Characterization of Subgrade Soils at Simulated Field Moisture

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It is important to assess the strength characteristics of subgrade soils at equilibrium moisture content (EMC), generally a few percentage points wet of optimum moisture content (OMC). Investigation of the effect of saturation—degree and mode—above OMC on the resilient modulus (M_R) of laboratory compacted subgrade soils is the topic of this paper. Three modes of saturating (wetting) are investigated: (*a*) capillary saturating, (*b*) vacuum saturating, and (*c*) molding wet of optimum. EMC and 96 percent saturation are the two different degrees of saturation considered. The M_R of soil samples, both coarse- and fine-grain, are evaluated for different combinations of degree of saturation and saturating mode. The test results indicate that the degree of saturation above OMC has a nominal effect (20 percent) on M_R of coarse-grain soils, whereas it has a severe effect (50 to 75 percent decrease) on the M_R of fine-grain soils. Another finding is that both degree of saturation and saturating mode affect the M_R of fine-grain soils. For interpretation of the results, particularly how M_R is affected by saturation, the four-phase concept for unsaturated soils is used.

Soils are characterized by the constants relating stress state variables or stress state variables to deformation state variables depending on the type of problem at hand. The constants relating stress state variables are cohesion and angle of internal friction for the shear strength equation, and pore pressure parameters for the pore pressure equation. Young's modulus, Poisson's ratio, bulk modulus, and so forth are the constants relating stress to strain. Sands are better characterized by bulk modulus and shear modulus than Young's modulus and Poisson's ratio, according to a work by Domaschuk and Wade (*1*). The hyperbolic equations for tangent Young's modulus and secant bulk modulus facilitating the use of generalized Hooke's law for the analysis of stresses and displacements in soil masses has been proposed (*2*). The constants for the hyperbolic tangent Young's modulus and tangent bulk modulus for a range of soils are tabulated elsewhere (*3*). All of the previously mentioned characterizations are suitable for a wide range of loading, including failure state.

The relative importance given to the behavior of soil under repeatedly applied stresses, compared with the behavior under gradual loading, can be attributed to the interest in simulating highway loading, and to developing a rational design procedure limiting the permanent deformations and deformation modulus of highway foundation for comfortable riding conditions. The characterizing parameter chosen for subgrade soil is designated as resilient modulus (M_R). M_R is the ratio of deviatoric stress to the resilient elastic axial strain.

AASHTO T274-82 encompasses the pioneering test specification proposed by AASHTO (*4*). Later, this test procedure was revised to AASHTO T292-91 I and subsequently to AASHTO T294/SHRP P46. The preceding referenced test methods are proposed for determining the dynamic elastic modulus (M_R) under conditions that reasonably represent real-world stress states of subgrade materials subjected to moving wheel loads. Application of repeated axial deviator stress of fixed magnitude, duration, and frequency to an appropriately prepared and conditioned cylindrical test specimen entails the test procedure designated in T274-82. During the test, the specimen is subjected to a static all-around stress. The resilient axial strain response of the specimen is measured and used for calculating the dynamic stress-dependent M_R. Numerous researchers have studied M_R of subgrade soils: Fredlund et al. (*5*), by molding samples at different moisture contents and densities; Edil and Motan (*6*), by preparing samples at optimum, dry and wet of optimum, and equilibrating to various soil suctions using moisture extractors; and Thompson and Robnett (*7*), by molding samples at optimum moisture content, optimum +1 percent, and optimum +2 percent and all of them at 95 and 100 percent of AASHTO T99 unit weight.

Pavement life depends on the performance and condition of its components. During the service life, subgrade undergoes moisture variations and consequently large strength fluctuations as well. To quantify the effect of the ambient conditions, AASHTO Guide (1992) proposed that an "effective modulus" be used in the design process. Effective modulus is an average modulus weighted with respect to seasonal changes. It is critical that the changes taking place in the strength characteristic of proposed subgrade soil at the expected field condition be investigated beforehand.

