ENGINEERING PROPERTIES OF COMPACTED CLAY CONDITIONED BY SATURATION AND FREEZE-THAW CYCLES

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This research quantitatively evaluates the effect of saturation and freeze-thaw cycles on the rheological characteristics of a compacted subgrade. Kaolin samples compacted by 25, 40, and 80 blows of a drop hammer were tested over a wide range of moisture contents and densities. The failure and rheological parameters investigated that relate to soil strength are unconfined compressive strength, modulus of elasticity, creep modulus, and complex elastic modulus. Laboratory compacted samples were saturated under controlled boundary stress conditions in a specially designed chamber and were then subjected to nine freeze-thaw cycles before testing. Results show that volumetric swelling, although less than the volume of absorbed water, increases as compaction energy increases and that soil structure also changes under saturation and freeze-thaw cycles. Rheological parameter values seem to be independent of the compaction energy levels used. Results also show that compacted cohesive subgrades exposed to saturation and freeze-thaw cycles in the field will experience major reductions in load-carrying capacity. Therefore, it is recommended that the design of rigid and flexible pavements over cohesive subgrades for areas in which cyclic freezing and thawing occurs should focus greater attention on providing adequate subgrade drainage so that initial saturation of the subgrade is minimized.

•SUBGRADE soils under roadway service conditions frequently experience increases in the degree of saturation because of the capillary rise of groundwater or the infiltration of surface waters. Experience indicates that an increase in moisture content is accompanied by a reduction in dry-unit weight and a coincidental loss of soil strength. This problem is further complicated by seasonal variations in climate. When the ambient temperature falls below freezing, the moisture within the upper reaches of the soil mass freezes and results in a volume increase and the development of ice lenses within the soil matrix, which are reflected as a loss of strength. Of even greater significance to the function and maintenance of highways and airfields is the loss of subgrade strength, which occurs during thaw. As ambient temperatures rise, thawing of the subgrade progresses from the surface downward. Free water from the thawed ice cannot easily drain downward because of the underlying ice barriers, and, in the absence of adequate drainage facilities, it produces highly saturated conditions in the upper parts of the soil and significant loss of strength (5). Consequently, pavement failures frequently occur during the spring thaw as a direct result of the loss of strength of the underlying base course or subgrade soils.

This paper deals specifically with the effects of saturation and subsequent freeze-thaw cycles on the strength characteristics of cohesive pavement subgrades. The

Publication of this paper sponsored by Committee on Frost Action.

*This paper is based on work performed while the authors were with the Ohio State University.

system in which the compacted soil subgrade is first saturated and is then subjected to cyclic freeze-thaw conditions will be designated saturated closed. This system has been used in the laboratory to simulate the complex conditions of adverse water and freezing temperatures affecting subgrade soils in the field. Similar techniques have been used to condition soils to saturation and freeze-thaw cycles in other research programs to evaluate the influence of frost action on compacted soil (17, 18).

OBJECTIVE AND SCOPE

Physical properties such as moisture content and density can be used to analyze the efficiency of the soil compaction process but cannot be directly incorporated in the pavement design methods (10). To realistically define the true nature of soil support, an engineer must know the effects of these parameters on the engineering properties of the soil. Why physical properties fail to give the desired information or even may lead to wrong information has been well demonstrated by Seed and Chan (13). Their investigation showed that, although the same density can be achieved at different moisture contents, the engineering properties will not be the same: Soils compacted to a given density at different moisture contents may exhibit different engineering properties depending on the method of compaction used and the resulting soil structure developed. Considering that physical properties cannot fully satisfy the requirements for pavement design and performance evaluation, a question about other limiting engineering properties that need to be selected has been raised (8, 9). Attempts to answer this question were made by treating the compacted subgrade as a linear viscoelastic material (most traffic loads fall within this range of subgrade materials) (8, 10, 11). The viscoelastic properties can be evaluated by selected rheological tests that are all interrelated by the viscoelastic theory.

An earlier publication (10) used concepts of the viscoelastic theory to investigate the effect of freeze-thaw cycles on the failure and rheological strength parameters of compacted kaolin. We have used these concepts to further evaluate the effect of simulated highway environmental conditions on the engineering properties of compacted soils.

The failure and rheological strength parameters used include the unconfined compressive strength, $\sigma'c$; modulus of elasticity, E; creep modulus, Ec; and complex elastic modulus, $|E^*|$. The unconfined compression test was used to obtain $\sigma'c$ and E, and the unconfined creep test was used to evaluate Ec and $|E^*|$. $|E^*|$ was evaluated by converting the axial creep response of the soil in the time domain to the frequency domain by using Fourier transformations (10).

This investigation was to study the effect of initial compaction energy, molding moisture, content, and degree of saturation on the engineering properties of soils exposed to temperature-induced cyclic freezing and thawing. The fundamental rheological strength parameter used in the study is the linear viscoelastic moduli. This parameter can, more realistically, evaluate the true in-service, stress-strain characteristics and load-carrying capacity of compacted highway subgrades.

MATERIALS AND SAMPLE PREPARATION

Because of its uniformity, low-level swelling characteristics, and absence of thixotropic effects, kaolin was selected to evaluate the effect of compaction, saturation, and freeze-thaw cycles on the rheological characteristics of soil.

Soil samples $1\frac{5}{16}$ in. (3.33 cm) wide and 2.816 in. (7.153 cm) high (Harvard size) were prepared by using the Ohio State University standard drop hammer compactor that has a 3.62-lb (1.64-kg) hammer and a 10-in. (25.4-cm) drop as measured from the top of the sample (7, 10). All samples were prepared by compacting the soil in five layers of equal weight and by applying the desired number of drop hammer blows. The compacted samples were wrapped in plastic bags, completely coated with wax, and stored in a humid room for several days so that they could develop a homogeneous distribution of moisture throughout. The samples were then conditioned under stringently controlled boundary stress conditions.

