Predicting Resilient Modulus of Unbound Granular Base/Subbase Material

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Abstract: **This research paper presents the results of modeling the resilient modulus (MR) of unbound granular base/subbase layers by means of the material index properties and stress state. The database employed in this study was collected from literature studies which includes 16 unbound granular materials (nine of them from Virginia, US while the other seven were from different quarries in Egypt). The database includes Liquid limit (LL), plastic limit (PL), plasticity index (PI), weighted PI (WPI), maximum dry density (MDD), optimum moisture content (OMC), passing sieve No. 4 (Pass#4), passing sieve No.200 (Pass#200), and 233 number of MR measurements. Two common literature MR-predictive models were used K-θ and Universal models as the base models. By using the fitting curve toolbox (CFTOOL) in the MATLAB program, the values of the regression coefficients of both models were recalibrated to predict the MR for each material individually. Both models regression coefficients (k-values) were correlated with the index properties of the soils (LL, PL, WPI, MDD, OMC, Pass#4 and Pass#200). Then, the index properties of the investigated UGMs, that affect the MR measurements, were correlated with the recalibrated regression coefficients of both models. Results showed that MR predictions based on index properties and stress state were satisfactory having a coefficient of determination, R^2 of 0.80, and 0.79 for universal and K-θ models, respectively.**

I. INTRODUCTION

Appropriate characterization of pavement materials is a prerequisite in the development of any mechanistic–empirical design method. It is also considered an essential factor for evaluating viable design alternatives. However, due to the complexities through any mechanistic design process, the current characterization alternatives for road materials require necessary simplifications. Whereas in order to obtain the desired material properties, additional testing capabilities are required [1].

With the release of the new American Association of State Highway and Transportation Officials (AASHTO) Design Guide [2], there has been much emphasis on using the resilient modulus (MR) as the preferred parameter to describe the load-

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deformation relationship for unbound granular materials (UGMs) and subgrade soils. MR is an indication of the resilience of pavement materials and soils under repeated traffic loads. The resilient properties of UGMs were first discovered by [3], who inferred that the deformation of such materials under transient loading is elastic in the sense that it is recoverable. The more realistic concept of MR was later introduced by [4]. In characterizing the elastic response of UGMs and subgrade soils and their relation to failures in asphalt pavements, Seed et al. [4] defined "resilient modulus" as the ratio of the additional axial stress (deviator stress) to the resilient strain as presented in Equation (1). Resilient modulus, MR is described as the cyclic deviatoric stress (σ_d) over the recoverable axial strain (ε_r) as follows [4-5].

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

Where, MR = resilient modulus (in MPa), σ_d = deviatoric stress (in MPa) = (σ_1 - σ_3), σ_1 = major principal stress (in MPa), σ_3 = the minor principal stress (in MPa), ε_r = recoverable (resilient) strain

Throughout literature, numerous research studies have attempted to characterize the resilient behaviour of UGMs [6-9]. It is found that the resilient properties of UGMs are affected by many factors such as stress level, density, fines content, liquid limit (LL), plasticity index (PI), gradation, maximum grain size, aggregate type, particle shape, and moisture content [10- 15]. The degree of stress has the greatest impact on the resilient behaviour of granular materials [15].

The resilient modulus can be determined by Repeated Load Triaxial Testing (RLTT) [16]. Different test protocols are available in literature for conducting RLTT to evaluate the permanent deformation and resilient modulus properties of UGMs, e.g. AUSTROADS [17] and Transit New Zealand TNZ T/15 [18]. Also, Long Term Pavement Performance (LTPP) Protocol P46 was developed by the Federal Highway Administration (FHWA) as a standard protocol for MR testing [19]. The LTPP Protocol P46 and AASHTO T307, [20] recommended standard loading Sequences to be applied on granular base/subbase course materials for determining their MR values. As the MR has been involved more strongly in pavement design procedures since late 1950s, a huge amount of MR data was developed by researchers and practitioners. According to ASHTO T307 test protocol, the MR of the granular materials is experimentally obtained by applying RLTTs on cylindrical specimens of 150 mm diameter and 300 mm height.

The repeated dynamic haversine loading waveform is employed in LTPP Protocol P46 or AASHTO T307, with a loading time of 0.1 second. This is followed by a resting period of 0.9 second during which only a seating load equal to 10% of the peak stress is applied to the specimen as the testing material recovers from the loading impact. Such one cycle is simulating one axle travelling over a pavement section followed by a resting time before the second axle passes over the same section [21].

