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EFFECTS OF MOISTURE CONTENT ON THE RESILIENT MODULUS OF COMPACTED SUBGRADE SOILS IN AN ARID REGION

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ABSTRACT: The purpose of this study is to illustrate how the resilient modulus of three soils with varying grain size composition and mineralogy of their fines content is affected by moisture variations. The resilient modulus, a parameter measuring the subgrade material stiffness, was tested at five different states of moisture and compaction. For each of the three types of soils, the effects of moisture variation on the determined resilient modulus were shown. Since floods or severe soaking will alter the moisture condition for soils compacted at a dry of optimal state, this study recommends adjusting the resilient modulus determined by the laboratory. Although the ranges given here are pertinent to local soils, the general pattern will be the same for soils with comparable mineralogy and structural characteristics. Wetness was found to have the greatest effect on fine-grained, plastic, and highly plastic soils. In the Greater Khartoum region, where a compaction water content tolerance of +/- 2% is implemented during pavement construction, a 10% drop in MR is advised for fine-grained clayey soils.

Keywords: Resilient modulus, California bearing ratio, Compaction, Plastic soils.

1. INTRODUCTION

According to the AASHTO road test findings, the surface deflection of pavements is closely related to the deformation of the subgrade soil [1]. About 60 to 80 percent of the deflection measured at the surface was found to develop within the subgrade. Therefore, the stiffness of the subgrade is considered a major factor contributing to surface deflection. Resilient modulus (M_R) measures the elastic material stiffness when subjected to dynamic loading. It is a fundamental material property that is used within the Mechanistic-Empirical Pavement Design Guide MEPDG for the design of flexible pavements [2]. The resilient modulus test is designed to simulate the behavior of subgrade soils and pavement granular materials (base and subbase layers) when subjected to traffic loading within a pavement system. Consequently, sample preparation, conditioning, and testing are conducted so as to simulate field conditions. The standard method of testing is described in the AASHTO T-292 test method [3].

The AASHTO Design Guide requires the selection of an "Effective Roadbed Soil Resilient Modulus". It is a single M_R value that is representative of the entire year. The guide contains the methodology for selecting the effective subgrade resilient modulus. It starts with estimating seasonal variations in resilient modulus and then assigning relative damage factors on a monthly or bi-monthly basis. The damage factors are summed and the average is determined. The resilient modulus corresponding to the average damage factor is then used for design. Elliot and Thornton [1] suggested a simple approach that could be used in the United States to select a design M_R value based on testing the soil for a single representative ”time of the year” water content. They investigated the seasonal variation of resilient modulus at the AASHTO Road Test, determined the seasonal load damage effects for pavements with various thicknesses of asphalt, and found that for this representative time, the weighing factor is about the same for different pavement thicknesses. Late spring was considered a reasonable first approximation of the appropriate time of year for most of the United States.

Khartoum, the capital of Sudan, is a tri-metropolis consisting of Khartoum, Khartoum North (Bahri) and Omdurman (Figure 1). Khartoum has witnessed huge development in infrastructure, particularly in road construction, during the last two decades. Extensive distress and failures related to road pavements in Greater Khartoum were reported [4]. Those defects were attributed to improper design, excessive loads, and poor drainage, leading to poor subgrade conditions [5]. Omer, Elsharief, and Mohamed noted that most of the pavement failures at the defective road sections in Greater Khartoum were triggered by the shoddy rainwater drainage system, concluding that heavy loads and weak subgrades are major causes of pavement distress [4].

As mentioned above, the mechanistic design approach considers environmental changes and introduces an adjustment factor for M_R based on seasonal variations in the environment. The hot dry arid climate of Khartoum results in subgrade soils and fill materials being prepared and compacted dry of optimum. Therefore, the placement conditions and subsequent environmental changes during the lifetime of pavements in Khartoum result in the subgrade being influenced by a wide range of moisture content variations.

The above review has pointed out that the stiffness parameter, M_R, is the main input pavement design parameter for the subgrade materials. It is deduced that the effective “design” roadbed M_R could be influenced by the climate, environmental conditions to which the subgrade soil is been subjected, the placement conditions during construction and subgrade type. It is apparently evident that there is an overwhelming need to study the major factor influencing M_R of subgrade materials, most important is water content.