The subgrade is generally prepared by compacting to 95 to 100 percent of dry unit weight and at optimum moisture content (OMC), as determined by AASHTO T99. Upon sealing the ground surface, subgrade soil (with a pavement) exhibits an increase in the average water content at the shallower part of the subgrade and a decrease in fluctuations of water content over time (*8*). The moisture attained after construction is in equilibrium with the environment and is called the equilibrium moisture content (EMC). The moisture movement and moisture equilibria under covered areas have been studied by numerous researchers (*9–11*). Historically research studies of the effect of moisture on soils have coincided with a growing need to evaluate the climatic dependency of the soil parameters in highway construction projects. It has been reported (*9*) that the moisture stability beneath the greater part of the paved area is similar at every test site regardless of the climatic conditions. It was concluded (*10*) that the subgrade moisture content shows continuous small variations with seasons. Considerable work has been devoted to quantifying the factors that affect EMC. The factors known to influence EMC include the type of subgrade soil, level of water table in the vicinity, condition of the surface layer, and so forth. A moisture index designated as Thornthwaite moisture index (TMI) was developed (*12*), which relates subgrade moisture conditions to climatic indices, such as precipitation, evapotranspiration, mean monthly air temperature, and number of hours of daylight per

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day. TMI is gaining acceptance for empirically estimating moisture conditions in pavement subgrade soils. The Corps of Engineers' study on subgrades of flexible airport pavements in Mississippi and in a few other states concludes: (*a*) the EMC in subgrade soils is often near the plastic limit and directly proportional to the liquid limit, (*b*) the degree of saturation corresponding to EMC of plastic soils exceeds 85 percent, and (*c*) the annual rainfall has no effect on EMC (*13*). Investigations of theoretical methods of estimating EMC include those of Black et al. (*14*), Russam (*15*), Coleman and Russam (*16*), and the researchers at the British Road Research Laboratory (*17*). According to a work by Chu and Humphries (*18*), the moisture content of the laboratory compacted soil sample at 0.914 m (3 ft) of water suction, applied at the top and bottom of the sample, can duplicate the field moisture content in noncoastal areas. In their work, investigations were conducted for correlating subgrade moisture with local factors such as type of subgrade soil, environmental factors, and so forth. The results, which covered 32 sites, showed that the finer the soil the greater the difference between the EMC and OMC. The maximum difference observed was approximately 8 percent at 55 percent fines content (−#200). The data trend is such that the EMC in a few soils, particularly with fines content less than 25 percent, was smaller than the OMC. Subsequently, efforts were made to develop a relatively simple procedure (capillary wetting) for conditioning soil specimens to simulate anticipated field moisture conditions.

For laboratory-compacted specimens, AASHTO T274-82/AASHTO T292-91 I test procedures suggest a backpressure saturating after molding the sample at optimum moisture content. This is a quick method of saturating when compared with the method prescribed elsewhere (*18*). AASHTO T294-92 I/SHRP protocol 46 (revised version of AASHTO T292-91 I) stipulates testing the sample at OMC and 95 percent maximum dry unit weight; however, it does not include backpressure saturating.

The objective of the study is to investigate the effect of field subgrade moisture (or EMC) on M_R and to determine the effect of saturation—degree and mode—on resilient modulus of subgrade soils. Different modes of saturating (wetting) studied include:

- Capillary saturating under 0.914 m (3 ft) of water suction (*18*). (A schematic diagram of the setup is shown in Figure 1).
- Vacuum/backpressure saturating as specified in AASHTO Designation T274-82/AASHTO T292-91 I, with slight modifications.
- Incorporating EMC or other predetermined moisture during sample preparation, and molding at a unit weight matching that attained during capillary saturating.

For interpretation of the results, particularly how M_R is affected by saturation, the four-phase concept for unsaturated soils is used (*19*).