The MR test procedure's overall goal is to simulate the stress condition operating on a material element at a specific position within the pavement structure. The confining pressure, which is applied inside a triaxial cell, reflects the element's existing geostatic stresses, while the applied deviatoric stress represents the transient stress induced by moving wheel loads on the pavement surface and imposed on the same element of material at the same time. The MR is determined after measuring the resulting strains using Equation (1).

On the other hand, the RLTT is time consuming, expensive, and complicated to be conducted by normal technicians. These limitations hinder the adoption of the modern design methods unless other options are provided for generating such inputs. Many researchers have studied the development of MR-predictive models based on physical properties of tested materials such as plastic limit (PL), LL, PI, maximum dry density (MDD), optimum moisture content (OMC), particle gradation, and fines content.

II. FACTORS AFFECTING RESILIENT MODULUS

A. Index Properties

UGMs are typically characterized using various geotechnical parameters such as gradation, fines content, particle shape, maximum/nominal maximum aggregate size, LL, PI, uniformity coefficient (Cu), and coefficient of curvature (Cc). Many researchers showed that the modulus of these materials depends, to some extent, on some or all of these parameters [22].

El-Badawy et al. [23] studied the effect of material type and gradation on the MR values of eight granular base and four subbase materials from various quarries in Egypt. They concluded that material gradation has a considerable impact on both the MR of UGMs. Raad et al. [24] studied the behaviour of typical granular materials with different gradations under repeated triaxial loading according to AASHTO T274-82 testing protocol [25]. Their results referred that the densest-graded aggregate had the highest MR values, whereas the open-graded aggregate had the lowest MR values. Thom and Brown [26] investigated the behaviour of crushed dolomitic limestone with seven various gradations ranging from one size to a dense gradation. The reported that evenly graded aggregate was only slightly stiffer than well-graded aggregate.

B. Stress State

The MR is obviously a stress-dependent parameter due to the nature of the RLTT [27]. The deviatoric and confining stresses are the two primary types of stresses that affect the MR values. The RLTT protocol employs these types of stresses.

Sweere [28] demonstrated that MR of granular materials is greatly dependent on the sum of primary stresses and confining stress. In terms of physics, MR rises as the total of primary stresses and confining stress rises.

In addition, Morgan [29] found that MR reduces marginally with rising deviator stress and constant confining stress.

C. Moisture Content and Density

The MR of UGMs is highly dependent on moisture content or saturation level, in both laboratory and in-situ situations, whereas MR decreases with an increase in the moisture content [30-32]. Andrei et al. [33] studied the effect of moisture content on both UGMs and subgrade soils. They found that water content had a little impact on the MR of base materials compared to subgrade soils. Heydinger [34] also noted that the moisture content of fine-grained soils is the major factor for predicting the seasonal changes of MR value.

Several studies showed the effect of density variations on MR. Such studies indicated that the MR increases with increasing the density [35]. Barksdale and Itani [36] found that the MR increases significantly with only increasing the material density at low levels of mean normal stress, while the effect of density was found to be less significant at high stress levels. Andrei et al. [33] showed that density strongly influences the relationship between MR and moisture content and suggested adding density as an indicator to the MR-predictive model that was developed considering moisture content.

III. RESILIENT MODULUS PREDICTION MODELS

From literature, various models were developed to predict the MR of UGMs based on index characteristics, stress state and moisture content [22]. The following subsections present the well-known established models for predicting the MR of coarse materials that have been published in the literature.

A. Models Based on Stress State

It is well known that MR is stress dependent. This means that there is a MR value corresponding to a single applied stress. Therefore, it is common to represent MR in terms of the stress state parameters. Different researchers proposed various MR-predictive models based on stress state.

One of the most common models dealing with the influence of stress on material stiffness is the expression simply based on the sum of the principal stresses (bulk stress). Seed et al. and Hicks [37, 38] developed the following relationships which are known as K−θ or bulk stress model as shown in Equations (2) and (3):

$$(2) \quad MR = K_1 \theta^{K_2}$$

$$(3) \quad MR = K_1 \left(\frac{\theta}{Pa} \right)^{K_2}$$

where MR = Resilient modulus (MPa), θ = bulk stress = $(\sigma_1 + \sigma_2 + \sigma_3)$, Pa = reference pressure (atmospheric pressure,

0.101325 MPa), and K_1, K_2 = regression constants depending on the material properties. Looking at its simplicity, the $K-\theta$ model is widely accepted by engineers and practitioners for analysing granular material stiffness based on stress state. Notwithstanding, this model has several flaws. The main flaw is that it does not account for shear stress and strain developed during loading. Also, this model could not properly handle volumetric strains or dilative behaviour of soil materials.