Preliminary studies were to select the duration for saturating the soil specimen under controlled boundary stress conditions that simulated a stress field within the subgrades immediately underlying the pavement. Thompson and Thomas (14) suggested a ratio of lateral to vertical stress, K_o, of 0.4. Jaky (3) has shown that K_o can be obtained by the relationship

$$K_o = 1 - \sin \phi$$

where ϕ is the angle of internal friction of the soil. In this relationship $K_o = 0.62$ for the kaolin; a value of 0.6 for K_o was used for the study.

The saturation of the samples was carried out until a steady state degree of saturation of 97 to 98 percent was achieved. Figure 1 shows a plot of the degree of saturation versus time (in days) for a soil sample that had an initial moisture content of 23 percent and that was prepared by drop hammer compaction energy of 40 total blows. Figure 1 shows that the compacted soil will attain 97 to 98 percent saturation within 12 to 18 hours; however, at such saturations the soil swelled excessively, and the resulting moisture content was close to its liquid limit.

Creep data indicated flow characteristics, and nonlinear behavior at test conditions with low stress levels was observed. The test is extremely critical and, in our opinion, does not represent normal highway subgrade conditions. Therefore, so that the complex freezing and thawing phenomenon existing in the field could be approximated, the specimens were saturated to a constant moisture content of 35 to 36 percent, which is close to the plastic limit of the soil. Usually it takes 8 hours or more to attain this moisture state in the saturation device.

The following procedure was adopted to saturate the samples by using specially designed equipment shown in Figures 2 and 3:

1. The sample stored in the humid room is weighed, and the weight recorded.

Figure 1. Degree of saturation versus time in capillary saturation device for identical specimens.

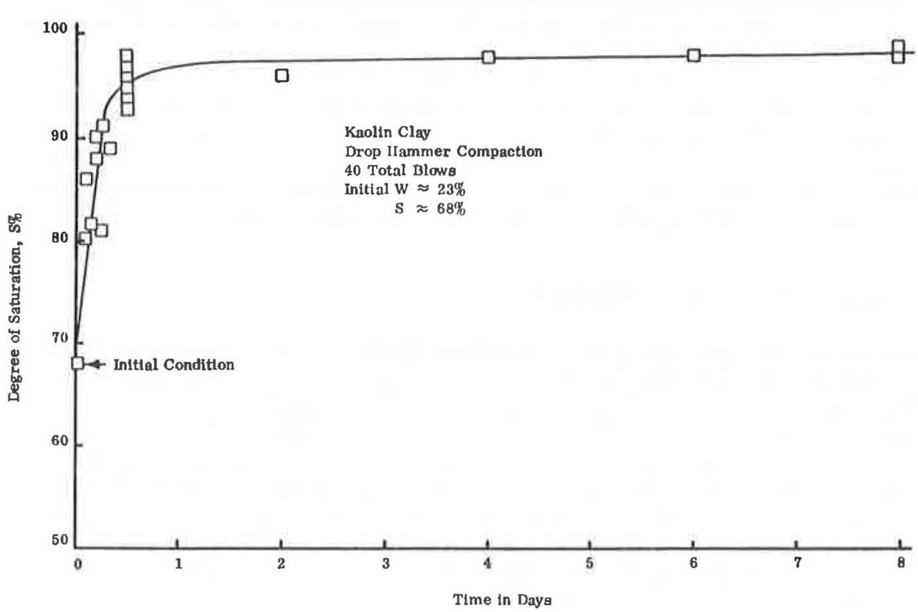


Figure 2. Capillary saturation device for boundary stress conditions.

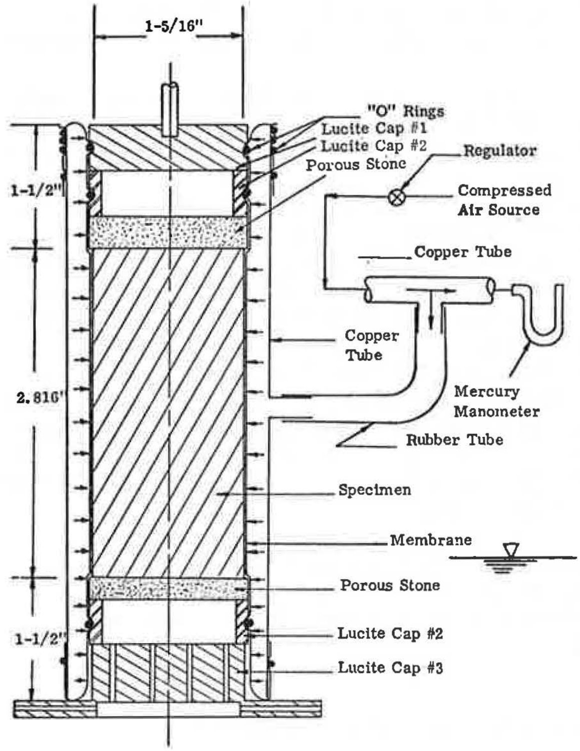
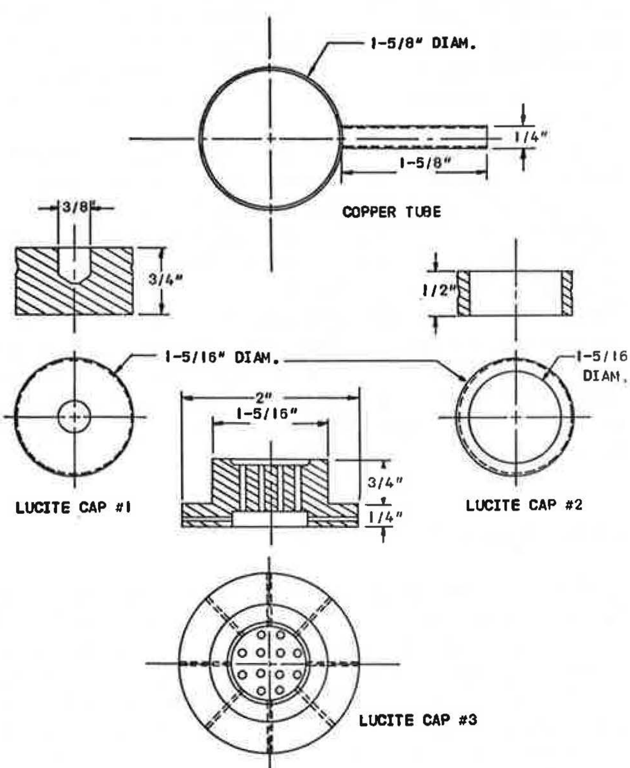


Figure 3. Details of capillary saturation device.



