Estimation of Subgrade Resilient Modulus from Soil Index Properties

Magdi M. E. Zumrawi, Mohamed Awad

Abstract—Determination of Resilient Modulus (M_R) is quite important for characterizing materials in pavement design and evaluation. The main focus of this study is to develop a correlation that predict the resilient modulus of subgrade soils from simple and easy measured soil index properties. To achieve this objective, three subgrade soils representing typical Khartoum soils were selected and tested in the laboratory for measuring resilient modulus. Other basic laboratory tests were conducted on the soils to determine their physical properties. Several soil samples were prepared and compacted at different moisture contents and dry densities and then tested using resilient modulus testing machine. Based on experimental results, linear relationship of M_R with the consistency factor 'F_c' which is a combination of dry density, void ratio and consistency index had been developed. The results revealed that very good linear relationship found between the M_R and the consistency factor with a coefficient of linearity (R^2) more than 0.9. The consistency factor could be used for the prediction of the M_R of compacted subgrade soils with precise and reliable results.

Keywords—Consistency factor, resilient modulus, subgrade soil, properties.

I. INTRODUCTION

THE most important part of flexible pavement design, is the determination of resilient modulus (M_R) to characterize the subgrade soil. M_R is a measure of elastic modulus of a material at a given stress and is expressed as the ratio of applied deviator stress to recoverable strain. AASHTO [1] pavement design guide requires the use of M_R to represent the material strength of pavement layers. Therefore, an accurate measurement of M_R is needed to ensure the efficiency and accuracy of the pavement design.

The resilient modulus of soil is typically determined using the Repeated Load Triaxial (RLT) test. However, this test requires a well trained personnel and expensive laboratory equipment. In addition, it is considered to be relatively time consuming. Alternatively, empirical equations from previous studies have been used to determine resilient modulus in the last three decades. The resilient modulus of subgrade soils is related to several parameters, such as the soil support value (SSV), the R-value, the California bearing ratio (CBR), the Dynamic Cone Penetration Index (DCPI) and the soil physical properties [2].

This paper was initiated to evaluate the use of soil index properties as an alternative for determining the MR of subgrade soils through basic tests. For this purpose, laboratory

M. M. Zumrwai is with Civil Engineering Department, University of Khartoum, Khartoum, Sudan (phone: 00249912355758; e-mail: magdi.zumrawi@ yahoo.com).

tests to measure M_R and soil index properties were performed on different subgrade soils. Statistical analysis was performed to develop equations that predict the resilient modulus.

II. LITERATURE REVIEW

A. General

The resilient modulus is a fundamental engineering material property that describes the nonlinear stress-strain behavior of pavement materials under repeated loading. It is defined as the elastic modulus based on the recoverable strain under repeated loads [3]. Seed et al. [4] originally introduced the concept of resilient modulus of a material, and defined this material property as "the ratio of applied dynamic stress (σ_d) to the resilient or elastic strain component (ε_r) under a transient dynamic pulse load". The resilient modulus is calculated from (1):

$$M_R = \frac{\sigma_d}{\varepsilon_r} \qquad (1)$$

In the resilient modulus test, the soil behavior under cyclic loading shows a nonlinear stress-strain relationship [4]. The soil resilient modulus is measured in a RLT compression test, known as the resilient modulus test. The equipment used in this type of test is similar to that used in common triaxial compression test. During the test, specimens are subjected to testing sequences that consist of the application of different repeated axial deviator stress under different confining pressures. Also during the test, the recoverable induced axial strain is determined by measuring the resilient deformations of the sample across a known gauge length. The AASHTO established a standard testing method [5] as the official laboratory test for determination of resilient modulus of soils.

B. Factors Influencing M_R

Factors that influence the resilient modulus of subgrade soils include physical condition of the soil (moisture content and unit weight), loading condition or stress state, soil type and its structure and consistency limits. The effect of some of these factors on the resilient modulus of subgrade soils is significant. Many studies have been conducted to investigate these effects on the resilient modulus. Li and Emest [6] reported that a resilient modulus range between 14 and 140 MPa can be obtained for the same fine-grained subgrade soil by changing parameters such as stress state or moisture content. Therefore, it is essential to understand the factors affecting the resilient modulus of subgrade soils.

