic moisture in terms of rainfall and evapotranspiration yields a moisture index in this range, an advantage of improved mechanical properties as a function of soil suction can be taken. In terms of moisture content, this significant range corresponds to ($w_{optimum}$) to ($w_{optimum}$ - 2 percent).

8. Number of loading cycles results in significant increases in resilient modulus and residual strain (the latter is not very desirable) and some increase in compressive strength.

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## REFERENCES

1. A.L. Robnett and M.R. Thompson. Development of Testing Procedure: Phase I—Interim Report, Resilient Properties of Subgrade Soils. Illinois Cooperative Highway Research Program, Department of Civil Engineering, Univ. of Illinois, Urbana, Transportation Engineering Series 5, No. 139, June 1973.
2. H.B. Seed, D.K. Chan, and C.E. Lee. Resilience Characteristics of Subgrade Soils and Their Relation to Fatigue Failures in Asphalt Pavements. Proc., 1st International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, MI, 1962, pp. 611-636.
3. C.L. Monismith and others. Prediction of Pavement Deflections from Laboratory Tests. Proc., 2nd International Conference on the Structural Design of Asphalt Pavements, Ann Arbor, MI, 1967, pp. 109-140.
4. H.B. Seed and others. Prediction of Flexible Pavement Deflections from Laboratory Repeated-Load Tests. NCHRP, Rept. 35, 1967.
5. Water on Roads: Prediction of Moisture Content of Road Subgrades. Organization for Economic Cooperation and Development, Paris, 1973.
6. B.J. Dempsey and A. Elzeftawy. Interim Report—Moisture Movement and Moisture Equilibria in Pavement Systems. Illinois Cooperative Highway Research and Transportation Program, Department of Civil Engineering, Univ. of Illinois, Urbana, Transportation Engineering Series 15, No. 161, 1976.
7. R.L. Lytton. Theory of Moisture Movement in Expansive Clays. Center for Highway Research, University of Texas, Austin, Research Rept. 118-1, Sept. 1969.
8. D. Croney and J.D. Coleman. Soil Structure in Relation to Soil Suction (pF). Journal of Soil Science, Vol. 1, 1954, pp. 75-84.
9. L.A. Richards. Physical Condition of Water in Soil. In Agronomy: No. 9—Methods of Soil Analysis, Madison, WS, P.1, 1965, pp. 128-152.
10. T.B. Edil and R.J. Krizek. Influence of Fabric and Soil-Water Potential on the Mechanical Behavior of a Kaolinitic Clay. Geoderma, Vol. 15, 1976, pp. 831-840.
11. C.W. Thornthwaite. An Approach Toward a Rational Classification of Climate. Geographical Review, Vol. 38, No. 1, 1948, pp. 55-94.
12. M.P. O'Reilly, K. Russam, and F.H.R. Williams. Pavement Design in the Tropics. British Road Research Laboratory, Crowthorne, Berkshire, England, Technical Paper 80, 1968.
13. E.K. Sauer and C.L. Monismith. Influence of Soil Suction on Behavior of a Glacial Till Subjected to Repeated Loading. HRB, Highway Research Record 215, 1968, pp. 18-23.
14. B.G. Richards and R. Gordon. Prediction and Observation of the Performance of a Flexible Pavement on an Expansive Clay Subgrade. Proc., 3rd International Conference on the Structural Design of Asphalt Pavement, Ann Arbor, MI, 1972, pp. 133-143.
15. B. Shackel. Changes in Soil Suction in a Sand-Clay Subjected to Repeated Triaxial Loading. HRB, Highway Research Record 429, 1973, pp. 29-34.

