Dummy Regression to Predict Resilient Modulus of Cohesive Subgrade Soils

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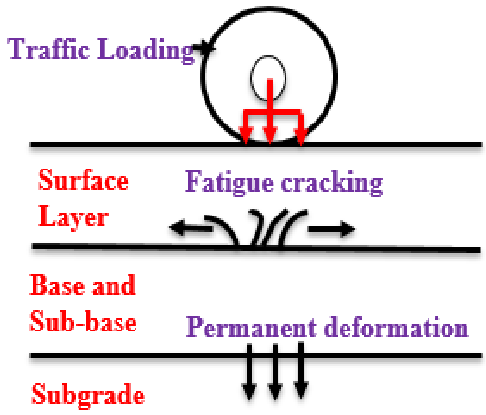
***Abstract*—Owing to a significant contribution of resilient modulus of subgrade soils in the overall performance of roads or railways, it is crucial to provide the best prediction of it. In other words, regarding road pavements, the behavior of pavements depends on the resilient deformations. This paper presents a new predictive equation for the resilient modulus of cohesive subgrade soils (A-4a and A-6a) using dummy regression. The results show that resilient modulus (M_R) values exhibited a slight increase as the confining pressure increases. A-4a compacted at Optimum Moisture Content (OMC) found to attain higher values when compared to other conditions and different soils. A prediction model using dummy variables is proposed and shown to be able to predict the resilient modulus of cohesive subgrade soils over a range of stress states and water contents.**

***Index Terms*—Pavements, resilient modulus, cohesive soils, prediction model, dummy regression**

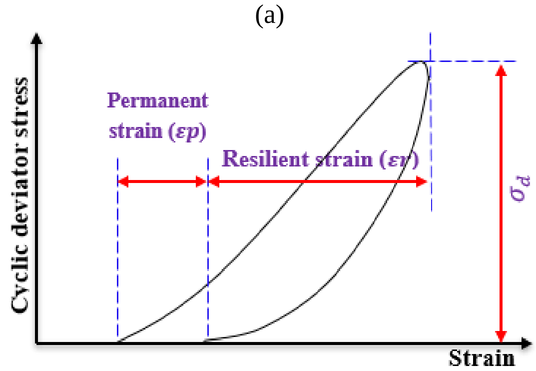
I. Introduction and Background

The overall performance of roads or railways is well-dependent on how strong, stiff, and saturated the subgrade soil layer is when subjected to moving loads. Regarding road pavements, under heavy traffic loads, subgrade soils may deform and contribute to distress in the overlying pavement structure. This distress normally takes the form of cracking and rutting, that affect both the functional condition and structural health of flexible pavements. Two key criteria that are used in the design of pavement layers are the fatigue cracking at the bottom of the surface layer and the permanent deformation at the surface of the subgrade soils (Fig. 1a). The fatigue cracking failure is found closely related to the resilient behavior of the pavement materials in response to the traffic loading [1]. The resilient modulus (M_R) represents the stress-strain behavior of unbound materials under repeated traffic loading.

Numerically, M_R is the ratio of the deviatoric stress to the resilient or recoverable strain after a large number of load cycles: $M_R = \sigma_d / \varepsilon_r$ (see Fig. 1b). In other words, among other parameters in both Mechanistic-Empirical Pavement Design Guide (MEPDG) and American Association of State Highway and Transportation Officials (AASHTO), the resilient modulus (M_R) of subgrade soil has the most significant effect on designing pavement structures [2-4]. Therefore, the study of the resilient strain characteristics of subgrade soils under repeated loading and its accurate evaluation is important for the effective and economical design of flexible pavements.