Stress State

The resilient modulus of any soil is a function of the state of stress. Lee et al. [7] reported that stress state which includes the deviator and confining stress greatly influences the resilient modulus value. Many researches showed that the resilient modulus increases with the increase of the confining stress [4], [8]-[10]. In general, the effect of confining stress is more significant in granular soils than in fine-grained soils [8]. Li and Emest [6] found that for fine-grain soils, resilient modulus decreases with an increase in deviator stress. Rada and Witczak [9] reported that for loading characteristics, factors such as 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 response.

Soil Physical State

The soil physical state such as moisture content and dry density has a significant influence on the resilient modulus of fine grained subgrade soils [6].

The effect of dry density on the resilient modulus of subgrade soils has been investigated by many researchers [11]-[13]. Resilient modulus is greatly influenced by the dry density of compacted soils. The soils compacted at higher dry densities exhibit a significant increase in resilient moduli. Thompson [14] stated that soils compacted to the maximum dry density yield higher resilient moduli. Barksdale and Itani [15] reported that the resilient modulus increased markedly with increasing dry density.

The moisture content plays a major role in the resilient response of cohesive soils subjected to resilient modulus testing [16]. Dawson et al. [16] found that below the optimum moisture content, stiffness tends to decrease with increasing moisture level, apparently due to development of suction. Beyond the optimum moisture content, as the material becomes more saturated and excess pore water pressure is developed, the effect changes to the opposite and stiffness starts to decline fairly rapidly. As moisture content increases and saturation is approached, positive pore pressure may develop under rapid applied loads which may cause a reduction in effective stress and permanent deformation resistance of the soil [16]. The combination of a high degree of saturation and low permeability due to poor drainage leads to high pore pressure, low effective stress, and consequently, low stiffness and low deformation resistance. Butalia et al. [17] investigated the effects of moisture content and pore pressures buildup on the resilient modulus of Ohio soils. Tests on unsaturated cohesive soils showed that the resilient modulus decreases with the increase in moisture content.

Jin et al, [18] studied the resilient modulus of subgrade soils and found that the resilient modulus value decreases as the water content increases up to a certain bulk stress. Also, they found that the effective resilient modulus, which reflects the overall capacity of subgrade soils to support the pavement during the year, does not vary much with depth. Fig. 1 illustrates the variation of the resilient modulus for a fine grained soil with different moisture contents [19].

Other Factors

There are other factors that affect the resilient modulus of subgrade soils. These factors include soil type and properties such as amount of fines and plasticity characteristics. In addition, the sample preparation method and the sample size have influence on the test results. Material stiffness is affected by particle size and particle size distribution. Thompson and Robnett [8] reported that low clay content and high silt content results in lower resilient modulus values. Thompson and Robnett [8] also showed that low plasticity index and liquid limit, low specific gravity, and high organic content result in lower resilient modulus. Lekarp et al. [20] reported that the resilient modulus generally decreases when the amount of fines increases. Janoo and Bayer [21] noticed an increase in the resilient modulus with the increase in maximum particle size.
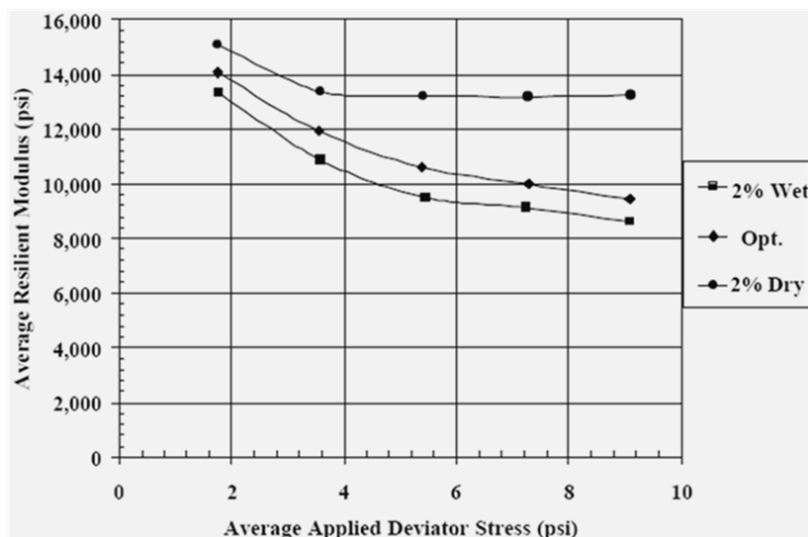

Fig. 1 Variation of Resilient Modulus at Different Moisture Contents for Fine-Grained Soils [19]

Seed et al. [4] reported that the compaction method used to prepare soil samples affected the resilient modulus response. In general, samples that were compacted statically showed higher resilient modulus compared to those prepared by kneading compaction.