Recognizing the defects of confining pressure and $K-\theta$ models, many other models were developed by other researchers. One of them is known as octahedral stress state model developed by [9] which appears to be more feasible and realistic due to the introduction of deviatoric stress/octahedral shear stress into $K-\theta$ model as shown in Equations (4) and (5):

$$(4) \quad MR = K_1 Pa \left(\frac{\theta}{Pa} \right)^{K_2} \left(\frac{\sigma_d}{Pa} \right)^{K_3}$$

$$(5) \quad MR = K_1 Pa \left(\frac{\theta}{Pa} \right)^{K_2} \left(\frac{\tau_{oct}}{Pa} \right)^{K_3}$$

where; τ_{oct} = octahedral shear stress = $\frac{\sqrt{2}}{3}(\sigma_1 - \sigma_3)$, and

K_1, K_2, K_3 = regression constants,

In the Mechanical-Empirical Pavement Design Guide (MEPDG) [39], the regression model for predicting MR was modified based on Equation (5). It is well-known as the universal Witczak model for predicting MR as shown in Equation (6).

$$(6) \quad MR = K_1 Pa \left(\frac{\theta}{Pa} \right)^{K_2} \left(\frac{\tau_{oct}}{Pa} + 1 \right)^{K_3}$$

B. Models Based on Material Properties

Due to the intricacy of the MR testing process and the high cost of the required equipment for conducting such test, it has been desirable to find out approximate but reliable methods for estimating MR. In fact, the AASHTO design guide recommends that agencies involved in pavement design establish their own correlations to predict MR based on material properties i.e., PI, LL, water content (WC), dry density (γd), percentage passing sieve No. 200, and percentage passing sieve No. 40, Cc, and C_U.

Rahim and George [40] examined the importance of material index properties in predicting MR of Mississippi soils. Two equations have been proposed, referred to as Mississippi equations, one for fine-grained soil and another for coarse-grained soil. The equations were developed based on 12 soils from Mississippi, and had been validated with other eight soils,

also from Mississippi as shown below in coarse-grained soil equations (7):

-Coarse-grained soil:

$$(7) \quad MR = 307.4 \left(\frac{\gamma_d}{w_c}\right)^{0.86} + \left(\frac{P_{200}}{\log_{cu}}\right)^{-0.46}$$

Where MR = Resilient modulus (ksi), γ_d = maximum dry density (pcf), P_{200} = percentage passing #200 sieve, LL = liquid limit (%), wc = water content (%), and C_U = uniformity coefficient (%).

El-Ashwah, A et al [41] used ten samples for granular base and subbase materials from different places in Egypt. The effect of soil properties on the MR values measured in the laboratory was studied. The K1-K2-K3 universal constitutive model (Equation 6) was used for the estimation of the regression coefficients, by correlating them with soil properties. The resulting models were as follows:

$$(8) \quad K_1 = -16952.1342 + 34.7540\,(P200) + 247.2035\,(OMC) + 86.2138\,(LAA) + 5896.3842\,(G_s) - 132.1777\,(MDD)$$

$$(9) \quad K_2 = -3.8348 + 0.0104\,(P200) + 0.3213\,(OMC) + 0.0491\,(LL) - 1.9586\,(G_s) + 2.5788\,(MDD)$$

$$(10) \quad K_3 = -2.5433 - 0.0670\,(P200) - 0.1190\,(LL) + 1.4228\,(G_s) + 1.4104\,(MDD)$$

where; LAA = Los Angeles abrasion (%), MDD = maximum dry density of the test specimen (gm/cm^3), OMC = optimum moisture content (%), P200 = percentage passing #200 sieve, LL = liquid limit, and G_s = bulk specific gravity.

IV. RESEARCH OBJECTIVES

The objectives of this study are to recalibrate the two well-known MR-predictive models from literature that can reflect realistic behaviour of UGMs and to correlate the resulted models' regression coefficients with basic material properties. To achieve these objectives, the measured MR of sixteen different UGMs from Egypt (7 materials) and Virginia, US (9 materials) were selected to recalibrate both literature models' regression constants. New predictive relationships were developed to correlate the soil index characteristics of the selected UGMs in this study with the new calibrated regression coefficients.