2. RESEARCH SIGNIFICANCE

This paper presents the effects of moisture content variations on the resilient modulus of compacted subgrade soils of different types. This would help in a rational selection of the design M_R values. The Greater Khartoum was chosen to demonstrate these effects. The subgrade soils need to be compacted to a level that considers all expected environmental changes in arid and semi-arid climate conditions. An adjustment factor for lowering the design value of MR by 10% is introduced for fine-grained soils.

3. ESTIMATION AND FACTORS INFLUENCING RESILIENT MODULUS

The resources needed to conduct the resilient modulus test are expensive and require a strong technical background. The correlations and models suggested to predict the M_R are either crude with very poor correlation factors or reliable but with a large number of parameters to be identified. The resilient modulus M_R, estimated from the CBR tests, is given in different formulae, e.g., Huekelom and Klomp (1962) suggested using a factor of 1500 to obtain the M_R in terms of psi or 10.34 in terms of MPa [6]. The dynamic cone penetrometer test can be used to predict CBR values [7]. This may also be used to estimate the resilient modulus.

Factors that influence M_R of subgrade soils mainly include the type of soil and its placement condition, i.e., moisture content, density, and stress level.

Moisture content and density have significant effects on the resilient modulus of subgrade soils. The resilient modulus decreases with the increase of the moisture content and, subsequently, the degree of saturation [8- 12].

The resilient modulus increases with the increase in dry density of compacted subgrade soils [13, 10]. Test results indicated that this effect is small compared to the effects of moisture content and stress level [14]. Along the compaction curve at any dry unit weight (density) level, the resilient modulus has different values when the soil is tested dry of optimum moisture content and wet of optimum moisture content. The resilient modulus of the soil compacted on the dry side of optimum is larger than that when the soil is compacted at the wet of optimum.

The resilient modulus of cohesive soils is usually described as a function of deviator stress. The increase in the deviator stress results in decreasing the resilient modulus of fine-grained cohesive soils [15]. For granular materials, the resilient modulus increases with increasing deviator stress and confinement [14].

Stress duration, stress frequency, sequence of load, and number of stress repetitions necessary to reach an equilibrium-resilient strain response have little effect on resilient modulus [14, 15]. The resilient modulus increases with the increase of the repeated number of loads. AASHTO T 307 requires the specimen to undergo 500-1000 conditioning cycles before testing to provide uniform contact between the soil specimen and the top and bottom platens [14, 16].

Thompson and Robnett reported that low clay content and high silt content result in lower resilient modulus values [17]. Resilient modulus decreases with a high plasticity index and liquid limit, low specific gravity, and high organic content [17]. The resilient modulus increases with the increase in maximum particle size and decreases when the amount of fines increases [18, 19]. Given the compaction method, test specimens that were compacted statically showed higher resilient modulus compared to those prepared by kneading compaction [20]. Fine materials can affect the compaction characteristics and this will be reflected in the resilient modulus [21]. Additives like geopolymers, waste marble powder, and others (lime, cement, etc.) can add to the stability of the subgrade materials [22, 23].

4. MATERIALS, TESTS PROGRAM, AND METHODS

The soil formation stratification in Khartoum and Khartoum North gives a topsoil “blanket” of very stiff to hard, desiccated, silty clay of low to high plasticity [24]. The silty clay changes to clayey silt, silty sand, and poorly graded sand as the depth increases, i.e., the formations become coarser with depth. The alluvial formations overlie an older Nubian Sandstone Formation (NSF). The clay blanket in Khartoum and Khartoum North varies in thickness and properties and is known to be potentially expansive, hazardous, and problematic with varying degrees of swelling potential [25, 26].

The situation is different in Omdurman where the Nubian formation is either exposed on the ground surface or covered by a thin layer of dune sand, silty, sandy clay and/or gravelly soil imported by the series of drainage channels discharging into the White Nile or the River Nile. The topsoil is, therefore, dominated by a decomposed to highly weathered Nubian sandstone formation, which appears as dense to very dense clayey or silty sand.

Therefore, the topsoil that acts as subgrade for road pavements is generally medium to highly plastic silty clay (CL to CH) in Khartoum, low to medium plastic sandy, silty clay in Khartoum North (CL, ML), and silty/clayey sand (SC, SM, decomposed Nubian sandstone) in Omdurman.

The soils tested in this study were selected to provide a geotechnical representation of three typical subgrade soils of Greater Khartoum. Soil A was collected from Alfitaihab in Omdurman, Soil M from Manshiah in Khartoum, and Soil H from Hag Yousif in Khartoum North (Figure 1). Soil A is described as decomposed sandstone, and soil M is potentially expansive, highly plastic clay, whereas soil H is low plastic clayey sand.