Ruttanaporamakul [22] conducted a study on resilient moduli properties of compacted and unsaturated subgrade soils. He studied two different cohesive soils, Minnesota has high liquid limit 86% and plasticity index 53% and Louisiana of low liquid limit 23% and plasticity index 12%. The soils were prepared at five different moisture contents and dry densities and tested for measuring resilient modulus as presented in Table I. As observed from table, the compaction moisture content and their corresponding dry densities greatly affected the values of resilient modulus of the soils. It is clear that the soils compacted at higher dry densities and lower moisture contents exhibit a significant increase in resilient moduli. Also, the soil with low liquid limit and plasticity index has higher resilient modulus.

TABLE I

RESILIENT MODULI AND COMPACTION PARAMETERS FOR TWO COHESIVE SOILS [22]

Soil	Water content, %	Dry density, pcf	M_R, ksi	M_R, MN/m²
Minnesota (CH)	92.5	21.0	7.0	48.3
	95.0	23.5	4.5	31.1
	96.0	26.0	3.9	26.9
	95.0	28.5	2.6	17.9
	92.0	31.0	2.2	15.2
Louisiana (SC)	118.7	9.1	10.0	69.0
	120.7	10.3	8.0	55.2
	121.7	11.4	7.5	51.8
	120.7	12.5	4.6	31.7
	118.7	13.7	3.6	24.8

C. Correlations for Predicting M_R

Various correlations have been developed by previous researchers to predict the resilient modulus of subgrade. These correlations have taken different forms depending on the soil parameter(s) that are considered to have significant effect on predicting the resilient modulus. Table II shows some correlations that have been proposed to estimate resilient modulus for fine-grained soils. These equations are empirical relationships which correlate the resilient modulus to some soil properties such as CBR, R-value, and DCP. Soil index parameters such as soil fraction passing # 200 sieve, Atterberg limits (LL, PL), moisture content and dry density are also used in some of the correlations.

The developed equations given in Table II suffer from some problems. As it can be seen from table, the equations have no definite trend between resilient modulus and soil passing # 200 sieve. In (11), it can be noticed that M_R increases with increase in PI and this is inconsistent with the principles of soil mechanics: The higher the PI the less stable the soil is. Regarding the moisture content and the percent clay effects on M_R, different equations show different trends. In (9), M_R increases with an increase in moisture content and clay content and this result contradict the soil basic principles. In several equations, for example, (10), M_R decreases with increase in density. From a physical point of view, one would expect M_R to increase with the density.

A cursory study of the previous equations suggest that soil index properties such as Atterberg limits, moisture content and dry density significantly affect M_R. Due in part to nonlinear behavior of soil, stress state becomes an important parameter as well.

TABLE II

SOME CORRELATION FOR PREDICTION OF RESILIENT MODULUS

Correlation Equation	Equation No.	Reference
$M_R(MPa) = 10\,CBR$	(2)	Heukelom [23]
$M_R(MPa) = 37.3(CBR)^{0.71}$	(3)	Green and Hall [24]
$M_R(MPa) = 17.6(CBR)^{0.64}$	(4)	NCHRP [25]
$M_R(psi) = 3,000(CBR)^{0.65}$	(5)	Paterson and Maree [26]
$M_R(psi) = 7013.065 - 2040.783\ln(DCPI)$	(6)	Hassan [27]
$M_R(psi) = A + B(R - value)$	(7)	Asphalt Institute [28]
$M_R(psi) = 3500 + 125(R - value)$	(8)	Yeh and Su [29]
$M_R(ksi) = 37.431 - 0.4566\,(PI) - 0.6179\,(W_c) - 0.1424\,(P_{200}) + 0.1791\,(\sigma_3) - 0.3248\,(\sigma_d) + 36.722\,(CH) + 17.097\,(MH)$	(9)	George [30]
$M_R(MPa) = 16.75\left(\left(\dfrac{LL}{W_c \cdot \gamma_d}\right)^{2.06} + \left(\dfrac{P_{200}}{100}\right)^{-0.59}\right)$	(10)	George [30]
$M_R(psi) = 342780 - 359S - 325\sigma_3 + 86PI + 107P_{200}$	(11)	Farrar and Turner [31]