(a)



(b)

Figure 1. Schematic of a typical asphalt pavement structure (a) and response of soil to one loading cycle (b)

Manuscript received May 12, 2021; revised July 24, 2021; accepted August 15, 2021.

doi: 10.18178/ijscer.10.4.172-177

Over the past few decades, the literature review showed that M_R of subgrade materials has been influenced by various factors such as stress, number of load cycles, physical properties, moisture content, fines content, degree of compaction, and material type [5-8]. For instance, Khoury Naji found that the M_R–moisture content relationships varied with soil types and M_R values varied inversely with changes of moisture content [9]. Niu and research team reported that the magnitude of the resilient modulus decreased by 18% - 27% from its value under unfrozen state depending on confining pressure applied during the triaxial compression tests [10]. Furthermore, the resilient modulus of various coarse and fine grained subgrade soils during full freeze-thaw cycling were studied and results revealed that all the soils exhibited a substantial reduction in the resilient modulus (approximately 20-60% depending on soil types) after freeze-thaw cycle [11]. Resilient modulus of fine-grained soils increases slightly with increasing confining stress. This behavior is typical for cohesive soils [6, 12].

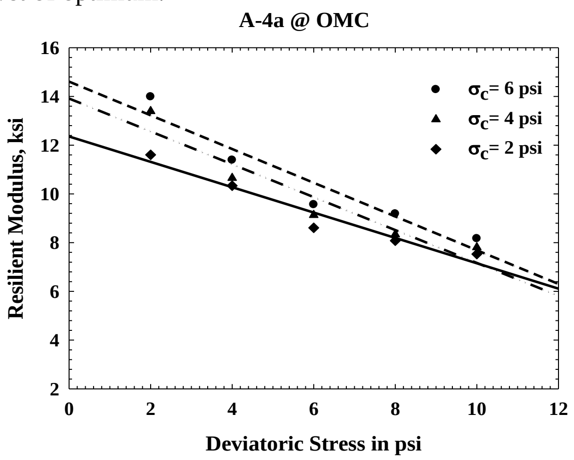
Several investigators proposed constitutive models to predict the M_R by relating applied stresses using model parameters, such as power model [13], Khasawneh and Al-jamal model [14] and the model by MEPDG [15]. Other proposed models incorporating the soil suction into applied shearing or confining stresses, such as Fan Gu model [16], Zhang et al. model [17], Liang et al. model [18], Cary and Zapata model [19] and Han and Vanapalli model [20]. California Bearing Ratio (CBR) is one of the most commonly used methods to predict resilient modulus. Simple correlation equations have been reported to predict MR from the CBR, such as AASHTO model [21] and Ahmed Ebrahim model [22].

Although many researchers put considerable efforts to study the M_R it remains needed to achieve a better understanding. Therefore, the purposes of this study are to investigate some of the factors (different levels of moisture content and stresses) that affect the M_R of cohesive subgrade soils, and develop statistical models to predict the M_R of cohesive subgrade soils at different levels of moisture content and stresses using dummy regression. The subgrade materials used are A-4a and A-6a and the experimental results of resilient modulus were obtained using triaxial tests following the AASHTO T307-99 procedures [23].

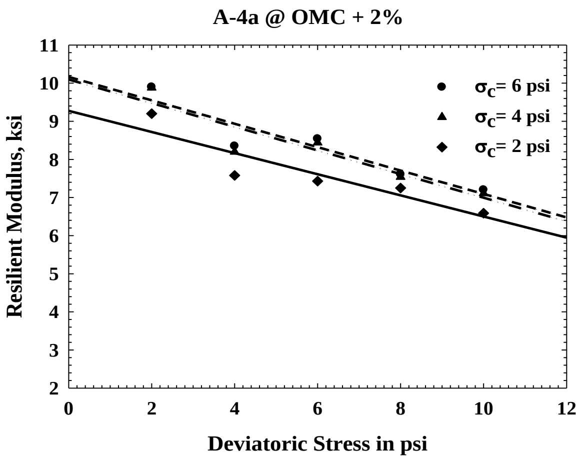
II. Results and Discussion

Fig. 2 indicates that the resilient modulus of A-4a decreases with the increase of the deviator stress (σ_d) under constant confining pressure (σ_c). Under constant σ_c of 6psi, the resilient modulus decreased from M_R = 13.985 ksi at σ_d =2 psi to M_R = 8.165 MPa at σ_d = 10 psi for A-4a soil. Based on results, A-4a at optimum moisture content showed higher resilient modulus values when compared to other soils with other conditions. Similarly, Fig. 3 shows the deviatoric stress effect on resilient modulus of A-6a at optimum moisture content and at 2% wet of optimum.