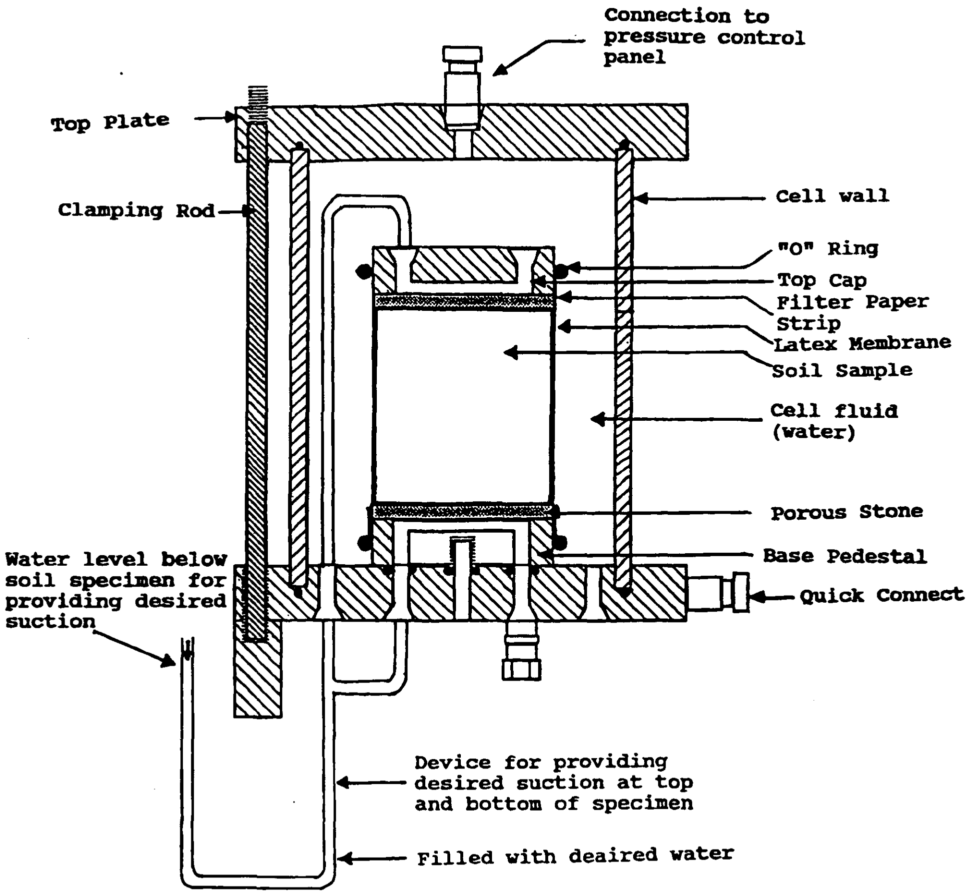

FIGURE 1 Setup for capillary saturating.

SAMPLE PREPARATION, CONDITIONING, AND TESTING

The classification and index properties of two coarse-grain and two fine-grain soils selected in this study are shown in Table 1. The soil, after mixing with a predetermined amount of water, was kept sealed in an airtight plastic bag in a humidity room for 24 hr before molding. Compaction of the specimen was in four layers by imparting 25 blows per layer. The sample, kept in the mold for 2 hr, was extruded and allowed to rebound for another 2 hr before further treatment or testing. Two conditioning procedures were followed: (*a*) capillary saturating and (*b*) vacuum or backpressure saturating. On average, capillary saturating takes 3.5 days, whereas vacuum saturating requires 1 to 3 hr. The vacuum saturating included the following steps:

1. A vacuum of 21 kPa (3 psi) was applied to the top of a specimen, which was isotropically confined by a pressure of 35 kPa (5 psi), until the air bubbles stopped coming out of the specimen.
2. The specimen was subjected to three sets of back pressures for equal amounts of time, with a differential pressure of 35 kPa (5 psi) between the bottom and top of the specimen. The confining pressure was maintained at a level 35 kPa (5 psi) greater than the highest back pressure. The set of back pressures applied at the bottom of the specimen include, 35, 69, and 103 kPa (5, 10, and 15 psi respectively).

The laboratory compacted and saturated specimens were loaded in the repeated load triaxial machine. AASHTO T274-82 (*20*) procedure was followed for M_R testing. The specimens were tested at the following conditions for each soil:

1. Molded at OMC and 97 percent AASHTO T99 unit weight;
2. Molded at OMC and 97 percent AASHTO T99 unit weight, and capillary saturated at 0.914 m (3 ft) of water suction;
3. Molded at OMC and 97 percent AASHTO T99 unit weight, and capillary saturated at 0 m of water suction;
4. Molded at OMC and 97 percent AASHTO T99 unit weight, and vacuum saturated to estimated EMC;
5. Molded at OMC and 97 percent AASHTO T99 unit weight, and vacuum saturated to maximum possible saturation (approximately 96 percent);
6. Molded at wet of optimum and corresponding unit weight, as obtained in a capillary saturated specimen at 0.914 m (3 ft) of water suction (as in test condition 2); and
7. Molded at wet of optimum and corresponding unit weight, as obtained in a capillary saturated specimen at 0 m of water suction (as in test condition 3).

The tests were repeated at each condition to obtain a triplet satisfying the Chauvenet's criteria (*21*), which states that all points should be retained within a band around the mean value, which corresponds to a probability of $1 - 1/(2N)$, where N = number of observations.