Note: CBR (%), DCPI = penetration index, mm/blow, R-value = Stabilometer value (1bs), A = 772 to 1155, B = 369 to 555, W_c = Moisture content (%), γ_d= Dry density, g/cm³, S = Degree of saturation, PI = Plasticity index (%), LL= Liquid limit (%), P200 = Percentage passing #200 sieve, σ_3= Confining stress (psi), σ_d= Deviator stress (psi), CH = 1 for CH soil and 0 otherwise (for MH, ML or CL soil), MH = 1 for MH soil and 0 otherwise (for CH, ML or CL soil).

III. RESEARCH METHODOLOGY

To achieve the objective of this study, a laboratory testing program was conducted on three soils, which comprise common subgrade soils in Khartoum state. The soils were subjected to basic tests to determine their physical properties,

compaction characteristics, bearing strength and resilient modulus.

A. Soils Used

Soil samples for this study were collected from three sites in Khartoum state. The first site is located at Almenshia (S1) in Khartoum which is famous of expansive clay of high swelling potential. The second site is located at Al Haj Yosif (S2) in Khartoum North which is covered with clay soil of moderate plasticity. The third site is located at Alfitahab (S3) in North Omdurman where the soil is generally clayey Sand of low plasticity.

Disturbed soil samples were obtained from subgrade soils of existing roads. The soil samples were collected from 1 m depth by manual excavation of the ground at both sides of existing roads. The soil samples from all three sites are cohesive soils, containing mostly clay with some varying amounts of fine gravel, fine sand and silt. The samples were placed in plastic bags and transported to the soil mechanics laboratory, university of Khartoum.

The studied soils were selected so that test results can be utilized to establish and validate correlations to estimate resilient modulus of Khartoum state soils from soil properties.

B. Soil Sampling and Testing

The three soils were initially air dried, crushed into small sizes and pulverized. The test samples were prepared by sieving the soils through sieve No.4 (4.75 mm). The fine material passing sieve No.4 was used in the experimental work. The soil samples were oven dried at 105-110 °C for 24 hours. The samples prepared for resilient modulus tests were mixed with distilled water to the desired moisture contents and manually compacted to different dry densities.

The three soils were subjected to standard laboratory tests to determine their physical properties and compaction characteristics. Soil testing consisted of the following: grain size distribution (sieve and hydrometer analyses), Atterberg's limits (liquid limit and plastic limit), specific gravity and Standard Proctor. These tests were conducted according to the standard procedures of the BS [32]. The measured properties of the soils tested are presented in Table III.

TABLE III
THE PROPERTIES OF THE SOILS USED

Property	S1	S2	S3
Gravel, %	1	0	2
Sand, %	9	63	80
Silt, %	35	15	10
Clay, %	55	20	10
Liquid Limit, %	77	40	24
Plastic Limit, %	27	16	12
Plasticity Index, %	50	24	12
Max. Dry Density, g/cm³	1.62	1.84	2.18
Optimum Moisture Content, %	20.2	10.1	8.4
Specific Gravity	2.76	2.70	2.66
Soil Classification (USCS)	CH	CL	SC