A-4a or A-6a with lower moisture content exhibited higher resilient modulus values compared to the other specimen (A-4a+2% orA-6a+2%) with higher moisture content under the same unit weight. The effect of increased moisture content of the soil on reducing the resilient modulus is significant. The soil compacted at moisture content more than the optimum showed lower values of resilient modulus with the increase of the deviator stress, in other words, the soil compacted at moisture content less than the optimum exhibited hardening and showed higher values of resilient modulus with the increase of the deviator stress. Also, Fig. 4 presents the effect of compaction water content and confining pressure on the resilient modules of A-4a and A-6a, respectively. Each sample has been compacted to two different moisture contents (viz., optimum and 2% wet of optimum). Fig. 4 shows that the resilient modulus of A-4a and A-6a decreases about 18% and 32% when water content increases respectively from optimum to 2% wet of optimum.

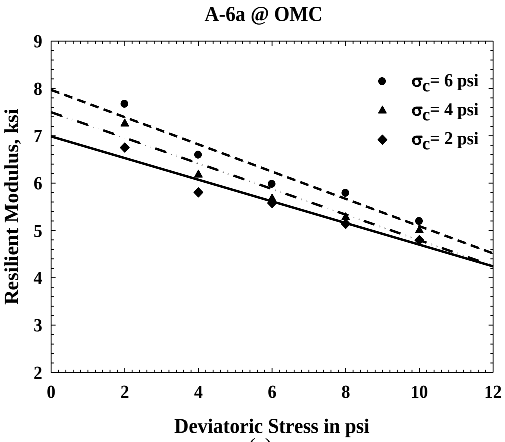


(a)

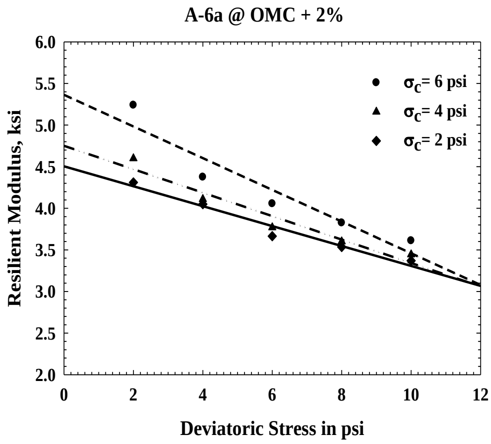


(b)

Figure 2. Deviatoric stress effect on resilient modulus of A-4a at optimum moisture content (a) and 2% wet of optimum (b)

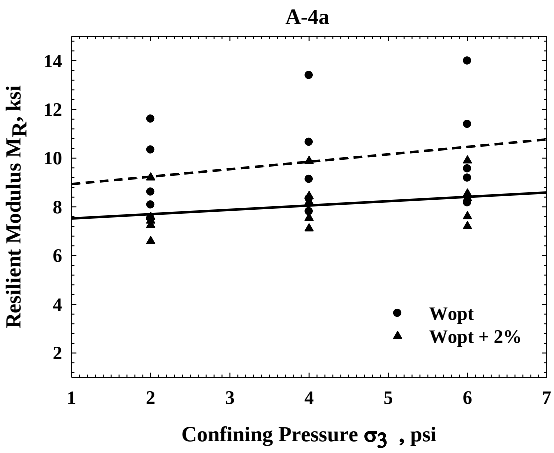


(a)