2. The final expected wet weight of the soil specimen is determined and recorded.
3. A stretched membrane on the tube is rolled back, and rubber O-rings are slipped over it.
4. The test specimen, saturated porous stones, and Lucite caps are introduced into the copper tube as shown in Figure 2, and the setup is placed in a tray filled with distilled water to a level about 0.25 in. (0.04 cm) higher than the lower end of the test specimen.
5. Lateral and axial pressures of 1.2 and 2.0 psi (8.3 and 13.8 kPa) are applied respectively to give $K_o = 0.6$.
6. Each end of the sample is exposed to half of the total time required to achieve selected saturation by switching caps 3 and 1, and the copper tube is carefully inverted. Any discrepancy in the final weight is adjusted either by saturating for additional time or by drying.
7. Subsequent to saturation, the sample is wrapped in a plastic bag, is sealed with wax, and is placed in the humid room so that it can be uniformly moisturized.
8. Each specimen is subjected to nine freeze-thaw cycles (10); the freeze cycle consists of 7 hours at a constant temperature of -20 F (-28.9 C), and the thaw cycle occurs overnight in the humid room. The last thaw cycle before creep testing is at least 2 days long.

The system used to condition the soil samples in the laboratory is an approximation of the complex clay-water-temperature system as it exists in nature. Such systems are often used to determine the engineering properties of soils for pavement designs (17, 18).

EXPERIMENTAL PROCEDURE

Unconfined creep and unconfined compression tests were used to find the rheological and strength parameters of a standard soil. The unconfined compression test is used to measure the undrained shear strength. The test was performed according to ASTM D2166-63T at a strain rate of 2.82 percent/min (0.2 cm/min for samples 7.15 cm high). Unconfined compressive strength and modulus of elasticity were also evaluated with this test.

For rheological creep tests, the test procedure consisted of cycling the axial load twice through the load and unload cycle to condition the samples. The third cycle (steady state condition for kaolin) was used to obtain the experimental data and consisted of 30 min of loading and 30 min of creep recovery in the unloaded state (10). Axial strain data, as a function of time, were used to calculate Ec and $|E^*|$ by transferring the experimental results from the time domain to the frequency domain (10). Based on viscoelastic linearity tests, 3.75 psi (25.9 kPa) was used as the axial stress for all creep tests. In the data analysis, $|E^*|$ corresponding to a frequency of $w = 0.1$ rad/s (vehicle speed of 0.065 mph or 0.1 km/h) was selected because subgrade materials loaded by low-speed traffic, as in parking areas, will exhibit greater deformations and fail earlier than high-speed roadway sections of equal design under the same traffic load and environmental conditions.

EXPERIMENTAL RESULTS

Widely used soil parameters such as dry density, unconfined compressive strength, penetration-needle resistance, and California bearing ratio, although convenient, do not exactly reflect the true stress-strain characteristics of the in-service conditions of the compacted soil because they are greatly influenced by environmental and loading conditions. These criteria also are not directly or fundamentally related to the strength and deflection parameters used in the structural design of rigid or flexible pavements; however, rheological parameters seem to describe the soil characteristics more rationally than many parameters currently used.

Moisture content of the subgrade does not generally remain constant subsequent to placement of a pavement, but, with the passage of time, it may increase because of (a) infiltration of rainwater through the permeable surface of the pavement, through cracks in the pavement surface, or at the pavement edges; (b) movement of the liquid or vapor from the water table; and (c) a high water table during the spring months or floods. Though it is possible to reduce the amount of infiltration to a great extent by proper design, most subgrade materials may reach an equilibrium moisture content quite in excess of their initial moisture contents. Final moisture content depends on factors such as soil type, initial moisture content and density, topography, compaction energy, type of compactor, and soil structure.

An increase in the moisture content can cause considerable loss of subgrade strength and support. Greater losses will occur if an increase in the moisture content is followed by periodic freezing and thawing conditions. Therefore, to study the changes in the rheological parameters under these conditions is significant. So that these conditions could be simulated in the laboratory, the as-molded soil samples were saturated to a final moisture content of 35.5 ± 0.5 percent under boundary conditions to produce $K_o = 0.6$, and then were subjected to nine freeze-thaw cycles, as determined from the preliminary studies (10).

Three compaction energy levels of 25, 40, and 80 blows with moisture contents ranging from about 22 to 32 percent were used. Specific molding moisture contents used for each compaction energy level were 22, 25, 29, and 32 percent for 25 and 80 blows; and 22, 25, 26, 29, and 33 percent for 40 blows. The moisture-dry density relationship for kaolin for various compactive efforts is shown in Figure 4.

The experimental results are discussed in the following two sections.

Effects of Saturation

The effect of saturation on swelling characteristics of soils has been investigated by many researchers (1, 2, 4, 6, 12, 13, 16). Ladd (4) points out that swelling characteristics are influenced significantly by (a) clay composition; (b) compaction conditions, i.e., molding water content, dry density, degree of saturation; (c) compaction method; (d) chemical properties of pore fluid; (e) confining pressure; and (f) time allowed for swelling. In this study, with the exception of compaction variables, all parameters were kept constant.

According to Ladd (4), clays compacted at a lower water content, at which the water deficiency in the double layer is high and the degree of saturation is low, will often swell more than clays compacted at a high water content. Lamb (5) points out that swelling based on water inhibition is due almost entirely to an increase in the size of the micelle. Therefore, because clays compacted on the dry side of optimum have a greater water deficiency (water needed to fully develop the double layer) than soils compacted on the wet side, the samples compacted on the dry side of optimum, in the presence of water, would be expected to swell more than those on the wet side of optimum.