ANALYSIS OF RESULTS

The M_R test results of four soils for the various saturation conditions are shown in Table 2. Table 3 lists the OMC and EMC and the corresponding degree of saturations of all four soils. Each test value listed in Table 2 is an average of a minimum of three tests. The percentage reduction of M_R with degree of saturation, for typical coarse-grain and fine-grain soils, is shown in Figure 2. As expected, M_R decreased with saturation, resulting in the following observations:

- The M_R of coarse-grain soils is not significantly affected by the amount and manner of saturating; the reduction is approximately 20 percent.
- The M_R of fine-grain soils is drastically reduced by saturation, the reduction being 50 to 75 percent depending on the degree of saturation, and the saturating method used.
- In the case of fine-grain soils, the saturating method used has a varying effect on the M_R of the specimens tested. The M_R-value of the vacuum-saturated specimen decreases exponentially with increasing degree of saturation, whereas it decreases linearly with capillary saturating and also with specimens molded wet of optimum.
- In case of fine-grain soils, the decrease in M_R for both capillary saturated specimen and those molded wet of optimum is nearly identical.

How reasonable these results are is addressed by comparing the M_R-trend with saturation of the authors' results with those of Thompson and Robnett (*7*). Thompson's results, expressed in two equations, are sketched in Figure 3. The authors' results are plotted in the same figure. The agreement of the two sets of data validates the test results. A recent study by Li and Selig (*22*) quantified the effect of soil physical state on M_R by two path-dependent equations

TABLE 1 Soil Characteristics (*25*)

Soil No.	Location Hwy/County	Passing #200 Sieve (%)	Atterberg Limits		Proctor Test Data		Soil Classification
			LL	PI	Maximum Unit weight, (kN/m³)	Optimum Moisture, (%)	Unified/AASHTO
3	MS7/Yalobusha	26	22	4	18.87	11.2	SM-SC/A-2-4
6	US61/Coahoma	97	68	38	15.31	23.0	CH/A-7-5(45)
7	US78/Benton & Union	51	26	7	19.36	13.0	ML-CL/A-4(1)
8	US98/Forrest & Perry	23	0	NP	19.30	10.7	SM/A-2

1 kN/m³ = 6.369 lbf/cu.ft

TABLE 2 M_R Determined Using Different Saturating Procedures

Soil No.		Modulus of Resilience, kPa						
		OMC[a]	Vacuum Saturating		Capillary Saturating		Molding wet of Optimum	
			EMC	S_r = 96%	EMC[b]	S_r = 96%	EMC	S_r = 96%
Coarse	#3	143,412	128,933	129,622	126,175	115,143	119,280	121,264
Grain	#8	150,307	137,896	137,896	136,517	144,101	126,864	131,277
Fine	#7	120,659	39,300	31,716	63,432	31,716	67,569	34,129
Grain	#6	140,996	47,574	Sample Failed	81,359	31,992	112,385	77,221

[a] OMC, optimum moisture content
[b] EMC (equilibrium moisture) attained by conditioning at 0.914 m of water suction
1 kPa = 0.145 psi

relating M_R to moisture content. One equation is for the path of constant dry unit weight, and the other for the path of constant compaction effort.

To authenticate the test results, the authors tested soil No. 7, a fine-grain soil, by compacting at constant AASHTO-T99 dry unit weight and at two different moisture contents, OMC + 2 and OMC − 2. The test results show a decrease by 34 percent and an increase by 19 percent for specimens molded at wet and dry of OMC, against predicted changes of 38.5 percent decrease and 23 percent increase, respectively, using Li and Selig's constant dry unit weight equation.

Unsaturated Soil Mechanics

In saturated soils, the mechanical behavior is defined by pore water pressure as it characterizes the state of moisture and governs the only stress-state variable—effective stress. In unsaturated soils, pore air and pore water pressures govern the two stress-state variables, net normal stress and matrix suction, defining the mechanical behavior. Scrutiny of the results in Figure 2 suggests that the stress-strain characteristics of unsaturated soils is not only influenced by the degree of saturation, but also by the way moisture is imbibed into the soil. In addition, moisture imbibition influences volume change characteristics, particularly in fine-grain soils. Volume change of soil structure is governed by variations in particle orientation, pore size, and surface activity. These factors play an important role in the water retention mechanisms affecting soil water

TABLE 3 OMC, EMC, and Corresponding Saturation (Sr) Levels

Soil No.		OMC, %/Sr, %	EMC, %/Sr[a], %
Coarse	3	11.2/75	13.1/86
Grain	8	10.7/67	11.4/73
Fine	6	23.0/86	26.0/90
Grain	7	13.0/83	14.1/90

[a] Volume change in specimen while saturating is taken into account in calculating saturation level at EMC

