Resilient modulus for unbound granular materials and subgrade soils in Egypt

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Abstract. Mechanistic Empirical (ME) pavement design methods started to gain attention especially the last couple of years in Egypt and the Middle East. One of the challenges facing the spread of these methods in Egypt is lack of advanced properties of local soil and asphalt, which are needed as input data in ME design. Resilient modulus (M_r) for example is an important engineering property that expresses the elastic behavior of soil/unbound granular materials (UGMs) under cyclic traffic loading for ME design. In order to overcome the scarcity of the resilient modulus data for soil/UGMs in Egypt, a comprehensive laboratory testing program was conducted to measure resilient modulus of typical UGMs and subgrade soils typically used in pavement construction in Egypt. The factors that affect the resilient modulus of soil/UGMs were reviewed, studied and discussed. Finally, the prediction accuracy of the most well-known M_r Prediction models for the locally investigated materials was investigated.

1 Introduction

Mechanistic Empirical (ME) pavement design methods has to be calibrated using specific pavement types, materials, specific local traffic and environmental conditions, which limit the possibility of using them, unless local calibration is conducted. In the Mechanistic-Empirical Pavement Design Guide (MEPDG), a pavement system is analyzed by computing the structural responses (stresses, strains, and deflections) based on the mechanical properties of different pavement materials. Then, the pavement distresses are predicted by empirical models using the computed critical strains and deformations.

The proper characterization of Unbound Granular materials (UGMs) and subgrade soils is essential in the design and rehabilitation of pavement structures. The resilient modulus (M_r) is used as a fundamental engineering property to describe stress–strain relationship of soil/UGM under cyclic loading. M_r is defined as the deviator stress (σ_d) divided by axial recoverable strain (ε_r) as shown in Equation (1).

$$M_r = \frac{\sigma_d}{\varepsilon_r} \quad (1)$$

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The MEPDG recommends the use of resilient modulus as level 1 input data (the highest level of accuracy) instead of California Bearing Ratio (CBR) for pavement design. Thus, the objectives of this paper are to:

- Present the state of the art regarding some factors affecting the resilient modulus of soil/UGMs and the available M_r predictive models for soil/UGMs
- Determine the resilient modulus of four typical UGMs and five subgrade soils that are used for pavement construction in Egypt.
- Apply some of the well-known resilient modulus models exist in the literature on the investigated materials to obtain material constants and recommend the most accurate model for the local materials.

2 Literature review

Several research studies have been conducted to characterize the resilient behavior of UGMs and fine grained subgrade soils [1]. Granular pavement layers demonstrate a nonlinear, time dependent and elastoplastic response under traffic loading [2, 3, 4]. On the other hand, traditional elasticity theories consider the response of granular materials as linear-elastic, which requires resilient modulus and Poisson's ratio [5].

Previous studies have shown that many factors affect the resilient modulus of UGMs and subgrade soils. Lekarp et al [6] and Azam et al [7] reported that the aggregate gradation, fine content, applied stress level, moisture content, matric suction, and density had significant effect on M_r. In the following subsections, the influence of these factors is briefed.

2.1 Soil index properties

Several studies investigated the effect of gradation, fines content, particle shape, maximum nominal aggregate size, liquid limit (LL), plasticity index (PI), coefficient of uniformity (C_u) and coefficient of curvature (C_c) on resilient modulus [8, 9, 10]. Raad et al. [8] studied the behavior of typical granular base materials with different gradations under Repeated Load Triaxial Test (RLTT) conditions. Results indicated that the dense graded aggregate exhibited the highest resilient modulus values compared to the open graded aggregate. In a similar study, Tian et al. [9] investigated the significance of UGMs gradation on M_r. Three different types of aggregate (Richard spurbase (RS) limestone with the value of Los Angeles Abrasion (LAA) of 24% ,Sawyer sandstone subbase aggregate with LAA of 28% and one base material) were investigated in this study. Test results show that the medium gradation of RS produced substantially higher M_r values than finer gradation, and slightly higher than coarser gradation. On the other hand for sandstone, the coarser gradation produced the highest M_r values than finer and medium limits. Similarly, Uthus et al. [11] noted that the soils with higher fine content, showed significant reduction in resilient modulus with slight increase in water content.