According to Seed, Chan, and Lee (13), swelling can be caused not only by osmotic pressures but also by compression of air in the voids as water permeates the soil material. This compression of air is able to produce sufficient pressure to cause an expansion of the soil mass, particularly when the soil structure is too weak to withstand these pressures (Fig. 5). Two observations can be made from Figure 5: (a) Volumetric swelling is always less than the volume of absorbed water; therefore, an increase in the degree of saturation must occur; and (b) for the same water pickup, volumetric swelling increases with an increase in compaction energy (an indication of increase in soil density).

Samples prepared with higher compaction energies have less air voids than those prepared with lower compaction energies. Consequently, for the same amount of water, compression of air will produce greater pressure in samples with low air voids than in samples with high air voids. Physicochemical phenomena and compression of air, however, occur concurrently, and both are significant for producing swell

Figure 4. Dry unit weight versus moisture content for drop hammer compaction.

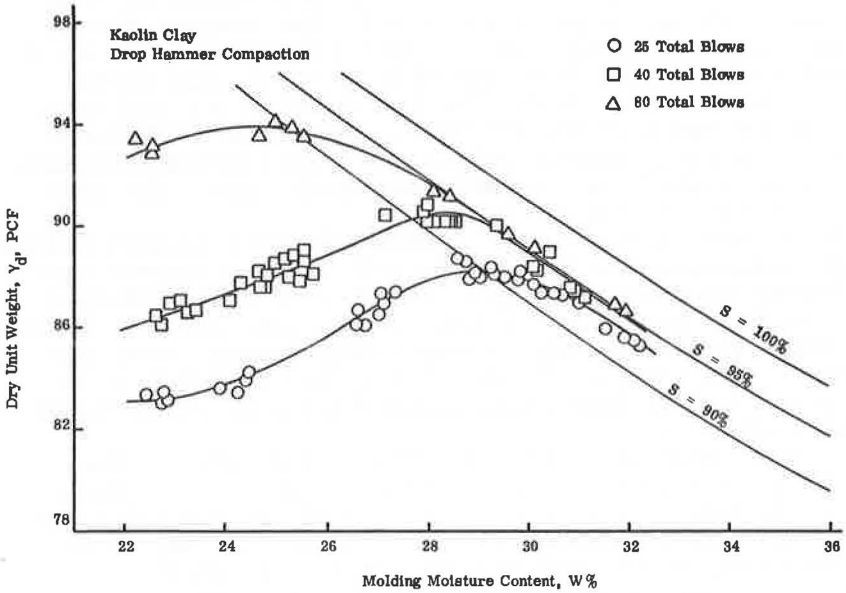
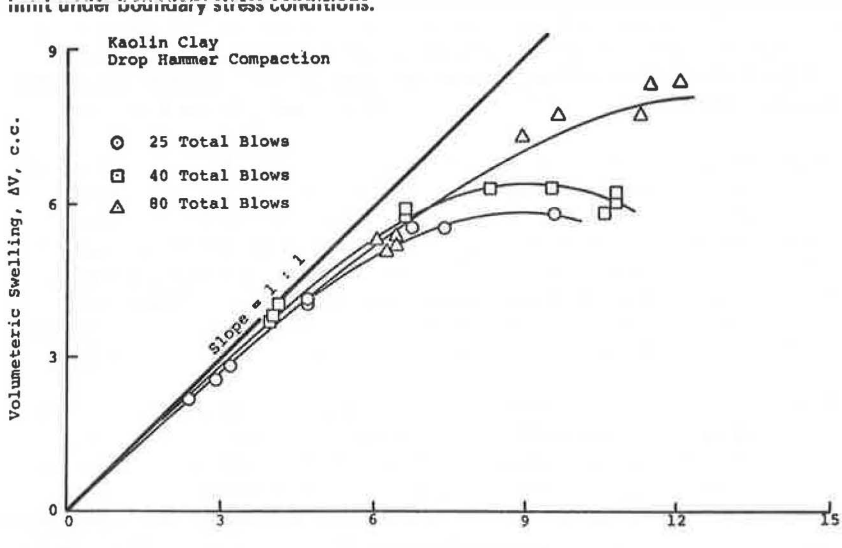


Figure 5. Relationship of volumetric swelling and water pickup for soaking to plastic limit under boundary stress conditions.



in compacted clays. Figure 6 shows the percentage of volumetric change after saturation versus initial moisture content for three levels of compaction energy. The results from Figures 5 and 6 substantiate the findings of other investigators that for any given dry density swelling decreases with increasing molding water content, whereas for any given molding water content the swelling increases with increasing density (an indication of increase in compaction energy). This conclusion is true mainly on the dry side of optimum because at higher moisture contents on the wet side of optimum the effect of compaction energy is practically negligible (Fig. 4).

From the standpoint of swelling characteristics, although it appears that compacting on the wet side of optimum will be beneficial, it is well known that such water contents will produce compacted materials with lower strength and higher compressibilities. Therefore, the choice of desired molding water content and dry density for a given method of compaction cannot be made merely from a single criterion such as lower swelling characteristics. The final decision should be based on criteria that will ensure a workable range for volume-change and stretch characteristics. This brings us to the effect of saturation and freeze-thaw cycles on the failure and rheological strength parameters of compacted clays.

Effects of Saturation and Freeze-Thaw Cycles

For the design of either rigid or flexible pavements, the modulus of elasticity and complex elastic modulus are the critical factors because they control serviceability, deformation characteristics, and the design thickness of the various structural components of a pavement. Thus, for most economical and structurally safe design, it becomes imperative that the variation of the rheological parameters and changes in the moisture content or degree of saturation be thoroughly investigated.

Figures 7 through 14 show plots of variations in the strength parameters, $\sigma'c$, E, Ec, and $|E^*|$, and initial moisture content and degree of saturation. Because of large scatter indicated on these plots, all data points can generally be approximated by one curve representing an average value, or they can be accommodated within a small band. This indicates that, for samples tested in the saturated closed system, the level of compaction energy does not appreciably affect the soil strength and that only molding moisture content or degree of saturation controls the behavior.