To measure the M_R, soil samples were initially compacted at different water contents and densities and then transferred to the resilient modulus testing machine. The M_R tests were carried out on the surface of the samples confined by the conventional CBR mould. The RLT test was conducted, to determine the resilient modulus of the investigated soils, following AASHTO [5] Fig. 2 illustrates the overall set-up of the resilient modulus test system utilized in this study.
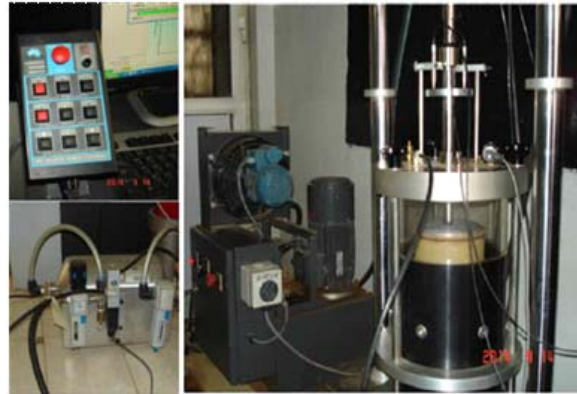

Fig. 2 The Resilient Modulus Test System

Each soil was compacted at five different moisture contents and dry densities. The resilient modulus tests were conducted on compacted soil samples. The tests results for the studied soils are presented in Table IV.

TABLE IV
SUMMARY OF TESTS RESULTS FOR THE THREE SOILS

Soil	Moisture content, %	Dry density, g/cm³	M_R, MN/m²
Soil 1	16.5	1.64	18.5
	18.5	1.56	17.0
	20.5	1.49	16.6
	22.5	1.45	16.0
	24.5	1.95	21.0
Soil 2	5.5	1.79	30.5
	8.1	1.81	28.2
	10.3	1.77	22.3
	12.1	1.75	20.8
	14.0	1.66	17.0
Soil 3	4.5	2.12	57.0
	6.5	1.89	44.0
	8.5	1.99	46.0
	10.5	1.99	43.0
	12.5	1.95	40.0

IV. RESULTS AND DISCUSSION

The primary objective of this study is to correlate the resilient modulus to simple and easy measured soil index properties. The soil parameters which affect resilient modulus values include moisture content, dry density (i.e. placement conditions) and soil consistency index (i.e. soil intrinsic properties).

A. The Consistency Factor

This factor which combines placement and intrinsic

parameters is termed consistency factor. The factor (F_c) is formed by combing some soil parameters, namely consistency index (CI), dry density (γ_d), density of water (γ_w), and void ratio (e) in a way reflecting the influence of each of them on resilient modulus (M_R) value and it is expressed by (12):

$$F_C = \frac{\gamma_d \cdot CI}{\gamma_w \cdot e} \qquad (12)$$

The CI is arithmetically 1-LI (where LI is the liquidity index) as given in (13):

$$CI = \frac{LL - w}{PI} \qquad (13)$$

where LL is liquid limit; w is moisture content; PI is plasticity index.

B. The Relationship between the Factor F_c and M_R
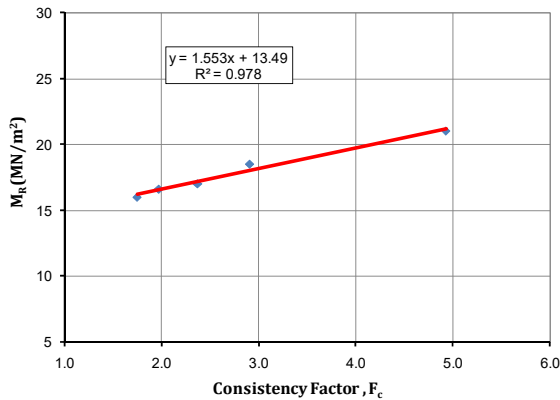
Fig. 3 Resilient Modulus versus Consistency Factor for Soil 1
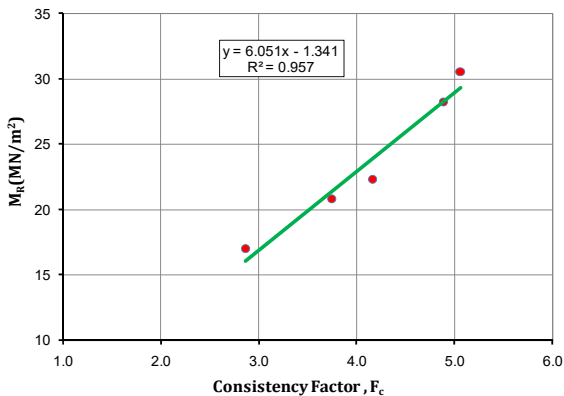