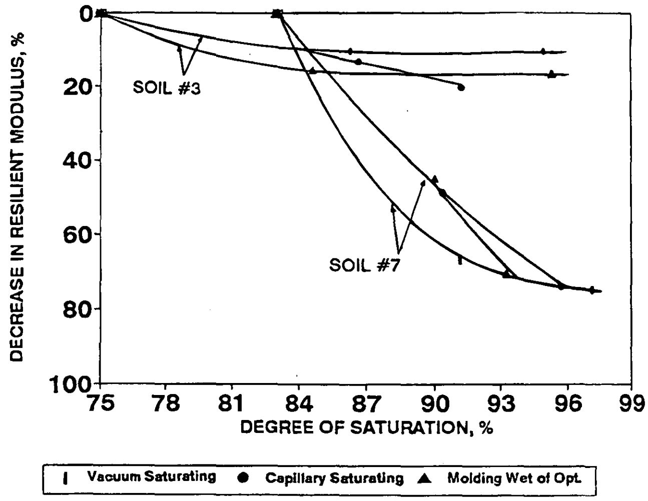

FIGURE 2 Reduction in M_R with degree of saturation for course- and fine-grain soil.

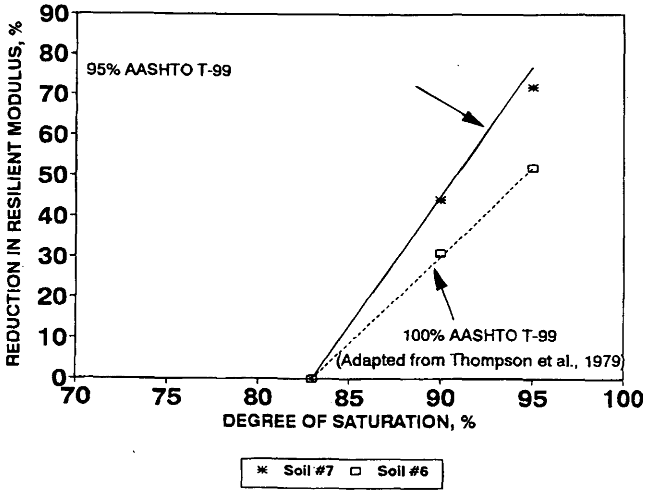

FIGURE 3 Reduction in M_R compared with those of Thompson and Robnett (7).

suction. Simply stated, water imbibition causes volume increase and simultaneous strength decrease. Although the volume changes of the conditioned specimen were measured, no attempt was made here to investigate its solo effect on M_R.

Strength and volume change characteristics can be uniquely related by applying the concepts of unsaturated soil mechanics (USM), as proposed by Fredlund and Rahardjo (*19*). According to USM concepts, unsaturated soil is made up of four phases: soil solids, water, air, and air-water interface (contractile skin). The most important property of the contractile skin is its ability to exert a tensile pull, otherwise known as surface tension, which causes the former to behave like an elastic membrane. Radius of curvature of the contractile skin is inversely related to the matrix suction. The contractile skin, when in contact with the soil solids, will apply a tensile pull between the soil solids, rendering it a major player in deciding the mechanical behavior of the soil system, apart from the soil solids. A partly saturated soil can be visualized as a mixture with two phases (soil solids and contractile skin) that come to equilibrium under applied stress gradients and the other two phases (water and air) flow under applied stress gradient. The disturbance in any of these phases will cause variation in the strength characteristic of the soil. How active the contractile skin is in the soil is dependent on the interaction of air and water phases with soil solids. At saturation levels less than 85 percent, the air phase in the soil is continuous and has interaction with soil solids (*23*). At levels greater than about 90 percent, the air phase is occluded in the water phase, leaving negligible interaction of air phase with soil solids (*24*), that is, the water suction decreases to 0. It stands to reason that when the air phase is occluded, the influence of air-water interface vanishes, as does its effect on soil strength. By process of elimination, therefore, transition of air phase from continuous state to occluded state occurs between 85 percent and 90 percent saturation levels. Figure 4 represents the soil structure constitutive surface adopted from a work by Fredlund and Rahardjo (*19*), which explains the importance of matrix suction and, indirectly, the effect of contractile skin on the strength of soil. Considering a constant plane of effective stress in Figure 4, the volumetric strain is inversely related to the matrix suction (stress-state variable attributed to contractile skin). Hence, the reduction in matrix suction increases the volumetric strain (heaving), resulting in a reduction in M_R. The specific result of decreases in M_R-values with reduction in matrix suction was experimentally shown (*6*).