We contend that the large scatter is caused by significant disturbance in the as-compacted soil structure as a result of adverse environmental conditions of saturation and subsequent freeze-thaw cycles.

Studies at Constant Initial Molding Water Content

Figures 7 through 10 show that the in-service creep modulus, modulus of elasticity, and complex elastic modulus of a conditioned-soil roadway decrease with an increase in the initial molding moisture content and that the unconfined compressive strength at failure shows a marginal increase for moisture contents to the dry side of the optimum.

Studies at Constant Initial Degree of Saturation

A given moisture content may be on the dry side of optimum for low levels of compaction energy and on the wet side of optimum for high levels of compaction energy. If one studies the response of the soils at a constant degree of saturation, this drawback can be avoided. Therefore, the variation of the selected strength parameter due to a range of compaction energy inputs was also studied at a constant degree of saturation (Figs. 11-14). Variations in the failure and the rheological parameters of the conditioned samples with initial degree of saturation indicate that, up to initial saturations of about 90 to 95 percent, these parameters for all practical purposes do not reflect

Figure 6. Percentage of volumetric change versus initial molding moisture content.

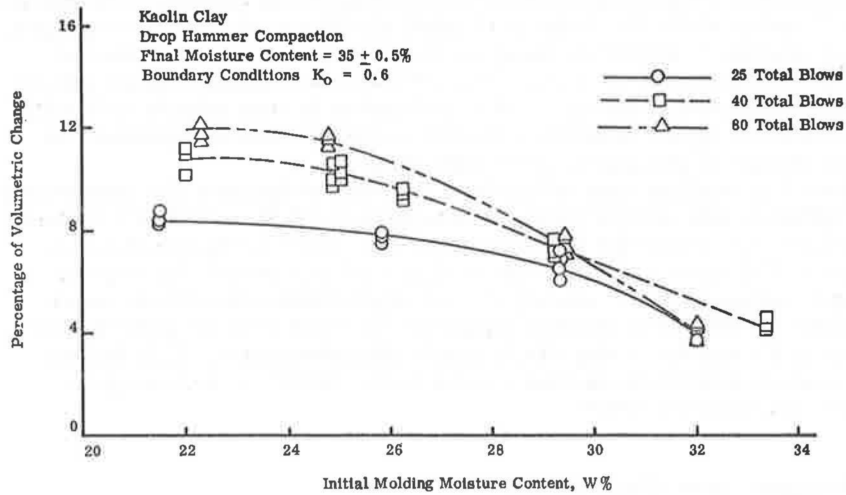


Figure 7. Unconfined compressive strength versus initial molding moisture content.

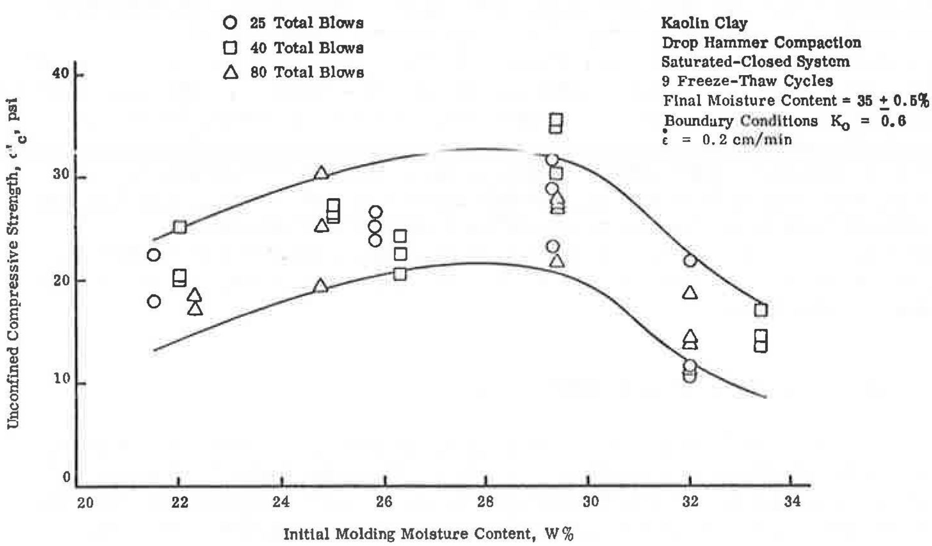


Figure 8. Modulus of elasticity versus initial molding moisture content.

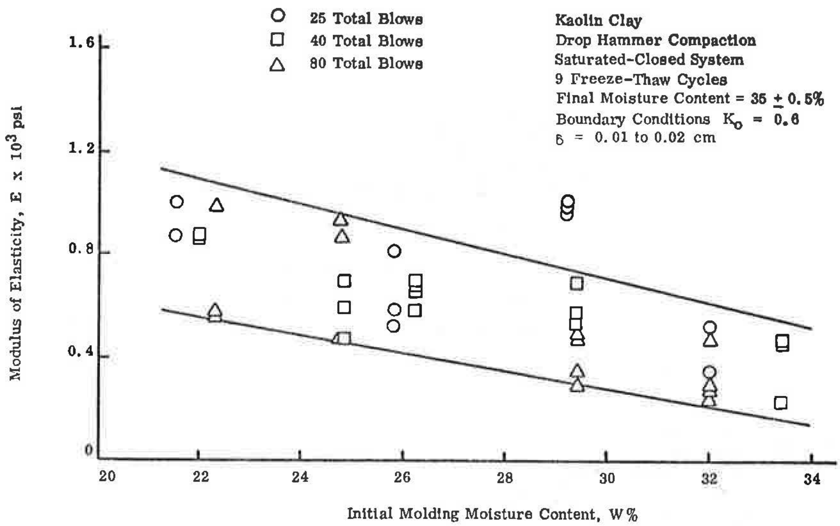


Figure 9. Creep modulus versus initial molding moisture content.