Fig. 4 Resilient Modulus versus Consistency Factor for Soil 2

The consistency factor F_c (12) is applied to the study tests data of the three soils and the data reported by previous researchers. Figs. 3-7 show the relationship of the resilient modulus with Factor "F_c" for the three soils tested and the data reported by Ruttanaporamakul [22] and given in Table I. It is clearly observed from these figures that resilient modulus

increases linearly with factor F_c for all the five soils. Smooth linear relationship was obtained for the consistency factor (F_c) and the degree of correlation is excellent for the three soils ($R^2 > 0.90$).
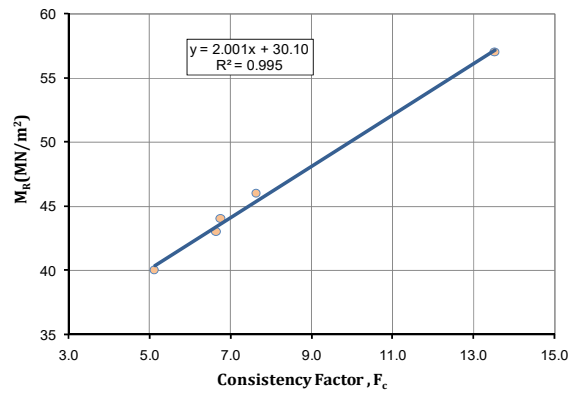

Fig. 5 Resilient Modulus versus Consistency Factor for Soil 3
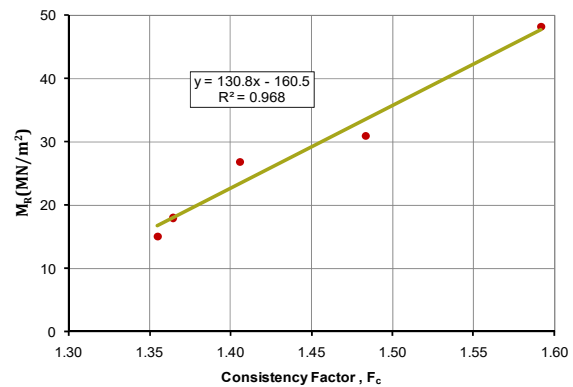

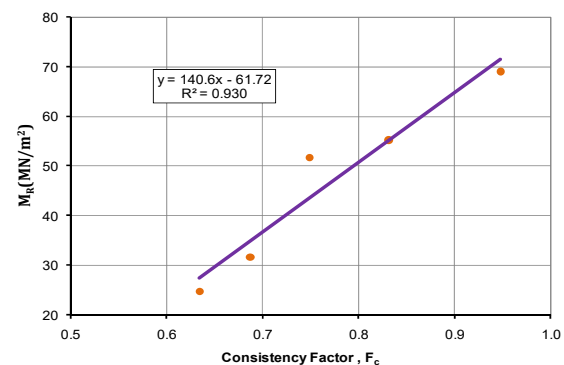Fig. 6 Resilient Modulus versus Consistency Factor for Minnesola Soil [22]

Fig. 7 Resilient Modulus versus Consistency Factor for Louisiana Soil [22]

The straight line shown in Figs. 3-7 can be expressed as:

$$M_R = M \cdot (F_C + F_0) \qquad (14)$$

where F_0 = the value of F_C at zero M_R value; M = the gradient

of the straight line.

By substituting the values of the straight line constants "F_0" and "M" as obtained for the five soils, the resilient modulus can expressed as:

$$\text{For soil 1} \quad M_R = 1.55(F_C + 8.69) \tag{15}$$

$$\text{For soil 2} \quad M_R = 6.05(F_C - 0.22) \tag{16}$$

$$\text{For soil 3} \quad M_R = 2.00(F_C + 15.04) \tag{17}$$

$$\text{For soil 4} \quad M_R = 130.8(F_C - 1.23) \tag{18}$$

$$\text{For soil 5} \quad M_R = 140.6(F_C - 0.44) \tag{19}$$

The MR values obtained from the developed equations (15)-(17) are compared with the measured values in Tables I and IV. The data trend in Fig. 8 indicates that there is a good agreement between the measured and predicted MR values and this result proved the validity of the developed equations.
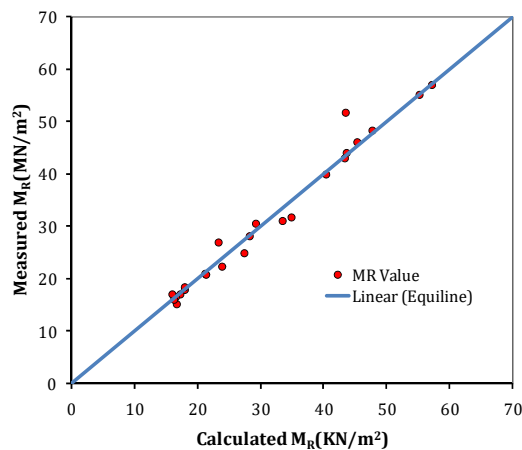

Fig. 8 Comparison between measured and calculated Resilient Modulus

V. CONCLUSION

Experimental work has been carried out to estimate the resilient modulus of subgrade soils from easy measured soil index properties. The following conclusions are drawn from the study.

- Several laboratory tests to measure the M_R and index properties were conducted on soil samples compacted at different moisture contents and dry densities.
- The consistency factor (F_c) is formed by combining the soil index properties (i.e. dry density, moisture content, void ratio, and consistency limits) in such a way reflecting the influence of each of them on M_R value.
- Analysis of tests results and data reported by previous researchers demonstrate very clearly that a direct linear relationship exists between M_R and the consistency factor (F_c).

- On basis of this linear relationship, reliable strong equations have been established between M_R and soil index properties.
- Comparison between the measured and the predicted M_R values for all the soil studied indicates that there is a good agreement between the measured and predicted M_R values.

REFERENCES

[1] American Association of State Highway and Transportation Officials. *AASHTO Guide for Design of Pavement Structures*, Washington, D.C, 1993.
[2] L. N. Mohammad, A. J. Puppala, and P. Alavilli. *Investigation of the Use of Resilient Modulus for Louisiana Soils in the Design of Pavements*, Final Report FHWA/LA-94/283, Louisiana Transportation Research Center, Baton Rouge, 1994.
[3] Y. A. Huang. *Pavement Analysis and Design*, Prentice Hall, Englewood Cliffs, NJ, 1993.
[4] H. Seed, C. Chan, and C. Lee, "Resilient Modulus of Subgrade Soils and Their Relation to Fatigue Failures in Asphalt Pavements," Proceedings, International Conference on the Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor, Michigan, 611-636, 1962.
[5] AASHTO. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, Part II Methods of Sampling and Testing. 25th Edition. American Association of State Highway and Transportation Officials, Washington, 2005.
[6] D. Li, and T. S. Ernest, "Resilient Modulus for Fine-Grained Subgrade Soils," Journal of Geotechnical Engineering, Vol. 120, No. 6, June, 1994.
[7] W. Lee, N. C. Bohra, A. G. Altschaeffi, and T. D. White, "Resilient Modulus of Cohesive Soils," J. Geotech. and Geoenviro. Engrg., ASCE, 123(2), pp. 131 – 136, 1997.
[8] M. R. Thompson and Q. L. Robnett, "Resilient Properties of Subgrade Soils," Transportation Engineering Journal, ASCE, 105(TE1), pp. 71-89, 1979.
[9] G. Rada and M. W. Witczak, "Comprehensive Evaluation of Laboratory Resilient Moduli Results for Granular Material," Transportation Research Record No. 810, Transportation Research Board, pp. 23-33, 1981.
[10] R. Pezo and W. R. Hudson, "Prediction Models of Resilient Modulus for Nongranular Materials," Geotechnical Testing Journal, GTJODJ, Vol. 17 No. 3, 1994, pp. 349 - 355.
[11] W. S. Smith and K. Nair.*Development of Procedure for Characterization of Untreated Granular Base Course and Asphalt Treated Course Materials*, FHWA, Final Report, FHWA-A-RD-74-61, Washington D.C, 1973.
[12] A. J. Allen. *Development of A Correlation Between Physical and Fundamental Properties of Louisiana Soils*, Master's Thesis, Dept. of Civil Eng., Louisiana State University, Baton Rouge, 1996.
[13] E. C. Drumm, J. S. Reeves, M. R. Madgett and W. D. Trolinger, "Subgrade Resilient Modulus Correction for Saturation Effects," Journal of Geotechnical and Geo-environmental Engineering, Vol. 123, No. 7, 1997.
[14] M. R. Thompson, "Factors Affecting the Resilient Moduli of Soils and Granular Materials," Workshop on Resilient Modulus Testing, Oregon State University, Corvallis, 1989.
[15] R. D. Barksdale, and S. Y. Itani, "Influence of Aggregate Shape on Base Behavior," Transportation Research Record 1227, Transportation Research Board, National Research Council, Washington, D.C., pp. 173-182, 1989.
[16] A. Dawson, M. Mundy and M. Huhtala, "European research into granular material for pavement bases and subbases," Transportation Research Record: Journal of the Transportation Research Board, (1721), 91–99, 2000.
[17] T. S. Butalia, J. Huang, D. G. Kim and F. Croft, "Effect of Moisture Content and Pore Water Pressure Build on Resilient Modulus of Cohesive Soils," Resilient Modulus Testing for Pavement Components, 2003, ASTM STP 1437.
[18] M. S. Jin, W. Lee and W. D. Kovacs, "Seasonal Variation of Resilient Modulus of Subgrade soils," J. Trans. Engrg., ASCE, 120(4), 1994, pp. 603 – 615.
[19] A. Maher, T. Bennert, and N. Gucunski.*Resilient Modulus Properties of New Jersey Subgrade Soils*, Final Report, The State of New Jersey