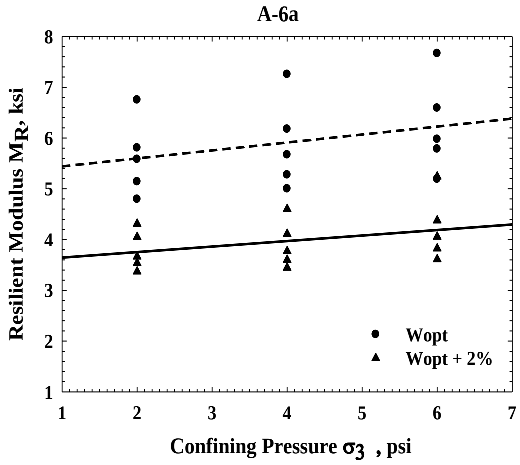


(b)

Figure 3. Deviatoric stress effect on resilient modulus of A-6a at optimum moisture content (a) and 2% wet of optimum (b)



(a)



(b)

Figure 4. Confining pressure effect on resilient modulus of A-4a (a) and A-6a (b) at different moisture contents

A model was developed for resilient modulus as a dependent variable with three independent variables (confining pressure, deviator stress and bulk stress); two of these variables are qualitative and the third is numerical. The results show excellent relationship in this model for all types of soil especially when using dummy regression. It is obviously shown in Table I that all the modelling results for resilient modulus prediction are statistically significant as reflected by the high F-values and high coefficients of determination (R^2). It is also shown that Durbin-Watson values ranging from 1.6 to 2.6 means there is no autocorrelation detected in the sample. For A-4a soil when the first and second dummy variables are used, sixteen (16) equations are produced as shown in Tables II and III. The same applies for A-6a at OMC and A-6a at 2% wet of OMC (see Tables 4 and 5).

For A-4a @ OMC, depending on SPSS, the confining pressure was excluded from the best model. That means the deviator stress is the most important stress factor, then comes bulk stress and both are considered in the prediction model. For A-4a @ 2% wet of OMC, on the other hand, deviator stress, bulk stress and confining pressure were important in predicting resilient modulus. In Tables II, III, IV and 5 E(Y): is the expected value of resilient modulus; BS: Bulk Stress; CP: Confining Pressure and X1; X2; X3; X4: categories of deviator stress for dummy variables.

TABLE I. RESILIENT MODULUS MODELING RESULTS

Type of soil	Modeling of M_R	R^2	Sig	F	Durbin Watson
A-4a @ OMC	M_R=11.568+0.102BS-5.977X_1-5.075X_2-4.303X_3-2.409X_4	0.978	0.000	80.6	2.1
A-4a @ 2% wet of OMC	M_R=8.742+0.059BS+0.269CP-5.977X_1-5.075X_2-4.303X_3-2.409X_4	0.986	0.000	95.5	2.6
A-6a @ OMC	M_R=6.492+0.052BS-2.646X_1-2.137X_2-1.691X_3-1.138X_4	0.986	0.000	124.7	1.7
A-6a @ 2% wet of OMC	M_R=4.242+0.036BS-0.098CP-1.532X_1-1.281X_2-1.032X_3-0.611X_4	0.954	0.000	27.5	1.6