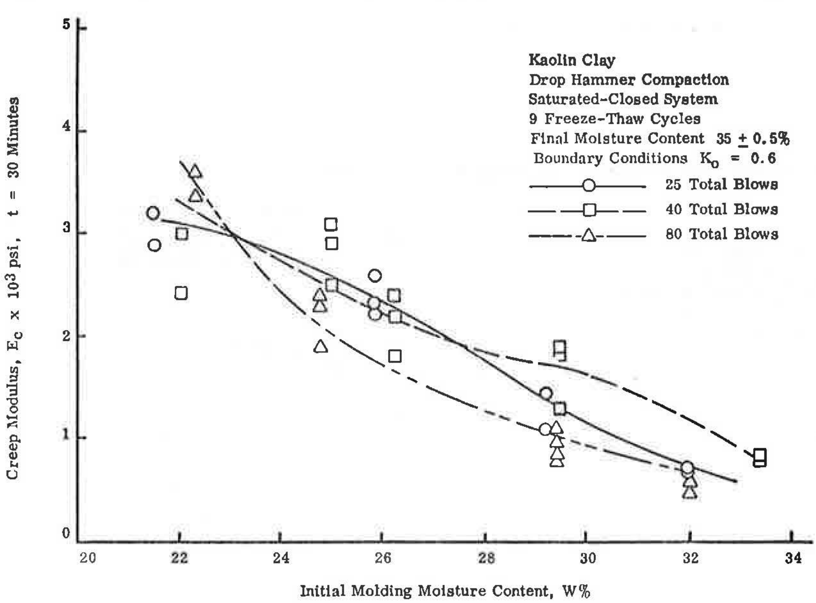


Figure 10. Magnitude of complex elastic modulus versus initial molding moisture content.

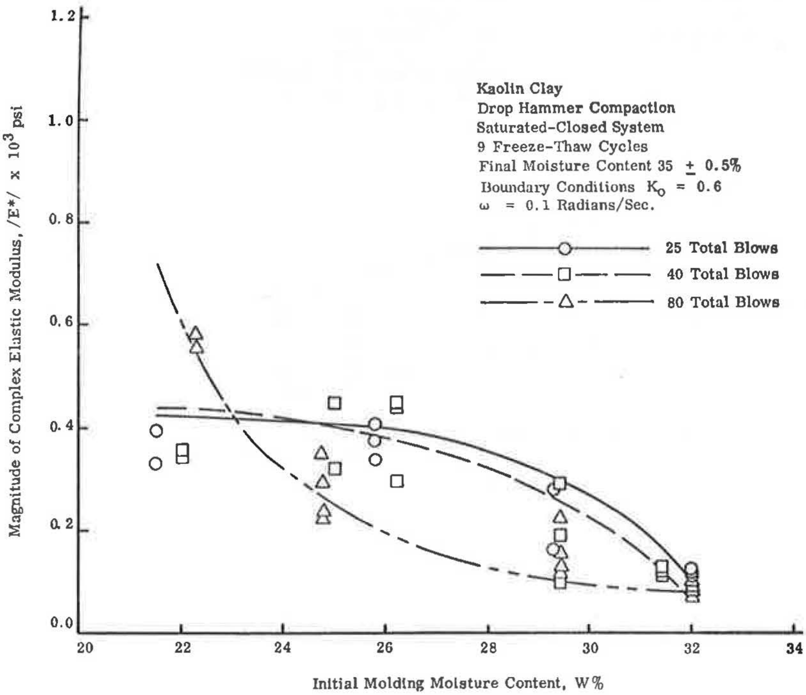


Figure 11. Unconfined compressive strength versus initial degree of saturation.

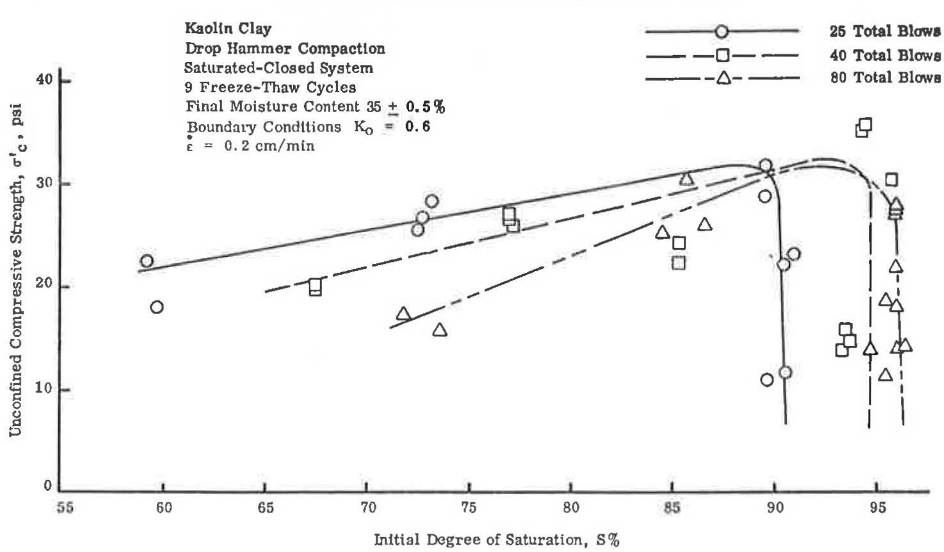


Figure 12. Modulus of elasticity versus initial degree of saturation.