16. E.V. Edriss, Jr., and R.L. Lytton. Dynamic Properties of Fine Grained Soils. Proc., 9th International Conference on Soil Mechanics and Foundation Engineering, Tokyo, Vol. 2, 1977, pp. 217-224.
17. D.G. Fredlund, A.T. Bergan, and E.K. Sauer. Deformation Characterization of Subgrade Soils for Highways and Runways in Northern Environments. Canadian Geotechnical Journal, Vol. 12, No. 2, 1975, pp. 213-223.
18. D.G. Fredlund, A.T. Bergan, and P.K. Wong. Relation between Resilient Modulus and Stress Conditions for Cohesive Soils. TRB, Transportation Research Record 642, 1977, pp. 73-81.
19. Soil Manual. Wisconsin Department of Transportation. 1972.
20. S.D. Wilson. Small Soil Compaction Apparatus Duplicates Field Results Closely. Engineering News-Record, May 1950, pp. 34-36.
21. T.W. Lambe. The Structure of Compacted Clay. Journal of Soil Mechanics and Foundations Division, Proc., ASCE, Vol. 84, No. SM2, 1958, pp. 1-34.
22. A.W. Johnson and J.R. Sallberg. Factors That Influence Field Compaction of Soils. HRB, Bull. 272, 1960, pp. 29-48.
23. T.B. Edil and S.E. Motan. Soil-Moisture Equilibria and Behavior of Highway Pavement Systems. National Science Foundation, Grant ENG75-10558, 1978, 68 pp.
24. R.J. Krizek and T.B. Edil. Experimental Study of Clay Deformability in Terms of Initial Fabric and Soil-Water Potential. Rheologica Acta, No. 13, 1974, pp. 803-813.

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# Comparison of the Precise Freezing Cell with Other Facilities for Frost-Heave Testing

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**Identification of frost-susceptible materials on the basis of their physical properties is too imprecise for many practical purposes, and direct freezing tests need to be employed. Heave is measured by two main types of test: the constant rate of penetration test and the constant boundary temperature test. The latter has the advantage of greater simplicity of operation and is easier to model mathematically. Nevertheless, its reproducibility is relatively poor and improvements are being sought. The development of a self-refrigerated unit (SRU) is outlined and likely future revisions to the constant boundary temperature test specification discussed briefly. A precise freezing cell (PFC) that uses the Peltier effect and permits unidirectional freezing with the boundary temperatures controlled to ±0.1°C has been developed. Specimens heave much less in the PFC than in the SRU because the heat extraction is more rapid and a constant temperature is applied to the moving boundary (top of specimen) rather than to the stationary boundary. Thus the penetration of the zero isotherm is accompanied by high suctions that favor ice penetration over segregation. The role of the PFC lies in research, not in routine testing, particularly in connection with the development and evaluation of mathematical models.**

The process of frost heaving, which occurs when the zero isotherm penetrates below the bound materials of a typical road structure (Figure 1), can be explained in terms of the capillary theory (1, 2, 3). This postulates that, to pass through the neck of a pore, the radius of curvature of the ice front ($r_{iw}$) must be reduced to a critical value ($r_o$) (Figure 2). The curved interface is associated with both a pressure difference and a freezing-point depression according to the equation

$$p_i - p_w = 2\sigma_{iw}/r_{iw} = L\Delta T/V_w T_o \qquad (1)$$

where

$p_i$, $p_w$ = ice and water pressures respectively (Pa),
$r_{iw}$ = radius of ice-water interface at a particular instant (m),
$\sigma_{iw}$ = interfacial energy (ice-water) (J/m$^2$),
L = latent heat of fusion (J/kg),
$\Delta T$ = freezing point depression (K),
$V_w$ = specific volume of water (m), and
$T_o$ = 273 K.

Because in the absence of restraint $p_i$ will not differ significantly from atmospheric pressure, $p_w$ will be less than atmospheric, which will give rise to a suction that draws water continuously toward the freezing front. In frost-susceptible materials, there is a tendency for the radius of curvature to remain above $r_o$ for long periods, which results in ice segregation and excessive frost heave. For materials with a range of grain (and hence pore) sizes, various suggestions have been made regarding the selection of a characteristic critical pore radius (4).

Identification of frost-susceptible materials continues to be a significant problem for both designers and research workers. Direct tests based on the fundamental work of Taber (5) have been developed by the U.S. Cold Regions Research and Engineering Laboratory (CRREL) (6-8) and by the U.K. Transport and Road Research Laboratory (TRRL) in Great Britain (9). In both, cylindrical specimens from either undisturbed samples or recompacted material are subjected to unidirectional freezing from the top, while their bases are kept in contact with unfrozen water.

In the CRREL procedure, the top temperature is adjusted to give a specified rate of penetration, while in