TABLE II. RESILIENT MODULUS DUMMY REGRESSION RESULTS FOR A-4A @ OMC

Model	Remarks
$E(Y) = 11.568+0.102BS-5.977X_1-5.075X_2-4.303X_3-2.409X_4$	General Equation
$E\ (Y/X_1 = 0; X_2 = 0; X_3 = 0\ \&\ X_4 = 0) = 11.568+0.102BS$	Equation 1
$E\ (Y/X_1 = 0; X_2 = 1; X_3 = 0\ \&\ X_4 = 0) = 6.493+0.102BS$	Equation 2
$E\ (Y/X_1 = 0; X_2 = 0; X_3 = 1\ \&\ X_4 = 0) = 7.265+0.102BS$	Equation 3
$E\ (Y/X_1 = 0; X_2 = 0; X_3 = 0\ \&\ X_4 = 1) = 9.159+0.102BS$	Equation 4
$E\ (Y/X_1 = 1; X_2 = 0; X_3 = 0\ \&\ X_4 = 0) = 5.591+0.102BS$	Equation 5
$E\ (Y/X_1 = 1; X_2 = 1; X_3 = 0\ \&\ X_4 = 0) = 0.516+0.102BS$	Equation 6
$E\ (Y/X_1 = 1; X_2 = 0; X_3 = 1\ \&\ X_4 = 0) = 1.288+0.102BS$	Equation 7
$E\ (Y/X_1 = 1; X_2 = 0; X_3 = 0\ \&\ X_4 = 1) = 3.182+0.102BS$	Equation 8
$E\ (Y/X_1 = 1; X_2 = 0; X_3 = 1\ \&\ X_4 = 1) = -1.121+0.102BS$	Equation 9
$E\ (Y/X_1 = 0; X_2 = 1; X_3 = 1\ \&\ X_4 = 0) = 2.190+0.102BS$	Equation 10
$E\ (Y/X_1 = 0; X_2 = 1; X_3 = 0\ \&\ X_4 = 1) = 4.084+0.102BS$	Equation 11
$E\ (Y/X_1 = 0; X_2 = 1; X_3 = 1\ \&\ X_4 = 1) = -0.219+0.102BS$	Equation 12
$E\ (Y/X_1 = 0; X_2 = 0; X_3 = 1\ \&\ X_4 = 1) = 4.856+0.102BS$	Equation 13
$E\ (Y/X_1 = 1; X_2 = 1; X_3 = 0\ \&\ X_4 = 1) = -1.893+0.102BS$	Equation 14
$E\ (Y/X_1 = 1; X_2 = 1; X_3 = 1\ \&\ X_4 = 0) = -3.787+0.102BS$	Equation 15
$E\ (Y/X_1 = 1; X_2 = 1; X_3 = 1\ \&\ X_4 = 1) = -6.196+0.102BS$	Equation 16

TABLE III. RESILIENT MODULUS DUMMY REGRESSION RESULTS FOR A-4A @ 2% WET OF OMC

Model	Remarks
$E(Y) = 8.742+0.059BS+0.269CP-5.977X_1-5.075X_2-4.303X_3-2.409X_4$	General Equation
$E(Y/X_1 = 0; X_2 = 0; X_3 = 0\ \&\ X_4 = 0) = 8.742+0.059BS+0.269CP$	Equation 1
$E(Y/X_1 = 0; X_2 = 1; X_3 = 0\ \&\ X_4 = 0) = 3.667+0.059BS+0.269CP$	Equation 2
$E(Y/X_1 = 0; X_2 = 0; X_3 = 1\ \&\ X_4 = 0) = 4.439+0.059BS+0.269CP$	Equation 3
$E(Y/X_1 = 0; X_2 = 0; X_3 = 0\ \&\ X_4 = 1) = 6.333+0.059BS+0.269CP$	Equation 4
$E(Y/X_1 = 1; X_2 = 0; X_3 = 0\ \&\ X_4 = 0) = 2.765+0.059BS+0.269CP$	Equation 5
$E(Y/X_1 = 1; X_2 = 1; X_3 = 0\ \&\ X_4 = 0) = -2.310+0.059BS+0.269CP$	Equation 6
$E(Y/X_1 = 1; X_2 = 0; X_3 = 1\ \&\ X_4 = 0) = -1.538+0.059BS+0.269CP$	Equation 7
$E(Y/X_1 = 1; X_2 = 0; X_3 = 0\ \&\ X_4 = 1) = 0.356+0.059BS+0.269CP$	Equation 8
$E(Y/X_1 = 1; X_2 = 0; X_3 = 1\ \&\ X_4 = 1) = -3.947+0.059BS+0.269CP$	Equation 9
$E(Y/X_1 = 0; X_2 = 1; X_3 = 1\ \&\ X_4 = 0) = -0.636+0.059BS+0.269CP$	Equation 10
$E(Y/X_1 = 0; X_2 = 1; X_3 = 0\ \&\ X_4 = 1) = 1.258+0.059BS+0.269CP$	Equation 11
$E(Y/X_1 = 0; X_2 = 1; X_3 = 1\ \&\ X_4 = 1) = -3.045+0.059BS+0.269CP$	Equation 12
$E(Y/X_1 = 0; X_2 = 0; X_3 = 1\ \&\ X_4 = 1) = 2.030+0.059BS+0.269CP$	Equation 13
$E(Y/X_1 = 1; X_2 = 1; X_3 = 0\ \&\ X_4 = 1) = -4.719+0.059BS+0.269CP$	Equation 14
$E(Y/X_1 = 1; X_2 = 1; X_3 = 1\ \&\ X_4 = 0) = -6.613+0.059BS+0.269CP$	Equation 15
$E(Y/X_1 = 1; X_2 = 1; X_3 = 1\ \&\ X_4 = 1) = -9.022+0.059BS+0.269CP$	Equation 16