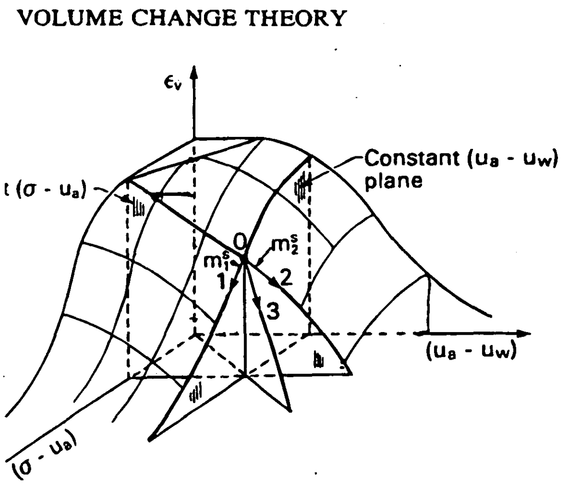

FIGURE 4 Soil structure constitutive surface (*19*).

M_R Affected by Soil Texture

From the description of the four phase system, it is clear that the contractile skin plays an important role in the strength of a soil. Therefore, alterations in the extent of contractile skin and its radius of curvature, both being a function of the particle shape and size, would result in a corresponding change in strength/M_R of an unsaturated soil. For example, a decrease in contractile skin or an increase in its radius of curvature accompanying moisture imbibition will reduce the M_R-values.

In coarse-grain soils, the surface area of the soil solids is relatively small and, hence, so is the contractile skin. Surface tension effects are relatively small in those soils compared with frictional effects in imparting strength. Insignificant strength decreases, therefore, would be realized with increases in degree of saturation. Neither the degree of saturation nor its mode of saturating has appreciable effect on M_R, as the relatively level plot of M_R versus degree of saturation indicates (Figure 2).

With very fine particles and a concomitant large surface area, fine-grain soils develop ample contractile skin at moisture levels close to optimum moisture. As the saturation is increased, the contractile skin and, therefore, soil suction, is reduced with accompanying strength loss. In other words, fine-grain soil, with extensive contractile skin, suffers large strength loss due to saturation. As the saturation is increased to high levels, such as 95 percent or so, the contractile skin loses its interaction with soil solids, that is air gets occluded in water phase. In the pores with air occlusion, surface tension disappears, and any further saturation will have a negligible effect on soil strength, as the rather constant M_R-values beyond 95 percent saturation indicate.

Effect of Saturating Mode on M_R

Not only the degree of saturation, but also the mode of saturating the specimen, has a decisive influence on strength. Examining the M_R-trend in Figure 2, it is clear that vacuum saturating has pronounced deleterious effect on soil strength compared with the other two saturating modes. These strength differences can be explained by considering the intactness of the contractile skin during moisture imbibition in each type of saturating procedure.

Capillary Saturating

The specimen is allowed to saturate under a preassigned suction to attain equilibrium between the soil water suction and the externally applied water suction. During saturation, the pore air pressure remains nearly constant, whereas the pore water pressure gradually increases from a large negative value as the external water is imbibed in the soil specimen. The reduction in capillary suction, accompanying moisture absorption, increases the radius of curvature of the contractile skin and correspondingly lowers the tensile pull on the soil solids. The result would be a gradual decrease in strength of the soil specimen, the decrease being linear until saturation reaches a particular level, perhaps characteristic of the soil, when the air phase begins to get occluded.

Vacuum Saturating

In this method of saturating, the vacuum applied to the specimen will reduce the pore air pressure, with corresponding reduction in soil water suction. Subsequently, differential back pressure is applied to both the bottom and top of the specimen, resulting in nonuniform moisture distribution [Figure 5(*a*)]. The forced-water entry under vacuum may disturb the contractile skin, promoting early occlusion of air phase. The precipitous decrease in M_R with degree of saturation corresponds to the forced-water entry phase, and the asymptotic M_R-value beyond 93 percent saturation is indicative of the air occlusion phase. Stated differently, the vacuuming of the specimen disturbs the air-water interface and in turn the contractile skin, causing substantial strength reduction.

Molding Wet of Optimum

Compaction of samples at wet of optimum (and corresponding unit weight, as obtained in a capillary saturated specimen) would result in poorly structured contractile skin, compared with that in samples molded at OMC and subsequently capillary wetted. The molding wet of optimum (MWO) samples, therefore, should yield a smaller M_R than those obtained from the latter specimens. The two procedures, however, resulted in nearly identical trend. It may be that the capillary saturated sample, by virtue of its nonuniform moisture distribution [Figure 5(*b*)], has undergone substantial strength loss with its ultimate strength equal to that of the MWO sample. Another observation worth mentioning is that the scatter of test results in MWO samples is larger than that observed in capillary saturated specimens.