2.2 Stress State

The stress state is the most significant factor on the resilient modulus of UGMs and subgrade soils. Several studies have reported that M_r of untreated UGMs is dependent on confining pressure and deviator stresses, which increases considerably with the increase of those stresses [7, 10, 2, 12, 13, 14]. Kolisoja [15] reported that Poisson's ratio of UGMs increases with increasing deviator stress and decreasing confining pressure. Cabrera [16] reported that M_r decreased significantly with the increase in maximum cyclic stress amplitude. Results also showed that M_r generally increases with the increase in confining pressure level.

2.3 Moisture Content and Matric Suction

Numerous studies stated that the M_r of UGMs and subgrade soils fundamentally depends on moisture content or matric suction in both laboratory and in-situ condition [14, 17].

Hicks and Monismith [18] showed that the resilient modulus significantly influenced by moisture content. Moreover, they found that a loss in modulus value was observed as the moisture content increases over the Optimum Moisture Content (OMC). Lekarp [6] concluded that the pore pressure controls deformational behaviour as opposed to the level of saturation. Thom and Brown [19] demonstrated that moisture has some greasing impact on particles, and consequently builds an increase in the deformation of the aggregate structure with a loss in resilient modulus even without a generation of any pore water pressure. While, Dawson et al. [20] found that the stiffness of well-graded UGM underneath the optimum moisture content tends to increase with the decrease of moisture due to development of suction, then diminished with increasing the moisture content in the wet side of the compaction curve. An obvious diminishment of resilient modulus as well as Poisson's ratio has been found by Lekarp [6] with the increase in moisture content, particularly at high level of saturation. Ekblad [21] demonstrated the impact of water content on resilient behavior of different gradations by changing the maximum particle size and the grading shape . The author reasoned that for the loss of resilient modulus has been more articulated by increasing the water content in the higher stress levels. Andrie et al [22] studied the effect of water content on both UGMs and subgrade soils. They observed that water content had little impact on the resilient modulus of base materials compared to the subgrade soils. Studies conducted by [23, 24, 17], found that the matric suction has been appeared to be a vastly improved predictor of engineering behavior than moisture content.

2.4 Resilient Modulus Prediction Models

Different models have been developed to predict the resilient modulus of UGMs and subgrade soils based on stress state, soil index properties and moisture content. The following subsections present most of the developed models found in the literature for predicting resilient modulus of coarse and fine-grained soils.

2.4.1 Models based on stress state

Numerous researchers have developed resilient modulus models to predicted (M_r) values depending on stresses for both coarse and fine-grained soils. For example, Hicks and Monismith [18] developed the very well-known K-θ model for UGMs based on bulk stress as described in Equation 2.

$$M_r = k_1(\theta)^{K_2} \tag{2}$$

Where M_r = resilient modulus, K_1, and K_2 = regression coefficients, θ = bulk stress = ($\sigma_1 + \sigma_2 + \sigma_3$), σ_1 = major principal stress, σ_2 = intermediate stress, σ_3 = minor principal stress.

May and Witczak [25] proposed a model that correlates the resilient modulus with the normalized measures of the mean stress and octahedral shear stress as follows:

$$M_r = K_0 * \left(\frac{\sigma_m}{P_a}\right)^{K_1} * \left(\frac{\tau_{oct}}{\tau_{ref}}\right)^{K_2} \tag{3}$$

Where P_a = atmospheric pressure, σ_m = mean normal stress = $((\sigma_1 + 2\sigma_3)/3)$, τ_{oct} = octahedral shear stress = $(\sqrt{2}/3)(\sigma_1 - \sigma_3)$, τ_{ref} = reference shear stress = $\frac{\sqrt{2}}{3}*q_f$; q_f = peak shear strength= ($d+\sigma_m*\tan\beta$); d and β are Druker–Prager failure parameters and K_o, K_1, K_2 = regression parameters.