V. DATA COLLECTION

A. Index Properties of UGMs

The database, which was employed in this study, is based on 16 different UGMs as described in Table 1, includes 9 materials from Virginia, US and 7 other materials from different quarries in Egypt. The database includes the laboratory-measured resilient modulus according to the AASHTO T307 and the basic properties of the UGMs, such as LL, PL, PI, WPI, MDD, and OMC, and passing percentage from sieve No. 200, and sieve No. 4 as given in Table 1. This data will be correlated to the new calibrated regression coefficients of the MR-predictive models. Descriptive statistics including mean, standard deviation, maximum, and minimum values of the investigated UGMs' index properties are presented in Table 2.

B. Resilient Modulus Measurements

Based on the literature studies, MR values of the investigated UGMs were obtained by performing RLTT tests according to AASHTO T 307-99 [45]. The stress levels employed in this standard are based upon the location of the material within the pavement structure as standardized by the test method. The test protocol for granular materials 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. Various combinations of confining pressures and cyclic axial stresses are applied within the loading sequences. For UGMs, the confining pressure ranges between 20.7 and 137.9 kPa, while the cyclic stress ranges between 18.6 and 248.2 kPa. After conducting the MR test, each testing sample has 15 representative MR measurements based on different combinations of stress state. [23]

VI. MR MODELLING

As stated in the literature review, researchers exerted many efforts to develop several models to predict the MR for both UGMs and subgrade soils. Below, two calibrated-literature models have been used to predict the MR based on regression coefficients and multiple soil properties. Before presenting the modeling effort, it is necessary to explain the criteria of the goodness-of-fit statistics used to measure the accuracy of the predictive models. The coefficient of determination (R^2), ratio of standard error of estimate to standard deviation of observed data (Se/Sy), and root mean square error (RMSE) can all be used to assess the prediction accuracy of the models.R^2 is the square of the correlation coefficient between the predicted and measured MR. The ranges of R2 between zero and one, with the higher values indicate better accuracy. The Se/Sy is an indicator of the relative accuracy improvement. Smaller values of Se/Sy mean better accuracy. RMSE is used to compare the

expected errors of different models of a variable, because it depends on the scale [46].

In this study, the K-θ model (Equation 2) and the universal model (Equation 6) were used to predict MR values for each UGM and for the 16 UGMs together. The regression coefficients for both models were recalibrated using the curve fitting technique employed in MATLAB's CFTOOL toolbox. The recalibrated regression coefficients as well as the goodness-fit-statistics for each investigated material individually based on the two predictive models are shown in Table 3.

These results show that the K-θ and Universal models are more suitable to predict the MR of the proposed UGMs. Figure 1. shows the measured versus predicted MR based on the two literature models by applying the developed models with the estimated regression coefficients (k-values) for each individual material which are shown in Table 3. The values of R2 presented in Figure 1 indicate excellent overall predictions with R2 of 0.99 and 0.97 for Equations 2 and 6, respectively, for the 16 UGMs. These results show that the K-θ and Universal models are more suitable to predict the MR of the proposed UGMs.

To find out the strength of the correlations between all properties, Table 4 represents the correlation matrix for all variables included in modelling. It is evident that the strength of the correlation between the values of MR and the properties of the materials is rather good, except that MDD is not considered strong enough.

A. Correlation of Calibrated Regression Coefficients with Index Properties of UGMs

More accurate estimations may be obtained using constitutive models based on the characteristics of soil indices [47]. Owing to the complexity, and expense of conducting MR test, it is favorable to be correlated with basic properties of the investigated UGMs to identify MR. Therefore, in this section, recalibrated regression coefficients of both K-θ model and Universal model are predicted based on the index properties of the 16 UGMs. Table 4 shows the strength of correlation between index properties of UGMs and MR. The variables of PL, WPI, OMC, MDD, Pass#4, and Pass#200, were correlated with the recalibrated regression coefficients as presented below. Figure 2 shows the measured versus predicted MR values, based on the two literature models listed in Equations 2 and 6. It can be seen from the figure that the proposed properties showed good prediction values for MR, where R2 for the K-θ model equation (2) was 0.79, while it was 0.80 for universal model equation (6). Both recalibrated models can be used for the prediction of MR with the same prediction accuracy, however the recalibrated universal model is more suitable to consider the octahedral shear stress term.