The test program comprised performing the following tests on the three subgrade samples:

- Routine classification tests
- Proctor compaction test
- California Bearing Ratio (CBR) Test
- Resilient modulus test

A summary of the test results for the classification and proctor compaction tests is given in Table 1.

The standard Proctor test was conducted in accordance with AASHTO –T99-90 (Standard Method of Test for Moisture–Density Relations of Soils Using a 2.5-kg Rammer and a 305-mm Drop). Seven batches of bulk samples were prepared at different moisture contents: three wets of optimum, three dries of optimum, and one batch at about optimum moisture content. The tests were performed and the results are shown in Table 2 and Figure 2.

The CBR and MR tests were performed on soil specimens prepared at optimum moisture content and at OMC-4, OMC-2, OMC+2, and OMC+4. The objective was to assess, within practical range, the effects of compaction dry of optimum and wet of optimum on M_R and CBR for the three subgrade soils. The effects of moisture variations, specifically wetting, could be assessed for each subgrade soil in an attempt to set a generalized guide for the selection of their design M_R.

This CBR test was performed in accordance with BS1377 (1990) part 7 on the three subgrade soil samples at five different moisture contents at optimum moisture, dry of optimum (OMC-4, OMC-2) and wet of optimum (OMC+2, OMC+4) [27]. For the CBR specimen preparation, each sample was watered, compacted, and soaked in water for four days. The CBR test results are presented in Table (2).

The resilient modulus test was performed using Load-Trac II equipment, which is capable of conducting resilient modulus tests in accordance with AASHTO T292, T 307, and LTPP Protocol P46. A cylindrical specimen of 71 mm diameter by 147 mm height was prepared to fit in the confinement chamber for the repeated load triaxial testing. The samples were prepared to achieve the target density and moisture content. It was placed in six layers to achieve uniformity in compaction. The test method, as stated in AASHTO T307, was followed. The sample was first conditioned by applying 1000 load cycles with a deviator stress of 27.6 kPa and a confining pressure of 41.4 kPa. The test constituted 15 sequences with different deviator stress values, as stated in the test method. Each sequence contained 100 cycles, and only the average of the last five cycles was considered. The obtained MR results will be used through a series of calculation steps and a software program to determine the desired MR for the specified field load and depth. The average M_R value that was measured in sequence 6 of the standard test (deviator stress 13.8 kPa and confining pressure of 27.6 kPa) was chosen to closely represent the material stiffness; Table (2) shows the computed M_R values for the three compacted subgrade samples tested at optimum water content, +-2% and +-4% of the optimum water content.

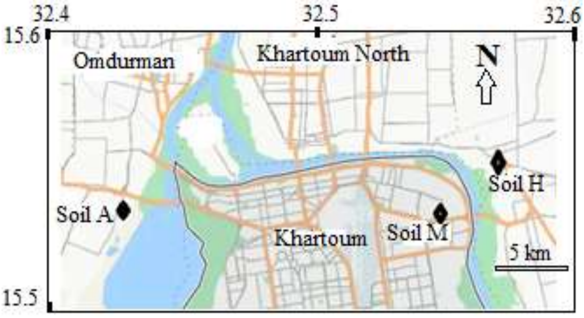

Fig.1 Soil A, Soil H, and Soil M locations

Figure 1 displays a simplified map of Khartoum, highlighting the three major cities of Omdurman, Khartoum, and Khartoum North. The map shows two rivers joining together to form the river Nile, which is heading north. The selected soil locations are not far from the river's route. Alluvial deposits consisting of sand, clay, and silt are very common in the area. The near-surface soils of Khartoum reveal formations with varying densities, ranging from loose to medium or dense to very dense sand. The clay also indicates variable stiffness, which varies from soft, stiff, very hard clay, and silty clay. This is mainly dependent on the mode at which the sedimentation occurs.