Department of Transportation, September 2000.

[20] F. Lekarp, U. Isacsson and A. R. Dawson, "State of the Art. I: Resilient Response of Unbound Aggregates" Journal of Transportation Engineering, Vol. 126, No.1, pp. 66-75, 2000.

[21] V, C. Janoo, and J. J. Bayer, "The effect of Aggregate Angularity on Base Course Performance," U.S. Army Corps of Engineers, ERDC/CRREL TR-01-14, 2001.

[22] P. Ruttanaporamakul, "Resilient Moduli Properties Of Compacted Unsaturated Subgrade Materials," M.Sc. thesis, the University of Texas at Arlington, July 2012.

[23] W. Heukelom and A. J. G. Klomp, "Dynamic Testing as a Means of Controlling Pavement during and after Construction," Proceedings of the 1st international Conference on the Structural Design of Asphalt Pavement, University of Michigan, Ann Arbor, MI, 1962.

[24] J. L. Green and J. W. Hall. *Non-destructive vibratory testing of airport pavement: Experimental tests results and development of evaluation methodology and procedure*, FAA-RD-73-205, Federal Aviation Administration, Washington D.C., 1975.

[25] NCHRP 1-37A Design Guide. *Mechanistic-Empirical Design of New & Rehabilitated Pavement Structures*, Transportation and Road Research Laboratory (TRRL), 2002.

[26] W. D. L. Paterson and J. H. Maree, "An interim mechanistic procedure for the structural design pavements," National Institute for Transport and Road Research, Pretoria, South Africa, 1978.

[27] A. Hassan. *The Effect of Material Parameters on Dynamic Cone Penetrometer Results for Fine-grained Soils and Granular Materials*, Ph.D. Dissertation, Oklahama State University, Stillwater, 1996.

[28] The Asphalt Institute. *Research and Development of the Asphalt Institute's Thickness Design Manual*, Ninth Edition, Research Report No. 82-2, 1982, pp. 60.

[29] S. T. Yeh and C. K. Su, "Resilient Properties of Colorado Soils," Colorado Department of Highways, Report No. CDOH-DH-SM-89-9, 1989.

[30] K. P. George. *Prediction of Resilient Modulus from Soil Index Properties*, Final Report, Conducted by the Department of Civil Engineering at University of Mississippi, Mississippi, November 2004.

[31] M. J. Farrar and J. P. Turner, "Resilient Modulus of Wyoming Subgrade Soils," Mountain Plains Consortium Report No 91-1, The University Of Wyoming, Luramie, Wyoming, 1991.

[32] BSI. *Methods of Test for Soils for Civil Engineering Purposes*, Part 2 (BS 1377-2). British Standards Institution, London, 1990.