TABLE IV. RESILIENT MODULUS DUMMY REGRESSION RESULTS FOR A-6A @ OMC

Model	Remarks
$E(Y) = 6.492+0.052BS-2.646\ X_1-2.137\ X_2-1.691\ X_3-1.138\ X_4$	General Equation
$E(Y/X_1 = 0; X_2 = 0; X_3 = 0\ \&\ X_4 = 0) = 6.492+0.052BS$	Equation 1
$E(Y/X_1 = 0; X_2 = 1; X_3 = 0\ \&\ X_4 = 0) = 4.355+0.052BS$	Equation 2
$E(Y/X_1 = 0; X_2 = 0; X_3 = 1\ \&\ X_4 = 0) = 4.801+0.052BS$	Equation 3
$E(Y/X_1 = 0; X_2 = 0; X_3 = 0\ \&\ X_4 = 1) = 5.354+0.052BS$	Equation 4
$E(Y/X_1 = 1; X_2 = 0; X_3 = 0\ \&\ X_4 = 0) = 3.846+0.052BS$	Equation 5
$E(Y/X_1 = 1; X_2 = 1; X_3 = 0\ \&\ X_4 = 0) = 1.709+0.052BS$	Equation 6
$E(Y/X_1 = 1; X_2 = 0; X_3 = 1\ \&\ X_4 = 0) = 2.155+0.052BS$	Equation 7
$E(Y/X_1 = 1; X_2 = 0; X_3 = 0\ \&\ X_4 = 1) = 2.708+0.052BS$	Equation 8
$E(Y/X_1 = 1; X_2 = 0; X_3 = 1\ \&\ X_4 = 1) = 1.017+0.052BS$	Equation 9
$E(Y/X_1 = 0; X_2 = 1; X_3 = 1\ \&\ X_4 = 0) = 2.664+0.052BS$	Equation 10
$E(Y/X_1 = 0; X_2 = 1; X_3 = 0\ \&\ X_4 = 1) = 3.217+0.052BS$	Equation 11

$E(Y/X_1 = 0;X_2 = 1;X_3 = 1 \& X_4 = 1) = 1.526+0.052BS$	Equation 12
$E(Y/X_1 = 0;X_2 = 0;X_3 = 1 \& X_4 = 1) = 3.663+0.052BS$	Equation 13
$E(Y/X_1 = 1;X_2 = 1;X_3 = 0 \& X_4 = 1) = 0.571+0.052BS$	Equation 14
$E(Y/X_1 = 1;X_2 = 1;X_3 = 1 \& X_4 = 0) = 0.018+0.052BS$	Equation 15
$E(Y/X_1 = 1;X_2 = 1;X_3 = 1 \& X_4 = 1) = -1.12+0.052BS$	Equation 16