Table1.Summary of the classification and compaction test results of the three soils

Soil properties	Soil (A)	Soil (M)	Soil (H)
Gravel (%)	0	0	1
Sand (%)	80	10	64
Silt (%)	12	35	15
Clay (%)	8	55	20
Liquid Limit (%)	24	77	40
Plastic Limit (%)	12	27	16
Plasticity Index (%)	12	50	24
Linear Shrinkage (%)	0.7	9.7	8.6
AASHTO Classification	A-2-6	A-7-6	A-6
USCS Classification	SM	CH	SC
Maximum Dry Density (g/cm^3)	2.06	1.48	1.82
Optimum Moisture Content (%)	8.0	20	10
Specific Gravity (Gs)	2.6	2.66	2.63

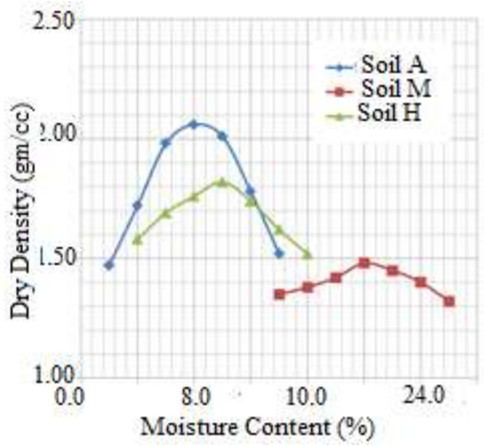

Fig.2 Dry density versus moisture content for Soil A, Soil H and Soil M

Reduction in the resilient modulus is shown in a bar diagram format in Figures 4, 5 and 6.

Table 2.CBR and MR test results for the three soils

Type of soil	Moisture content (%)	OMC -2%	OMC -4%	OMC	OMC +2%	OMC +4%
Soil (A)	Dry density (gm/cm^3)	1.78	2.01	2.06	1.98	1.72
	Water Content %	4.0	6.0	8.0	10.0	12.0
	Soaked CBR (%)	5.5	4.5	4.3	4.0	3.6
	MR (kPa)	57.6	47.0	45.9	44.8	39.3
Soil (M)	Dry density (gm/cm^3)	1.40	1.45	1.48	1.42	1.38
	Water Content %	16.8	18.0	20.0	22.0	24.0
	Soaked CBR (%)	2.0	1.6	1.5	1.3	1.2
	MR (kPa)	21.0	16.9	16.6	14.9	12.0
Soil (H)	Dry density (gm/cm^3)	1.62	1.74	1.82	1.76	1.89
	Water Content %	5.0	8.0	10.0	12.0	14.0
	Soaked CBR (%)	3.0	2.5	2.3	2.0	1.8
	MR (kPa)	28.2	25.9	20.0	20.0	17.8

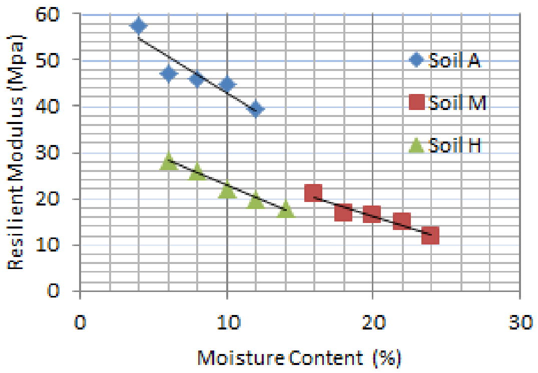

Fig..3 Resilient Modulus for Soil A, Soil M and, Soil H.

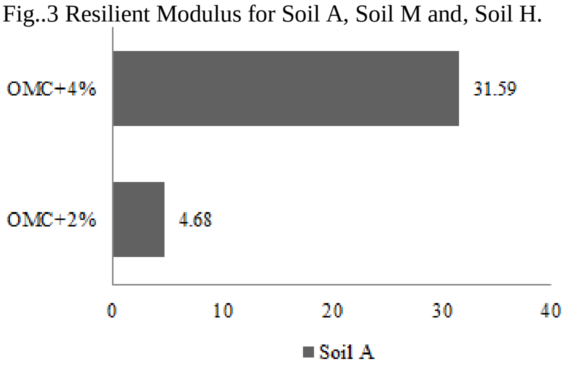

Fig.4 Reduction in MR for soil A compacted at (OMC+2) and (OMC+2).

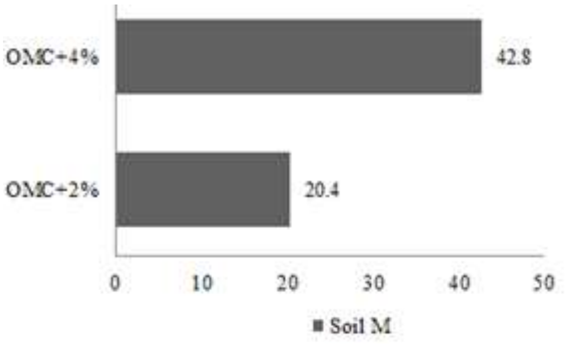

Fig.5 Reduction in MR for soil M compacted at (OMC+2) and (OMC+2).