Uzan [2] simplified Equation 3 by excluding the reference shear stress as follows:

$$M_r = K_1 pa \left(\frac{\theta}{pa}\right)^{K_2} \left(\frac{\tau_{oct}}{pa}\right)^{K_3} \quad (4)$$

Equation 4 was incorporated in the MEPDG with adding one to the shear stress term and it is well-known as the universal Witczak model [26].

$$M_r = K_1 pa \left(\frac{\theta}{pa}\right)^{K_2} \left(\frac{\tau_{oct}}{pa} + 1\right)^{K_3} \quad (5)$$

Rahim & George [13] proposed two sets of models for predicting resilient modulus for coarse and fine-grained soils depending on stress state as described in Equations 6 and 7, respectively:
For coarse-grained soils:

$$M_r = K_1 Pa \left(\frac{\theta}{(\sigma_d+1)} + 1\right)^{K_2} \quad (6)$$

For fine-grained soils:

$$M_r = K_1 Pa \left(\frac{\sigma_d}{(\sigma_c+1)} + 1\right)^{K_2} \quad (7)$$

Where σ_c = confining pressure and K_1, K_2 are regression model parameters.

2.4.2 Models based on soil index properties

It is desirable to develop simple models for the estimation of M_r based on the simple index properties to overcome the complexity of the resilient modulus test as well as the cost of testing, which requires expensive equipment and well trained technicians. Many correlations were developed to predict resilient modulus depending on materials properties and soil characteristics such as CBR, PI, LL, water content (WC), dry density (γ_{dry}), percentage passing sieve No 200 (p#200), percentage passing sieve No (40) (p#40), C_c and C_U. The MEPDG suggests that resilient modulus of fine-grained soils can be predicted using the following Equation that was modified by Heukelom and Klomp [27] for materials having CBR of < 10%:

$$M_r\ (psi) = 1500\ CBR \quad (8)$$

For materials with CBR > 10%, Equation 9 is used instead by MEPG [26] as follows:

$$M_r\ (psi) = 2555\ (CBR)^{0.65} \quad (9)$$

Rahim [28] developed correlations for coarse and fine grained soils as given in Equations (10) and (11) as follow:
For coarse-grained soils:

$$M_r = 324.14 \left(\frac{\gamma dry}{WC+1}\right)^{0.8998} * \left(\frac{P\#200}{Log\ CU}\right)^{0.4652} \quad (10)$$

For fine-grained soils:

$$M_r = 17.29(\left(\frac{\gamma dry}{WC+1}\right)^{2.18} + \left(\frac{P\#200}{100}\right)^{-0.609} \quad (11)$$

Where γ_{dry} is the relative dry density (%) to MDD), WC is moisture content (%)), P#200 is percentage of fines passing from sieve No.200, and (LL) is liquid limit (%).

Yan et al. [29] proposed two predictive models for subgrade soils based on gene expression programming (GEP) to correlate M_r with routine properties of subgrade soils as follows:

$$M_r = \text{atan}\ \{\gamma_{dry}\ (\frac{\gamma_d - U_C}{pi})\} + \{2 + (\frac{\sqrt{PI}}{P\#200})\} + \sigma_d + \{2 * \sin (\frac{\gamma_d * \exp(\text{atan}(sin P\#200))}{P\#200})\} + \{\sigma_d(\text{atan}(\text{sqrt}(P\#200)) - (\sigma_d * P\#200)/\gamma_{dry})\} + \{\text{atan}(\text{sqrt}(U_C) - \gamma_{dry}) + \text{atan}\ \gamma_{dry} \quad (12)$$

Where Uc = unconfined compressive strength

2.4.3 Models based on moisture content/degree of saturation

Several models have been developed to consider the impact of moisture content or degree of saturation on resilient modulus. For example, Li and Selig [30] predicted resilient modulus in terms of moisture content as follows:

$$M_r/M_{r\,OPT} = 0.98 - 0.28 * (W - W_{OPT}) + 0.29 * (W - W_{OPT})^2 \quad (13)$$

Where (Mr_{OPT}) is the resilient modulus at OMC, (W) is water content after test and (W_{OPT})is the OMC.

Andrie et al [22] modified the universal model (Equation 5) to include the moisture content effect. They developed two models, one for UGMs and one for the fine-grained soils as follow:

For coarse-grained soils:

$$M_r = 10^{a+\frac{b-a}{1+EXP(\beta+K_s(S-S_{opt}))}} K_1 p_a \left(\frac{\theta}{p_a}\right)^{K_2} \left(\frac{\tau_{oct}}{p_a}+1\right)^{K_3} \quad (14)$$

For fine-grained soils:

$$M_r = 10^{a+\frac{b-a}{1+EXP(\beta+K_w(W-W_{opt\_std}))}} K_1 p_a \left(\frac{\theta}{p_a}\right)^{K_2} \left(\frac{\tau_{oct}}{p_a}+1\right)^{K_3} \quad (15)$$

Where K_S: regression parameter for moisture and density effect, a is regression parameter at minimum of Log (M_r/M_{ropt}), b is regression parameter at maximum of Log ($M_r/M_{ropt.}$), β=Ln.((-b)/a), S - S_{opt} is the variation in degree of saturation, W is gravimetric moisture content, W_{opt}. gravimetric OMC corresponding to standard compaction and K_W is a regression parameter.