The task now is to determine what mode of saturating is appropriate to simulate field moisture, referred to here as the EMC. Comparing the three methods of wetting, vacuum saturating severely affects the contractile skin with a precipitous decrease in M_R-value. The other two procedures show nearly identical M_R loss with wetting. Each method has limitations, however. Capillary saturating is time consuming and the moisture distribution is relatively nonuniform, when compared with that of MWO [Figure 5(*b*)]. Had the moisture distribution of the capillary saturated specimens been uniform, the M_R would be higher.

Capillary saturating is recommended when EMC is unknown, but long-term M_R is warranted for design purposes. MWO is appropriate when the in situ moisture content, or EMC, and the corresponding dry unit weight are known or can be estimated.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Subgrade soil is susceptible to moisture variations subsequent to pavement construction. To what extent the strength characteristic of the subgrade soils is affected by moisture fluctuation is important during design and evaluation phases. Specimens of two coarse-grain and two fine-grain soils, conditioned in accordance with three different saturating (wetting) procedures, are tested for M_R. Saturating procedures tested include: (*a*) compacting at OMC and then capillary saturating at 0.914 m and 0 m (3 ft and 0 ft) of water suction, respectively, (*b*) compacting at OMC and then vacuum saturating to EMC and also to 96 percent saturation, and (*c*) compacting at EMC and at 96 percent saturation at respective reduced dry unit weights. The effect of various saturating procedures on M_R is evaluated using the four-phase system for unsaturated soils.

Observations related to decreases in M_R with the extent of saturation and saturating mode include:

1. An increase in degree of saturation above the OMC will result in decrease of M_R by approximately 20 percent and 50 to 75 percent in coarse-grain and in fine-grain soils, respectively.

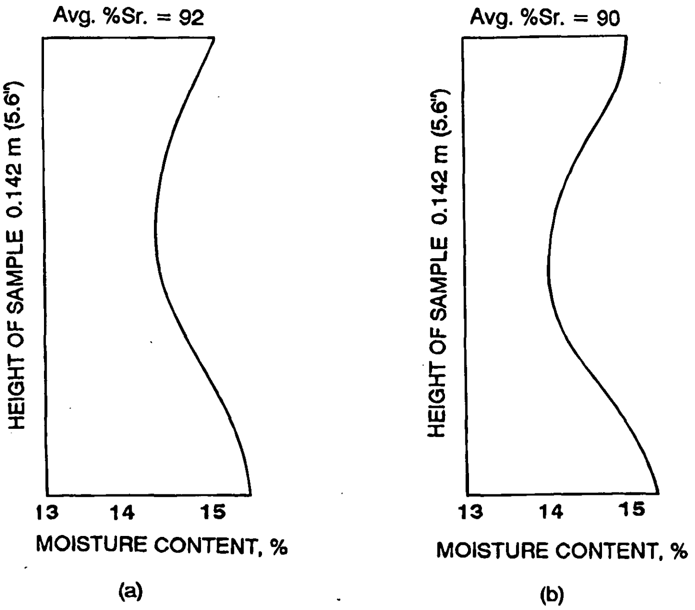

FIGURE 5 Moisture distribution in laboratory-conditioned samples after testing: (*a*) vacuum-saturated to EMC, (*b*) capillary saturated at 0.914 m (3 ft) of water suction. Sr = saturation level.

2. Besides degree of saturation, in fine-grain soils, the mode of moisture imbibition also influences the M_R.

3. Vacuum saturating causes drastic decreases in M_R-values compared with those observed with the other two methods (capillary saturating and MWO).

4. Moisture imbibition by capillarity and MWO result in a nearly identical decrease in M_R-value.

In evaluating the effect of partial saturation on strength/M_R of subgrade soils, three saturating procedures are investigated. They include:

1. Vacuum saturating as in AASHTO T 274-82,
2. Capillary saturating under 0.914 m (3 ft) of water suction, and
3. Molding samples at equilibrium or other predetermined moisture.

The following tentative recommendations for simulating field conditions are made:

1. Because vacuum saturating severely affects the air-water interface in the soil, it cannot simulate moisture imbibition akin to field conditions.

2. During the design phase, capillary saturating is recommended for evaluating the long-term M_R of the proposed subgrade soil, particularly when EMC is not known.

3. Molding at wet of optimum is recommended if the in situ moisture content and dry unit weight are known or can be estimated by empirical or approximate method.