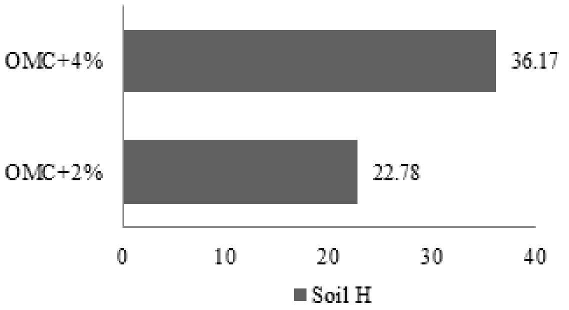

Fig.6 Reduction in MR for soil H compacted at (OMC+2) and (OMC+2).

5. RESULTS AND DISCUSSION

The resilient stiffness response of subgrade soils to traffic loads varies with the soil type, stress level, and water content variations. Assuming that the stress level is controlled or does not change, the two factors that govern the response in tropical climates are soil type and moisture variations. This discussion addresses two issues: first is the applicability of the developed correlations for estimating MR, and second, the effect of compaction water content on MR for Khartoum soils. Here, an attempt will be made to suggest compaction water content for which MR could be tested for the design of pavements in Khartoum.

5.1 Applicability of M_R Estimates

Basic data on classification and compaction parameters are given in Table 1 whereas data on strength and stiffness are given in Table 2 for specimens tested at OMC, +/- 2% and OMC+/- 4%.

Soil (A) is decomposed Nubian Sandstone. It is coarse grained consists of 80% sand, 12% silt and 8% clay with a plasticity index PI equals 12, and is classified as clayey silty sand (SM) according to the USCS and (A-2-6) according to the AASHTO. Previous studies suggest that the dominant mineral of the clay fraction of the Nubian Sandstone formation in Sudan includes kaolinite [28].

Soil M is of alluvium origin. It consists of 10% sand, 35% silt and, 55% clay with plasticity index PI equal to 50. It is classified as silty clay (CH) according to USCS and (A-7-6) according to the AASHTO classification system. It represents a typical potentially expansive black cotton clay soil subgrade for which montmorillonite is the dominant clay mineral [29]. It is dominant in Khartoum city and in the area between the Blue Nile and the White Nile.

Soil H is also of alluvial origin; it consists of 1% gravel, 64% sand, 15% silt and 20% clay with plasticity index PI equal 24. It is classified as silty clayey sand (SC) according to USCS and clayey soil (A-6) according to the AASHTO classification system. This soil contains 35% of fines, and the clay within the fines fraction is montmorillonite.

Soil M and Soil H are potentially expansive soils as they contain montmorillonitic clays within their fines fraction. Soil A is more stable as it contains a large quantity of sand, and the clay within the fines fraction is kaolinitic. The CBR values for Soil M range between 2 to 1, 3 to 2 for Soil H, and 6 to 4 for Soil A for -4% to +4% of optimum moisture. Here, the values are given to the closest whole value “integer,” as in normal practice. The test is conducted after prolonged saturation of the sample. Therefore, the montmorillonite clay fraction in Soil M and Soil H tends to swell, resulting in low CBR. Looking at the MR values, it is noticed that these values range between 21.0 kPa to 12 kPa for Soil M, 28.2 to 17.8 kPa for Soil H, and 57.6 to 39.2 kPa for Soil M for the water content range +4% to -4% of optimum. It was noticed that Soil M measured the smallest MR values and was more affected by the increase in water content than Soil H and Soil A.

The applicability of the various prediction models to Soil M and Soil H is questionable if we consider moisture variations because of their very low CBR values. The CBR values for the same soil fall within a very narrow range for OMC-4% to OMC+4% moisture content range; therefore, the M_R values obtained from the correlation equations will be less sensitive to moisture variations, as CBR is normally taken to the nearest whole number. The correlations could give acceptable estimates of M_R for Soil A, which is relatively stable, i.e., less affected by saturation. Therefore, for effective use of these correlation equations in the estimation of the MR of montmorillonitic clay soils, the CBR should be reported to the nearest first decimal.