- For K-θ Model Equation (2):

$$K_1 = (0.126591 * MDD) + (-0.060300 * WPI) + (0.001577 * Pass\#4) + (-0.805286 * OMC)$$

$$K_2 = (2.015906) + (-0.002087 * Pass\#4) + (-0.008741 * MDD) + (-0.006874 * PL) + (-0.000336 * Pass\#200)$$

- For Universal Model Equation (6):

$$K_1 = (-0.05961 * PL) + (0.022754 * MDD) + (-0.03304 * LL)$$
$$K_2 = (0.115393 * OMC) + (-0.00912 * Pass\#200) + (-0.006 * Pass\#4)$$
$$K_3 = (13.91739) + (-0.08505 * MDD) + (-0.023559 * OMC)$$

VII. CONCLUSION

Using a database of 16 UGMs from different locations through Egypt and Virginia, US, two well-known MR-predictive models from literature based on stress state were recalibrated. This database consists of the measured MR values according to AASHTO T307-99 in addition to all the index properties used to characterize the UGMs such as Atterberg limits, gradation parameters, and Proctor test parameters.

Both predictive models, K-θ and Universal models, were recalibrated by using the curve fitting toolbox (CFTOOL) in the MATLAB program. The values of the regression coefficients of both models were determined based on the measured MR values of each UGM and for all UGMs. The prediction results compared to MR measurements were excellent based on the goodness-of-fit statistics.

Due to the importance of identifying the MR of UGMs in pavement characterization, complexity, and expense of conducting its test, the basic properties of the investigated UGMs, that affect the MR measurements, were correlated with the recalibrated regression coefficients of both models to predict MR values. The prediction results compared to MR measurements were satisfactory with R2 of 0.80 for the 16 UGMs. The recalibrated universal model is more appropriate for the MR prediction to account the octahedral shear stress effect.

TABLE 1
INDEX PROPERTIES OF BASE/SUBBASE MATERIALS. [41- 44]

Material ID	Source	Atterberg Limits*				Proctor Test Results*		Granular Gradation	
		LL%	PL%	PI%	WPI%	MDD (kN/m³)	OMC%	Pass#4%	Pass#200%
BS-SM[41]	Egypt	23.19	19.06	4.13	41.3	22.13	6	45.3	10
BS-SU[41]		23.83	17.62	6.21	73.899	21.48	6	35.2	11.9
BS-S[41]		18.32	13.8	4.52	30.736	23.14	5.5	35.2	6.8
BASE0[42]		24.4	19.1	5.3	33.92	21.08	7.5	32.92	6.4
BASE1[43]		24.5	20.4	4.1	67.978	22.67	7.2	41.9	16.58
BASE2[43]		23	18.5	4.5	23.85	21.90	7.5	45.4	5.3
BASE3[43]		23	18.5	4.5	28.8	22.39	7.5	33	6.4
AGG–1 (Shelton)	Virginia, US[44]	29	24	5	61.75	20.70	8	50.89	12.35
AGG–3 (Abingdon)		19	17	2	18.88	21.46	5.6	48.37	9.44
AGG–4(Frazier North)		24	18	6	48.36	22.18	7.1	55.38	8.06
AGG–5 (Centreville)		29	21	8	72.64	22.07	7.65	45.02	9.08
P2AGG–2 (Boscobel)		37	25	12	107.28	22.98	8.5	47.62	8.94
P2AGG–6 (Staunton)		26	21	5	40.4	22.02	7.75	52.25	8.08
P2AGG–7 (Graham-Occoquan)		33	24	9	126.72	21.77	6.75	57.3	14.08
P2AGG–8 (Graham-Occoquan)		33	24	9	71.82	21.39	6.75	36.93	7.98
P2AGG–9 (Centreville)		29	21	8	68.96	21.39	7.5	47.11	8.62

*LL= Liquid Limit, PL= Plastic Limit, PI=Plasticity Index, WPI=Weighted Plasticity Index=PI*Pass#200, MDD= Maximum Dry Density, OMC= Optimum Moisture Content, Pass#4= percentage passing #4 sieve, Pass#200= percentage passing #200 sieve

TABLE 2.
DESCRIPTIVE STATISTICS OF BASE/SUBBASE MATERIAL PROPERTIES

| Index Property	Mean	Standard Deviation	Minimum	Maximum
LL%	26.40	4.88	18.32	37.00
PL%	20.34	2.82	13.80	25.00
PI%	6.06	2.46	2.00	12.00
WPI%	57.89	29.78	18.88	126.72
MDD (kN/m³)	139.09	3.57	131.80	147.33
OMC%	7.08	0.84	5.50	8.50
Pass#4%	44.52	7.74	32.92	57.30
Pass#200%	9.52	3.03	5.30	16.58