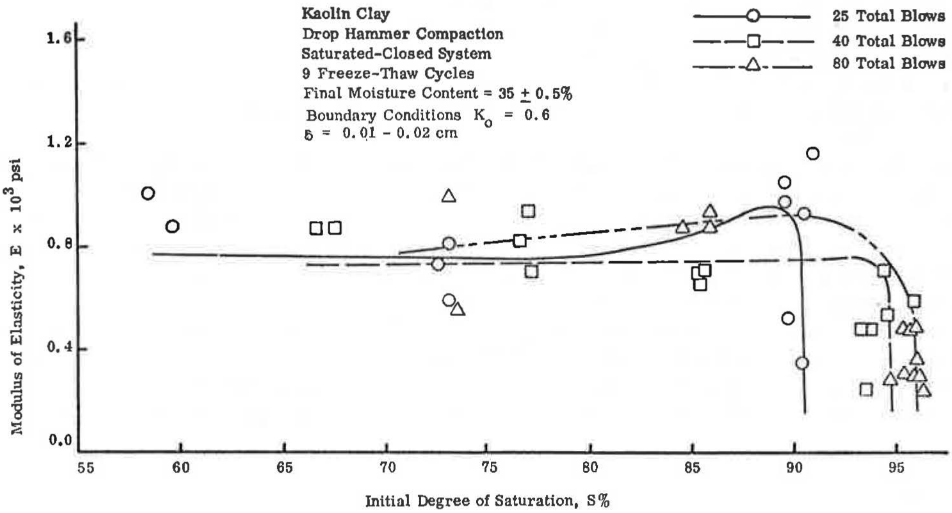
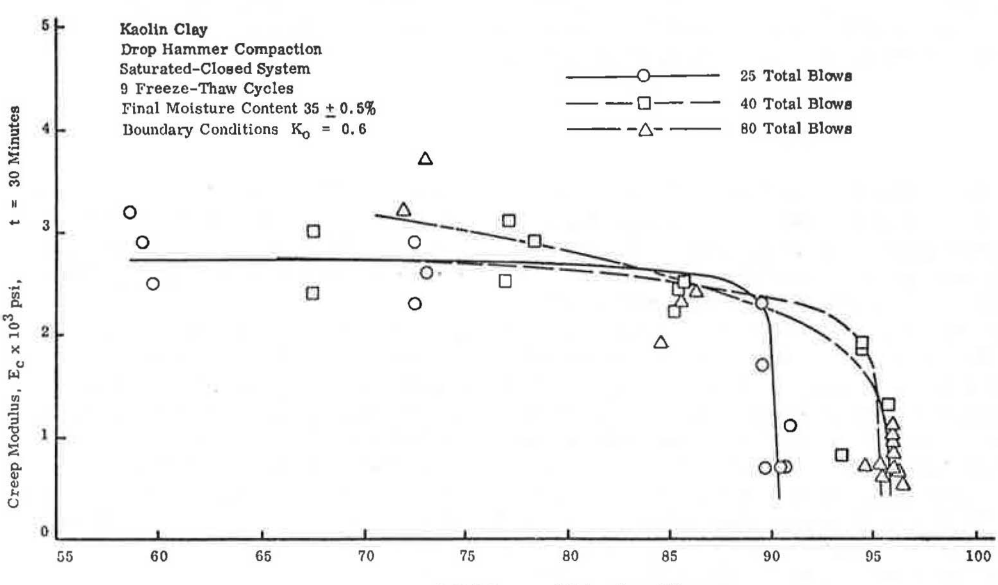


Figure 13. Creep modulus versus initial degree of saturation.



any major changes in their value (the lower limit corresponds to compaction energy of 25 blows, and upper limit to 40 and 80 total blows). Beyond these limits, soil strength falls suddenly and approaches its minimum. Before the limits of 90 or 95 percent initial saturations are achieved, some strength parameters might show a little increase or decrease, but this change is not of any consequence when it is compared to the overall drastic effects of conditioning the compacted samples by saturation and freeze-thaw cycles.

The adverse effects of saturation and freeze-thaw cycles on conditioning compacted subgrade can be better understood by comparing the results of as-compacted state (11) with those of the closed system (10) (in which as-compacted samples were tested after nine freeze-thaw cycles) and with those of the saturated-closed system. This analysis is given in Tables 1 and 2 for 25 and 40 drop hammer blows respectively.

The comparison of the different compaction conditions is not exactly at either a constant molding moisture content or a constant degree of saturation; therefore, discrepancy arises from preparing samples at different times. However, the data indicate that these variations will not significantly affect the overall comparison. The data further indicate the following for the closed system and saturated-closed system.

Closed System

For the closed system, major loss of stretch occurs for conditions on the wet side of the optimum. On the dry side of optimum, the loss of strength is less than about 10 percent, but, while on the wet side at higher moisture contents, strength loss can be as great as 80 percent. The loss, however, seems to decrease with an increase in the compactive effort. The parameter values achieved for the saturated-closed system are also equal to or smaller than those for the closed system for higher molding moisture contents on the wet side of optimum.

Saturated-Closed System

For the saturated-closed system, over most of initial moisture contents investigated, strength loss from about 75 to 90 percent of the as-compacted state occurs. The loss increases somewhat as the compactive effort increases, which directly reflects that, during saturation, volumetric swelling (an indication of reduction in unit weight) increases as the compactive effort increases.

Conclusions for failure strength parameters also hold for rheological parameters of E, Ec, and $|E^*|$. The loss of bearing capacity caused by saturation and freeze-thaw cycles has been reported by Townsend and Csathy (15) who observed a loss in strength as great as 70 percent. In the field, however, this loss in stability may decrease as thawing continues, and shear strength or bearing capacity may approach previous values of the closed system. Regaining strength will be significantly affected by the final state of the compacted soil structure before it is damaged by factors such as saturation and freeze-thaw cycles; frequency of such cycles; reduction in saturation, which will be directly influenced by draining ability of the subgrade soil; and the frequency and intensity of traffic during the thawing period.

PAVEMENT DESIGN CONSIDERATIONS

In the field, soils are seldom compacted at saturations less than about 80 percent. As such, more emphasis should be placed on investigating the changes in the rheological strength parameters of the pavement subgrade at saturations exceeding this limit. As noted, for saturations in excess of about 85 percent both the failure and the rheological parameters for the saturated-closed system drop to values between about 10 and 25 percent of the as-compacted state. This reflects proportionate reduction in the load-carrying capacity. If such conditions are allowed to develop in the field, they will

Figure 14. Magnitude of complex elastic modulus versus initial degree of saturation.