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REFERENCES

1. Domaschuk, L., and N. H. Wade. A Study of Bulk and Shear Moduli of a Sand. *Journal of Soil Mechanics and Foundation Division,* ASCE, Vol. 95, SM2, 1969.
2. Duncan, J. M., et. al. *Strength, Stress-Strain and Bulk Modulus Parameters for Finite Element Analysis of Stresses and Movements in Soil Masses.* Report UCB/GT/80-01, College of Engineering, University of California, Berkeley, 1980.
3. Boscardin, M. D., E. T. Selig, R-S. Lin, and G-R. Yang. Hyperbolic Parameters for Compacted Soils. *Journal of Geotechnical Engineering,* ASCE, Vol. 116, No. 1, 1990.
4. *Revised Guide for Design of Pavement Structures.* AASHTO, Washington, D.C., 1986.
5. Fredlund, D. G., A. T. Bergan, and P. K. Wong. Relation Between Resilient Modulus and Stress Condition for Cohesive Subgrade Soils. In *Transportation Research Record 642,* TRB, National Research Council, Washington, D.C., 1977.
6. Edil, T. B., and S. E. Motan. Soil Water Potential and Resilient Behavior of Subgrade Soils. In *Transportation Research Record 705,* TRB, National Research Council, Washington, D.C., 1979.
7. Thompson, M. R., and Q. L. Robnett. Resilient Properties of Subgrade Soils. *Journal of Transportation Engineering,* ASCE, Vol. 105, TE1, 1979.
8. Hardcastle, J. H. *Subgrade Resilient Modulus for Idaho Pavements.* Report RP110-D. FHWA, Department of Civil Engineering, University of Idaho, Moscow, 1992.
9. Atchison, G. D., and B. G. Richards. A Broad Scale Study of Moisture Condition in Pavement Systems throughout Australia. *Moisture Equilibria and Moisture Changes in Soils Beneath Covered Areas,* Butterworth, Australia, 1965.
10. Low, P. F., and C. W. Lovell Jr. The Factor of Moisture in Frost Action. In *Highway Research Bulletin 225,* HRB, National Research Council, Washington, D.C., 1959.
11. Dempsey, B. J., and A. Elzeftawy. *Moisture Movement and Moisture Equilibrium in Pavement Systems.* Interim Report UILU-ENG-76-2012. Department of Civil Engineering, University of Illinois, Urbana, Champaign, 1976.
12. Thornthwaite, L. W. An Approach Toward a Rational Classification of Climate. *The Geological Review,* Vol. 38, No. 1, 1948.
13. *Field Moisture Content Investigation.* Report No. 2, Technical Memorandum 3401. Corps of Engineers Waterways Experiment Station, Vicksburg, Miss., 1955.
14. Black, W. P. M., D. Croney, and J. C. Jacobs. Field Studies of the Movement of Soil Moisture. Technical Paper 41, *Road Research Laboratory,* England, 1958.
15. Russam, K. The Distribution of Moisture in Soils at Overseas Airfields. Technical Paper 58, *Road Research Laboratory*, England, 1962.
16. Coleman, J. D., and K. Russam. The Effect of Climatic Factors on Subgrade Moisture Conditions. *Geotechnique,* the Institute of Civil Engineers, Vol. 11, London, England, 1964.
17. *Estimation of Subgrade Moisture Content.* Leaflet L.F. 98, Road Research Laboratory, Crowthorne, England, 1967.
18. Chu, T. Y., and W. K. Humphries. *Investigation of Subgrade Moisture Conditions in Connection with the Design of Flexible Pavement Structures.* Final Report. College of Engineering, University of South Carolina, Columbia, 1972.
19. Fredlund, D. G., and H. Rahardjo. *Soil Mechanics for Unsaturated Soils.* John Wiley and Sons, Inc., New York, 1993, pp. 14–29, 38–49, 117, 178–188, 346–373.
20. *Standard Method of Test for Resilient Modulus of Subgrade Soils.* AASHTO Designation T274-82, Washington D.C., 1982.
21. Coleman, H. W., and W. G. Steele, Jr. *Experimentation and Uncertainty Analysis for Engineers.* John Wiley and Sons, Inc., New York, 1989, pp. 17–37.
22. Li, D., and E. T. Selig. Resilient Modulus for Fine-Grained Subgrade Soils. *Journal of Geotechnical Engineering,* ASCE, Vol. 120, No. 6, 1994.
23. Corey, A. T. Measurement of Water and Air Permeability in Unsaturated Soil. *Proceedings, Soil Science Society of America,* Vol. 21, No. 1, 1957.
24. Matyas, E. L. Air and Water Permeability of Compacted Soils. *Permeability and Capillary of Soils,* ASTM, STP 417, 1967.
25. George, K. P. *Resilient Modulus of Subgrade Soils using Gyratory Testing Machine.* Final Report MSHD-RD-92-096. Department of Civil Engineering, University of Mississippi, 1992.

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