TABLE 3.
REGRESSION COEFFICIENTS OF THE MODELS FOR THE INVESTIGATED UGM. [42- 44]

Materials ID	K-θ Model (Equation 2)					Universal Model (Equation 6)					
	K_1	K_2	R^2	Se/Sy	RMSE	K_1	K_2	K_3	R^2	Se/Sy	RMSE
BS-SM	21.480	0.491	0.982	0.132	3.609	1.999	0.427	0.233	0.985	0.122	3.417
BS-SU	19.010	0.476	0.947	0.229	0.422	1.610	0.339	0.498	0.980	0.142	3.923
BS-S	21.480	0.380	0.759	0.791	12.275	0.856	-0.004	2.327	0.713	0.536	10.740
BASE0	13.530	0.558	0.954	0.215	8.498	1.707	0.453	0.343	1.000	0.001	7.901
BASE1	3.063	0.733	0.957	0.208	12.114	0.874	0.598	0.412	0.976	0.155	12.638
BASE2	18.130	0.483	0.793	0.455	14.593	1.532	0.219	0.885	0.944	0.236	8.581
BASE3	32.110	0.393	0.874	0.355	9.058	1.841	0.232	0.547	0.960	0.200	5.157
AGG–1 (Shelton)	1.219	0.782	0.984	0.128	4.788	0.441	0.656	0.372	0.999	0.0002	0.00009
AGG–3 (Abingdon)	6.597	0.590	0.999	0.031	0.879	0.986	0.567	0.073	0.999	0.00003	0.00001
AGG–4(Frazier North)	8.267	0.595	0.981	0.137	0.697	1.241	0.492	0.329	0.990	0.001	0.038
AGG–5 (Centreville)	2.801	0.709	0.999	0.016	0.537	0.729	0.695	0.043	0.999	0.0001	0.006
P2AGG–2 (Boscobel)	1.351	0.725	0.845	0.394	14.899	0.359	0.340	1.156	0.999	0.006	0.020
P2AGG–6 (Staunton)	10.890	0.552	0.999	0.017	0.456	1.369	0.540	0.038	0.999	0.0003	0.010
P2AGG–7 (Graham-Occoquan)	2.768	0.635	0.823	0.420	14.321	0.475	0.270	1.137	0.999	0.0004	0.012
P2AGG–8 (Graham-Occoquan)	3.613	0.627	0.970	0.173	5.304	0.628	0.490	0.434	0.999	0.00005	0.002
P2AGG–9 (Centreville)	3.730	0.630	0.931	0.262	8.114	0.645	0.420	0.659	0.999	0.00005	0.0004

TABLE 4.
CORRELATION MATRIX BETWEEN MR AND UGMS' INDEX PROPERTIES

		Correlation Matrix between Model Parameters								
		MR	LL	PL	PI	WPI	MDD	OMC	Pass#4	Pass#200
1	MR, (MPa)									
2	LL%	-.493-**								
3	PL%	-.473-**	.933**							
4	PI%	-.436-**	.914**	.706**						
5	WPI%	-.487-**	.832**	.728**	.815**					
6	MDD (kN/m^3)	0.002	-.359-**	-.429-**	-.221-**	-.216-**				
7	OMC%	-.186-**	.584**	.607**	.465**	.253**	-.547-**			
8	Pass#4%	-.296-**	.252**	.333**	0.120	.314**	-0.110	.169**		
9	Pass#200%	-.249-**	.179**	.305**	0.008	.557**	-0.110	-.144-*	.283**	