Recently, Garcia et al. [31] developed a model taking into account the effect of moisture content and stress state on predicting resilient modulus as shown in the following Equation:

$$M_r = e^{1.98-0.0714(W-W_{OPT})} * \left(\frac{\sigma_d}{\sigma_3}\right)^{-0.2} \quad (16)$$

Where (W) moisture content after testing,

3 Investigated materials

In this paper, four typical limestone aggregates typically used in road construction in Egypt were investigated (3 bases, and one subbase). These materials were sourced from Ataqqa quarry in Suez governorate, Egypt. In addition, five subgrades soils (three clayey soils and two silty soils) were collected from subgrade soil around Mansoura city, Egypt.

3.1 Laboratory testing

The testing program was conducted on the investigated UGMs/soils to determine the index soil properties and resilient modulus. Lab testing included Particle Size Distribution (PSD)[32], AASHTO classification[33], specific gravity[34] , Atterberg limits [35], modified Proctor compaction [36], CBR [37], and RLTT [38].

3.2 Index engineering properties

Sieve analysis tests for UGMs were conducted in accordance with the ASTM C 136. Figure 1 presents the PSD for UGMs. The basic engineering properties of the investigated materials are summarized in Tables 1 and 2 for UGMs and subgrade soils, respectively along with the specification limits and the test standards.

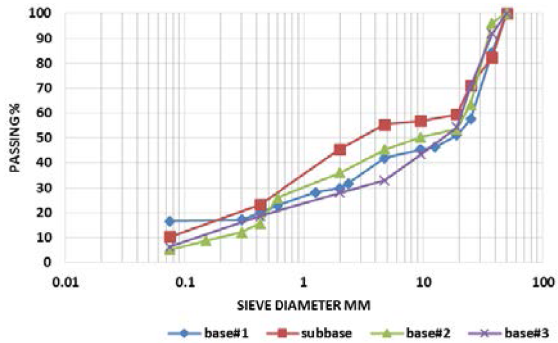


Fig. 1. Particle size distribution for the investigated UGMs.

Table 1. Basic engineering properties of the investigated UGMs.

Material	**Proctor Test**		**Atterberg limits**			**CBR**	**Specific gravity**		**Soil Class.**
	ASTM D 1557		**ASTM D 4318**			**ASTM D 1883**	**ASTM C 127**		**AASHTO M 145-91**
	MDD*gm/ cm^3	OMC, %	LL, %	PL, %	PI, %	%	Gs_b	%Water absorption	
Base #1	2.22	7.2	24	20.4	3.6	73	2.35	3.3	A-1-b
Base #2	2.181	7.5	23	18	5	60.4	2.46	1.6	A-1-b
Base#3	2.245	7.5	24.4	19.1	5.3	84	2.54	1.5	A-1-a
Subbase	2.225	7.2	29	NP		25	2.68	0.1	A-1-a

*MDD = Maximum Dry Density; OMC = Optimum Moisture Content; Gs_b= bulk specific gravity

Table 2. Basic engineering properties of the investigated subgrade soils

Material	**Proctor test**		**Atterberg limits**			**CBR**	**Soil type**	**Soil classification**
	ASTM D 1557		**ASTM D 4318**			**ASTM D 1883**		**AASHTO M 145-91**
	MDD g/cm^3	OMC, %	LL, %	PL, %	PI, %	%		
SG#1	1.762	18	68	42.2	25.8	5.61	Clay	A-7-5
SG#2	1.795	15	39.2	31.5	7.72	16.18	Silt	A-4
SG#3	1.437	18	59.1	32.9	26.2	5.3	Clay	A-7-6
SG#4	1.65	16.5	32	18.1	13.9	16.1	Silt	A-4
SG#5	1.57	20	70	45.4	24.6	5.6	Clay	A-7-6

3.3 Sample preparation for resilient modulus testing

A steel split mold of 300 mm high and internal diameter of 150 mm was used for sample preparation of the UGMs for the RLTT. For the clay and silt subgrade soils, a split mold of 200 mm height and 100 mm diameter was used. Duplicate specimens were compacted according to the modified Proctor compaction effort in six layers at MDD and OMC for each material.