5.2 Effects of Water Content on M_R

Figure 3 shows the effect of water content on the resilient modulus of the three subgrade soils. It is observed that Soil A measured high MR values compared to Soil H and Soil M. Soil A is a coarse-grained soil with stable fine content. Soil H measured higher MR values compared to Soil M mainly because of its higher sand content and lower clay content. However, the two soils showed a similar trend regarding the rate by which MR decreases with increase in water content. This could be due to the relatively high fine content in Soil H, causing it to behave more like a cohesive or fine-grained soil. A previous study on the effects of fines content and wetting on the drained strength of plastic silty sands has shown that wetted silty sands with 40% plastic silt compressed during shear (for both loose and dense states) and behaved like fine-grained soils [30]. Therefore, the behavior of Soil H could be controlled by the high plastic fines, which constitute 35% of the solid content.

The test results also showed that, for the three soils, the highest MR values were measured for the drier samples (OMC-4%), whereas the lowest was for the wettest samples (OMC+4%). This indicates that dry compaction leads to higher rigidity of the placed soil, whereas compacting the soil wet of optimum resulted in lower MR values.

This study attempts to take a close-up look at the effects of moisture on the outcome of resilient modulus. In order to exclude the density effect, a comparison of selected points from this study is performed. Resilient Modulus, MR, tested wet of optimum is compared to that tested at the optimum moisture content for points of + 2% OMC and + 4% OMC for the three types of soils investigated. Figures 3, 4, and 5 present bar diagrams indicating a reduction of MR measured at OMC+2 to MR at optimum moisture content. It can be observed that Soil A, which contains 80% sand and 20% fines and behaves as coarse-grained soil, experienced a loss in MR in the order of 2.3% only compared to a loss of 10% for Soil M and Soil H, which behave or tend to behave as fine-grained soils. This level of tolerance is frequently accepted during the construction of pavements, and therefore, we recommend reducing the design value of MR by 10% for fine-grained soils. The measured MR at optimum water content could be accepted for stable “granular” soils. The drop in MR in the case of the 4% above moisture is very high (>20%) and may be excluded as this deviation from optimum moisture value is not permitted during compaction. Drumm, Reeves, Madgett, and Trolinger (1997) called for a similar correction as they observed soils exhibited a decrease in resilient modulus with an increase in saturation but also found that the magnitude of the decrease in MR depends on the soil type [10].

Compaction dries of optimum, though improved stiffness would result in more swelling of expansive subgrades (Soil M and Soil H) if subjected to wetting. This study has shown that a large drop in MR took place when compaction water was increased beyond OMC+2%. It is therefore desirable to balance between minimizing loss of MR and controlling potential swelling. Compaction at OMC+2% could be accepted. Pavements constructed in expansive soil zones can benefit from this study [31, 32].

The work conducted by the Wisconsin Department of Transportation (WisDOT) through the Wisconsin Highway Research Program (WHRP) is valuable and provides materials of good reference to this topic [33].

6. CONCLUSION

Three soils from Khartoum, representing an arid climate, were selected and tested to study the effects of moisture content variations on their resilient modulus, MR. The selection was meant to give a factual representation of the subgrade quality of Khartoum subgrade soils. Soil M and Soil H are potentially expansive soils as they contain montmorillonite clay minerals within their fines fraction. Soil M is potentially highly plastic and has 90% fines content, whereas Soil H is low plastic clayey sand and contains 30% plastic fines. Soil M and H are very sensitive to moisture changes with regard to strength properties. However, Soil A is a stable decomposed Nubian sandstone containing 80% sand content, whereas the clay within the fines fraction is kaolinitic.

The fine-grained potentially expansive subgrades, Soil M and Soil H measured low MR compared to the stable Soil A. The resilient modulus, MR, increased with an increase in sand content and decreased with an increase in fine content and plasticity index.

For the same soil and compaction energy, MR is higher for the drier specimens. It decreases with an increase in the moisture content of the compacted soil. A large drop in MR took place when compaction water was increased beyond OMC+2% for the potentially expansive soils. It is, therefore, desirable to balance between minimizing loss of MR and controlling potential swelling for potentially expansive subgrade soils. Compaction at OMC+2% could be accepted.

As some degree of tolerance, with regard to moisture content variations (say +-2%), is commonly allowed in pavement construction; we advise lowering the design value of MR by 10% for fine-grained soils. For granular soils, the measured MR at the ideal “optimum” moisture content might be accepted. The decline in resilient modulus as saturation is increased is a function of soil type, mineralogy, and soil fabric.

7. ACKNOWLEDGMENTS

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