Note, N=232. *$p<.05$; **$p<0.01$
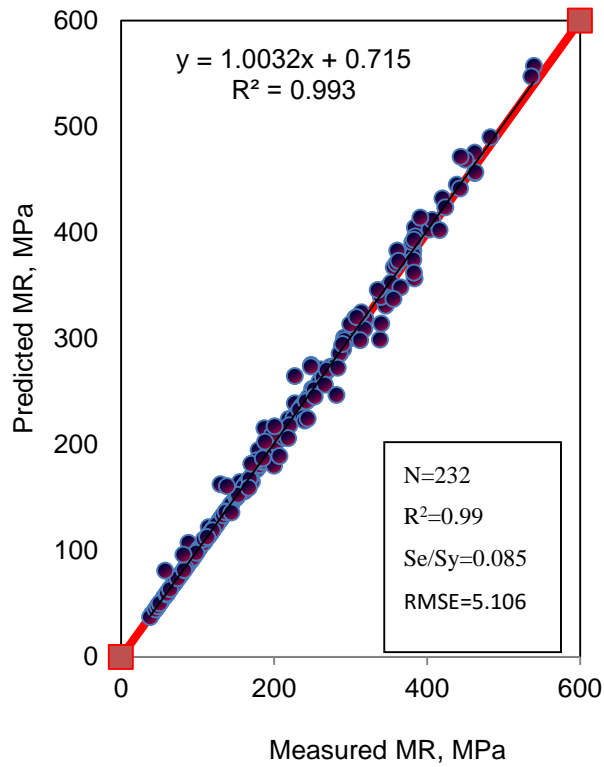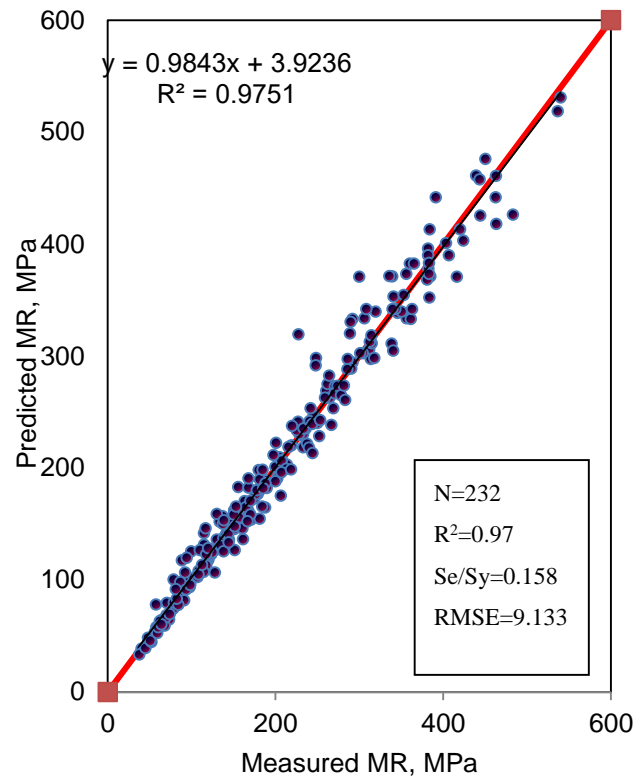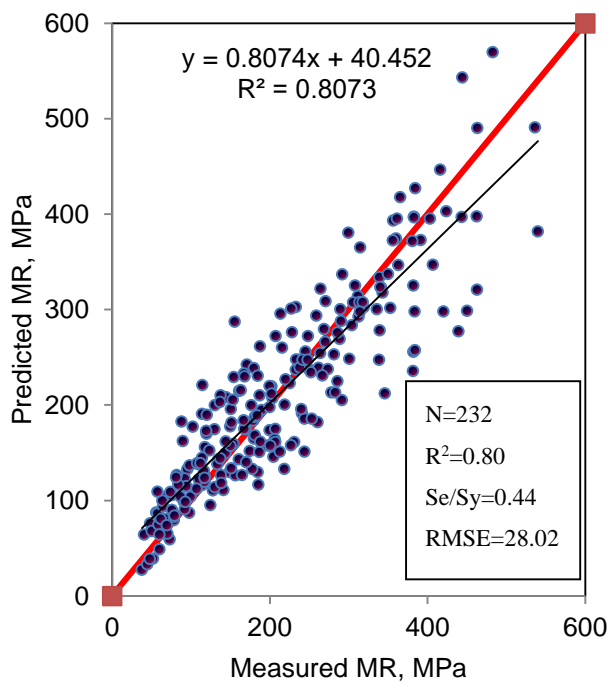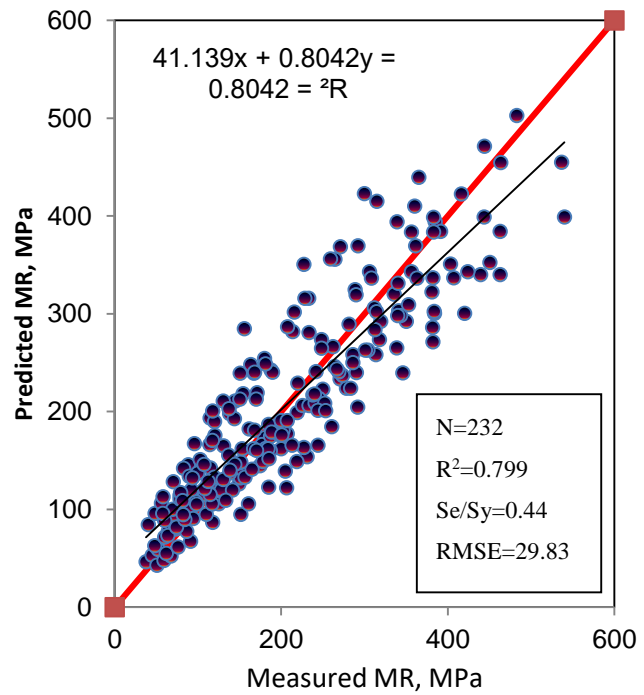
Figure 1. Measured Versus Predicted MR Values for the 16 UGMs based on the Recalibrated Regression Coefficients,
(a) Universal Model,   (b) K–θ Model