Generally, samples were left one day for curing before de-molding (Figure 2) and testing. The final height, diameter and weight of each specimen were recorded before testing. A rubber membrane was stretched around the specimen by the membrane expander and then the membrane was sealed to the top and bottom caps by means of O-rings as shown in (Figure 2).

Resilient modulus testing was conducted according to [34] using the Universal Testing Machine (UTM-25) located at the Highway and Airport Engineering Laboratory (H&AE-LAB), Faculty of Engineering, Mansoura University, Egypt. Two Linear Variable Differential Transducers (LVDTs) were mounted externally to the load cell in the UTM to measure deformations. The AASHTO T307 protocol for UGM and subgrade soils consists of a pre-conditioning sequence and 15 loading sequences. The number of load repetitions is 500 cycles for the conditioning stage and 100 cycles for each loading sequence. The load shape was haversine with 0.1 second loading duration and 0.9 second as rest period for UGMs, while it was 0.2 second loading duration and 0.8 second as rest period for subgrade soils. In the conditioning sequence, a confining pressure of 103.4 kPa and 93.1 kPa deviator stress were applied for UGMs, while the confining pressure and deviator stresses for subgrade soils were 41.4 kPa and 24.8 kPa, respectively. The resilient modulus was calculated as the average of the last five cycles of each sequence. The final moisture content was determined after each test. The properties of the tested samples after testing are presented in Table 3.

Fig. 2. Sample preparation and test set up.

Table 3. Final moisture content and relative compaction for test specimens.

Soil type	**Speciemn**								
	Base#1	**Base#2**	**Base#3**	**subbase**	**SG#1**	**SG#2**	**SG#3**	**SG#4**	**SG#5**
	A-1-b	**A-1-b**	**A-1-a**	**A-1-a**	**A-7-5**	**A-4**	**A-7-6**	**A-4**	**A-7-6**
WC, %	7.15	7.42	7.1	7.18	17.54	14.56	17.54	16.15	19.53
γ_{dry}, gm/cm^3	2.199	2.175	2.215	2.195	1.715	1.735	1.425	1.61	1.521
Relative Compaction, %	99.08	99.7	98.6	98.65	97.33	96.7	96.7	97.5	96.9

3.4 Results and analysis of resilient modulus testing

The relationships between the resilient modulus and the applied deviator stress under different confining pressures for base#1, SG#2 and SG#5 as an example are illustrated in (Figures 3, 4, and 5), respectively. It can be concluded from these figures that both of deviator and confining stresses have significant effect on resilient modulus values for both UGM and subgrade soils. As both of deviator and confining stresses increase, the resilient modulus was increased for UGM, while it was decreased for both subgrade soils. However, the impact of confining pressure on resilient moduli was less pronounced for clayey soils (SG#5). This finding agreed with previous studies [39, 28]. The variation in behavior between UGM and subgrade soils could be attributed to the sample physical properties such as percentage of passing sieve no. #200, fine and moisture contents as given previously in Tables 1 and 2.

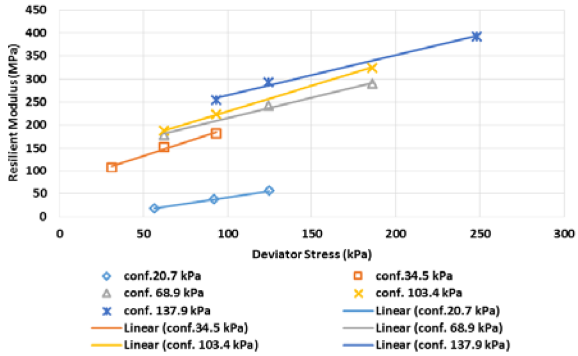


Fig. 3. Effect of deviator stress and confining pressure on resilient modulus for base#1.