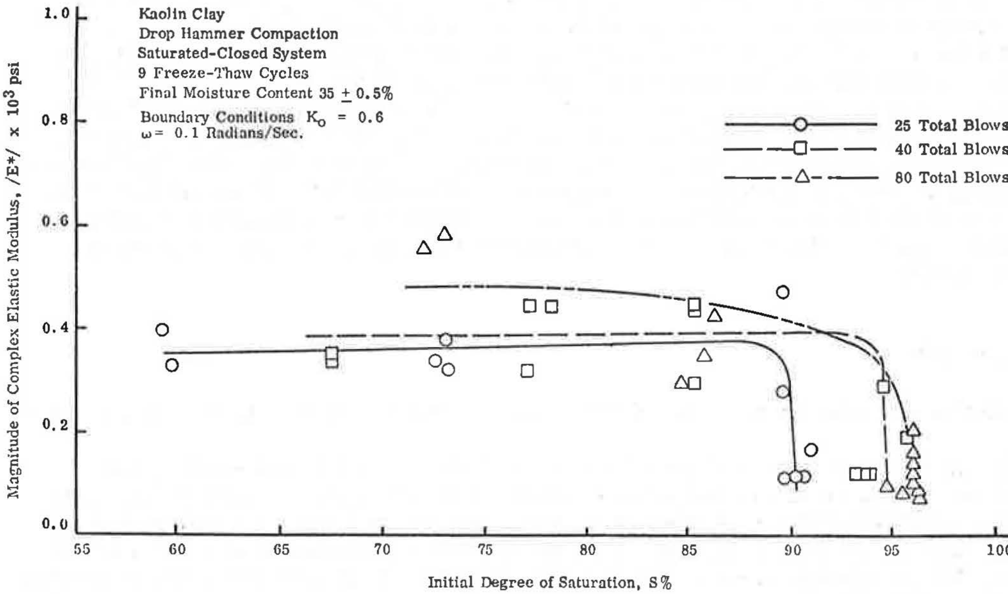


Table 1. Comparison of strengths in as-compacted state, closed system, and saturated-closed system for 25 drop hammer blows.

As-Compacted State		Closed System		Saturated-Closed System		Unconfined Compressive Strength (psi)			Ratio of Closed System to As-Compacted State (percent)	Ratio of Saturated-Closed System to As-Compacted State (percent)
Moisture Content (percent)	Saturation (percent)	Moisture Content (percent)	Saturation (percent)	Moisture Content (percent)	Saturation (percent)	As-Compacted State	Closed System	Saturated-Closed System		
22.02	59.5	22.02	59.5	21.5	59.16	135	125.3	20.2	92.80	14.97
25.50	72.5	25.50	72.5	25.8	72.78	156	145.5	26.7	93.24	17.13
29.30	89.1	29.30	89.1	29.2	88.3	147	103.6	35.7	70.47	20.28
32.61	92.0	32.61	92.0	32.0	90.5	80	16.1	14.8	20.11	18.50

Note: 1 psi = 6.9 kPa.

Table 2. Comparison of strengths in as-compacted state, closed system, and saturated-closed system for 40 drop hammer blows.

As-Compacted State		Closed System		Saturated-Closed System		Unconfined Compressive Strength (psi)			Ratio of Closed System to As-Compacted State (percent)	Ratio of Saturated-Closed System to As-Compacted State (percent)
Moisture Content (percent)	Saturation (percent)	Moisture Content (percent)	Saturation (percent)	Moisture Content (percent)	Saturation (percent)	As-Compacted State	Closed System	Saturated-Closed System		
22.09	66.8	22.09	66.8	22.0	67.2	180	173.3	21.7	96.26	12.07
24.72	76.5	24.72	76.5	24.91	77.0	201	182.3	26.4	90.68	13.11
26.24	85.7	26.24	85.7	26.20	85.3	201	167.6	21.4	83.36	10.67
30.24	92.5	30.24	92.5	29.40	94.4	135	38.4	33.6	28.44	24.90

Note: 1 psi = 6.9 kPa.

make a highway or airport pavement practically incapable of supporting heavy traffic loads. Even for the closed system, rapid loss of the carrying capacity of the compacted subgrade was observed for saturations in excess of about 85 percent (10).

On the basis of the reported research results for closed and saturated-closed systems, it is recommended that greater attention be given to the design of pavements constructed over cohesive subgrades in areas where seasonal temperature variations cause cyclic freeze-thaw conditions to occur. The proper design of surface and subsurface drainage facilities would minimize increases in the initial degree of saturation and subsequent loss of strength in the subgrade. Optimizing the soil compaction conditions will also reduce the influence of adverse environmental conditions, improve the pavement performance, and produce subgrades with better in-service strength characteristics.

CONCLUSIONS

The following are concluded for the materials and experimental conditions investigated:

1. Volumetric swelling is always less than the volume of water absorbed, i.e., an increase in the degree of saturation must occur. For any given compactive effect, an increase in saturation of the as-compacted soil state brings about a corresponding volume increase; the amount of increase depends on molding saturation or water content. However, the percentage of volumetric change decreases with increasing initial molding moisture content. In addition, for any given molding moisture content, percentage of volumetric change increases (an indication of reduction in the unit weight) as compactive effort increases.
2. Data indicate that significant changes in as-compacted soil structure may be anticipated when the soil is subjected to saturation and subsequent freeze-thaw cycles. For these simulated critical climate conditions the soil's rheological parameters decrease significantly and are almost independent of the compaction energy levels used.
3. Rheological parameters for saturations up to 90 to 95 percent do not seem to show any significant variations. The parameters values fall suddenly and approach their minimum after these critical saturations.
4. Irrespective of initial molding moisture content or degree of saturation investigated, values of rheological parameters for the saturated-closed system are approximately 75 to 90 percent lower than those of the as-compacted state. These are also equal to or smaller than the parameter values in the closed system for higher molding moisture contents on the wet side of the optimum at which reductions up to approximately 80 percent of the as-compacted state can occur. This quantitatively indicates the severity of environmental conditions where the compacted soil is first saturated and then subjected to freeze-thaw cycles.

ACKNOWLEDGMENTS

This research was sponsored by the Ohio Department of Transportation in cooperation with the U.S. Department of Transportation, Federal Highway Administration. The interest and cooperation of these agencies are gratefully acknowledged. The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Ohio Department of Transportation or the Federal Highway Administration.

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