Figure 2. Measured Versus Predicted MR Values for the 16 UGMs based on the Index Soil Properties,
(a) Universal Model,   (b) K–θ Model

AUTHORS CONTRIBUTION:

The following summarizes author statement outlining their individual contributions to the paper using the relevant roles:

1. *Yasser F. Al-Dulaimi*: Data collection and tools, data analysis and interpretation, investigation, methodology, and drafting the article. In addition, the corresponding author is responsible for ensuring that the descriptions are accurate and agreed by all authors.

2. *Ahmed M. Awed*: Conception and design of work, data interpretation, supervision, and critical revision of the article.

3. *Alaa R. Gabr:* Conception and design of work, data interpretation, supervision, and critical revision of the article.

4. *Sherif M. El-Badawy*: Conception and design of work, supervision, methodology, and final approval of the version to be published.

DECLARATION OF CONFLICTING INTERESTS STATEMENT:

The authors declare no potential conflicts of interest with respect to the research, authorship or publication of this article.

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TITLE ARABIC:

تنبؤ بمعامل المرونة الرجوعي لمواد الأساس والأساس المساعد الحبيبية غير المترابطة

ARABIC ABSTRACT:

تقدم هذه الورقة البحثية نتائج نمذجة معامل المرونة (MR) لطبقات الأساس والأساس المساعد الحبيبية غير المترابطة عن طريق خصائص مؤشرة للمواد وحالة الإجهاد. تم جمع قاعدة البيانات المستخدمة في هذه الدراسة من دراسات سابقة، والتي تشمل 16 مادة حبيبية غير مترابطة (تسعة منها من ولاية فرجينيا، الولايات المتحدة بينما كانت السبعة الأخرى من اماكن مختلفة في مصر). تتضمن قاعدة البيانات (حد السيولة، LL، حد اللدونة، PL، مؤشر اللدونة، PI، مؤشر اللدونة الموزون، WPI، أقصى كثافة جافة، MDD، محتوى الرطوبة الأمثل، OMC، نسبة المار من منخل رقم 4، ونسبة المار من منخل رقم 200، و233 قيمة لقياسات MR). تم استخدام نموذجين شائعين للتنبؤ بمعامل المرونة (نموذج θ-K ونموذج Universal) كنماذج أساسية للتنبؤ في هذه الدراسة. باستخدام صندوق أدوات المنحنى المناسب (CFTOOL) في برنامج MATLAB، تمت إعادة معايرة قيم معاملات الانحدار لكلا النموذجين للتنبؤ بمعامل المرونة لكل مادة على حدة. تم ربط معاملات الانحدار في كلا النموذجين) (قيم k بخصائص مؤشرة للمواد (LL و PL و WPI و MDD و OMC و Pass # 4 و Pass # 200 و بعد ذلك، تم ربط خصائص مؤشرة لل UGMs التي تم فحصها، والتي تؤثر على قياسات MR، مع معاملات الانحدار المعاد معايرتها لكلا النموذجين. أظهرت النتائج أن تنبؤات MR المستندة إلى الخصائص المؤشرة وحالة الإجهاد كانت مرضية مع معامل تحديد الارتباط (R2) عند 0.80 و0.79 لنموذج Universal ونموذج θ-K على التوالي..