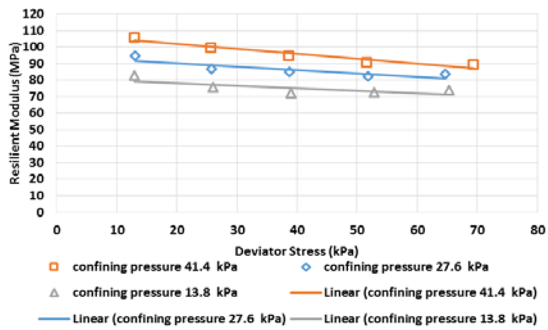


Fig. 4. Effect of deviator stress, and confining pressure on resilient modulus for SG#2.

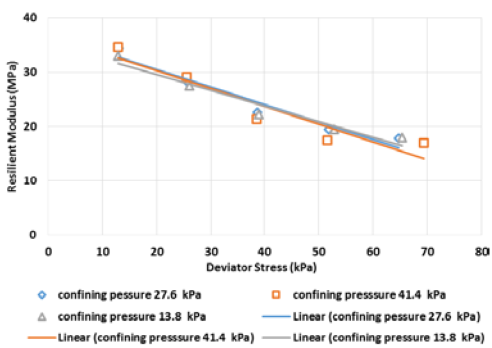


Fig. 5. Effect of deviator stress, and confining pressure on resilient modulus for SG#5.

4 Resilient modulus modelling

Some of the well-known published models in the literature was applied to the RLTT results i.e., K-θ, universal, and Rahim& George models to predict resilient modulus for UGM and subgrade soils. The K-Θ, universal, and Rahim &George stress models, which presented in Equations (2, 5, 6 and 7), respectively were used to predict resilient modulus for each material. Table 4 presents the regression constants of Equations 2, 5, 6, and 7 for each material. Resilient modulus prediction accuracy in terms of coefficient of determination, R^2

for UGMs was excellent for the four equations, however for subgrade soils prediction accuracy was ranged from fair to excellent.

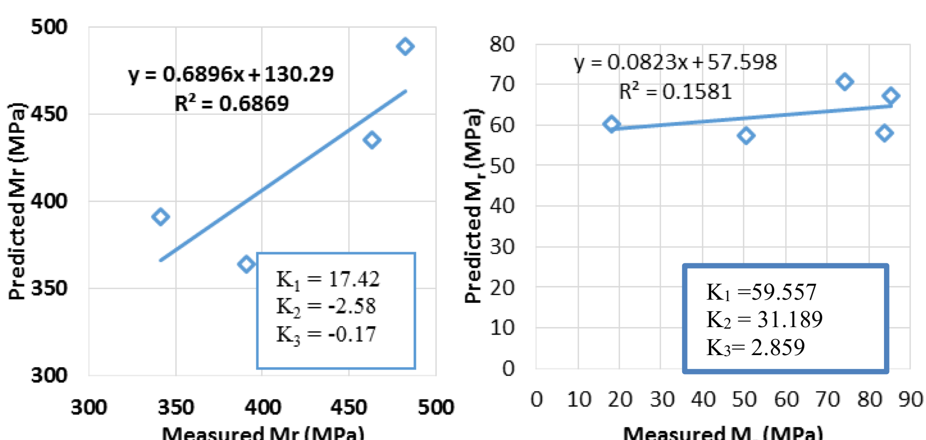
Table 4. Regression coefficients and prediction accuracy of Equations 2, 5, 6, and 7.

Soil type	Resilient modulus predictive models									
	K-θ model			Universal model				Rahim& George stress models		
	K_1	K_2	R^2	K_1	K_2	K_3	R^2	K_1	K_2	R^2
Base#1	3.91	0.69	0.98	0.91	0.467	0.797	0.99	3.242	0.69	0.99
Base#2	17.54	0.489	0.98	1.779	0.404	-0.211	0.86	7.51	0.60	0.98
Base#3	33.66	0.385	0.99	1.878	0.237	0.565	0.95	20.367	0.451	0.99
Subbase	3.64	0.67	0.98	0.965	0.737	-1.85	0.99	3.64	0.67	0.98
SG#1-	7.91	0.34	0.98	0.57	0.152	-0.59	0.81	0.585	-0.13	0.63
SG#2-	32.56	0.20	0.99	1.02	0.321	-1.36	0.99	1.09	-0.26	0.78
SG#3-	110.1	-0.09	0.97	0.511	-0.297	2.195	0.954	0.5142	0..364	0.78
SG#4-	37.02	0.12	0.98	0.05	-0.06	1.365	0.87	0.55	0.22	0.83
SG#5-	8.75	0.21	0.98	0.39	-0.06	-3.16	0.87	0.38	-0.53	0.98

It can be seen from the Table that there is no clear trend was noted for the values of the regression coefficients.

Equations (10 and 11) for coarse and fine grained materials, respectively were also utilized to predict the resilient modulus based on soil properties such as LL, PI, P#200, Cc and Cu.

Figures 6 and 7 present the prediction of the resilient modulus for the four UGMs and five subgrade soils, respectively using Equations 10 and 11 along with the values of the regression coefficients. It can be observed from Figures 6 and 7 that the prediction accuracy in terms of R^2 was fair and poor for UGMs and subgrade soils, respectively.



(a) (b)

Fig. 6 (a) M_r Prediction for UGMs using Eq. 10 (b) M_r Prediction for subgrade soils using Eq.11.

Moreover, Equation (16) was used to predict the resilient modulus values for fine-grained soils. The values of regression coefficients as well as the values of R^2 of Equation (16) are summarized in Table 5.

It can be seen from the Table that Equation (16) yielded excellent fit for all investigated subgrade soils.

Table 5. Values of regression coefficients of Equation 16.

Soil types	K_1	K_2	a	b	R^2
SG#1	53.89	0.06	3.49	1.026	0.99
SG#2	89.456	-0.140	4.344	0.99	0.99
SG#3	66.62	0.2156	3.702	1.0354	0.94
SG#4	64.09	0.101	4.64	1.01	0.99
SG#5	25.61	0.27	2.802	0.959	0.97

Finally, Equation (13) was used in order to predict resilient modulus for all materials including UGMs and subgrade soils and obtain one set of materials constants. Figure (7) shows the relationship between measured and predicted resilient moduli for all materials including UGMs and subgrade soils using Equation (13). It is clear from the figure that Equation (13) gave excellent fit with R^2 of 0.99 using the same values of regression coefficients presented previously in Equation 13. This means that Equation 13 is a general model and can be used to predict resilient modulus for UGMs and subgrade materials samples collected in this study.

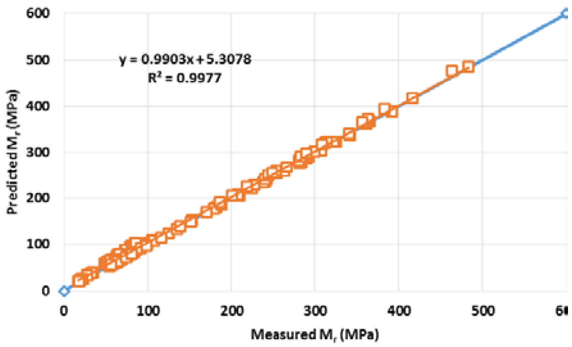


Fig. 7. Resilient modulus prediction for UGMs and subgrade soils using Equation 13

5 Summary and conclusions

Based on the literature review presented in this paper and the engineering properties of the investigated materials, the following conclusions can be drawn:

- There are many parameters that influence the behavior of UGMs and fine-grained soils under repeated loads. These factors are stress level, density, gradation, fines content, grain size, aggregate type, particle shape, and moisture content or matric suction. Researchers seem to agree that the resilient modulus is mostly influenced by the level of applied stresses and the amount of moisture content in the material.
- RLTT was conducted on three base materials, one subbase material, and five types of subgrade soils in order to determine resilient modulus values. Resilient modulus increased significantly with the increase in both deviator and confining stresses for UGMs, while it decreased for subgrade soils. Minimal influence of confining pressure on resilient modulus was observed for clayey soils.
- Number of well-known models was used to obtain the regression coefficients for each investigated material. Equation (13) was used to predict resilient modulus for all materials including UGMs and subgrade soils and get single set of regression coefficients. Models that used for predicting resilient modulus for each material fitted reasonably resilient modulus data with

accuracy in terms of R^2 varied from fair to excellent. Li and Selig model provided very excellent prediction accuracy with R^2 of 0.99 proving that it can be used as a general model for predicting resilient modulus for the nine investigated materials using Li and Selig regression coefficients.

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