TABLE V. RESILIENT MODULUS DUMMY REGRESSION RESULTS FOR A-6A @ 2% WET OF OMC

Model	Remarks
$E(Y)= 4.242+0.036BS-0.098CP-1.532\ X_1-1.281\ X_2-1.032\ X_3-0.611\ X_4$	General Equation
$E(Y/X_1 = 0;X_2 = 0;X_3 = 0 \& X_4 = 0) = 4.242+0.036BS-0.098CP$	Equation 1
$E(Y/X_1 = 0;X_2 = 1;X_3 = 0 \& X_4 = 0) = 2.961+0.036BS-0.098CP$	Equation 2
$E(Y/X_1 = 0;X_2 = 0;X_3 = 1 \& X_4 = 0) = 3.210+0.036BS-0.098CP$	Equation 3
$E(Y/X_1 = 0;X_2 = 0;X_3 = 0 \& X_4 = 1) = 3.631+0.036BS-0.098CP$	Equation 4
$E(Y/X_1 = 1;X_2 = 0;X_3 = 0 \& X_4 = 0) = 2.710+0.036BS-0.098CP$	Equation 5
$E(Y/X_1 = 1;X_2 = 1;X_3 = 0 \& X_4 = 0) = 1.429+0.036BS-0.098CP$	Equation 6
$E(Y/X_1 = 1;X_2 = 0;X_3 = 1 \& X_4 = 0) = 1.678+0.036BS-0.098CP$	Equation 7
$E(Y/X_1 = 1;X_2 = 0;X_3 = 0 \& X_4 = 1) = 2.099+0.036BS-0.098CP$	Equation 8
$E(Y/X_1 = 1;X_2 = 0;X_3 = 1 \& X_4 = 1) = 1.067+0.036BS-0.098CP$	Equation 9
$E(Y/X_1 = 0;X_2 = 1;X_3 = 1 \& X_4 = 0) = 1.929+0.036BS-0.098CP$	Equation 10
$E(Y/X_1 = 0;X_2 = 1;X_3 = 0 \& X_4 = 1) = 2.350+0.036BS-0.098CP$	Equation 11
$E(Y/X_1 = 0;X_2 = 1;X_3 = 1 \& X_4 = 1) = 1.318+0.036BS-0.098CP$	Equation 12
$E(Y/X_1 = 0;X_2 = 0;X_3 = 1 \& X_4 = 1) = 2.599+0.036BS-0.098CP$	Equation 13
$E(Y/X_1 = 1;X_2 = 1;X_3 = 0 \& X_4 = 1) = 0.818+0.036BS-0.098CP$	Equation 14
$E(Y/X_1 = 1;X_2 = 1;X_3 = 1 \& X_4 = 0) = 0.397+0.036BS-0.098CP$	Equation 15
$E(Y/X_1 = 1;X_2 = 1;X_3 = 1 \& X_4 = 1) = -0.214+0.036BS-0.098CP$	Equation 16

III. CONCLUSIONS

In conclusion, the resilient modulus results showed a decrease in the M_R values as the compacted water content and deviator stress increase. On the other hand, M_R values exhibited a slight increase as the confining pressure increases. A-4a compacted at OMC found to attain higher values when compared to other conditions for different soils.

The degree of moisture content along with the deviatoric stress had a significant effect on the fine-grained soil materials. This implies that an increase in one of these factors or both tend to yield a decrease in the resilient modulus values. A prediction model using dummy regression was proposed and shown to be able to predict the resilient modulus of cohesive soils over a range of stress states and water contents. All the developed models were found statistically significant at the 0.05 significance level with high R^2.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

MAK conducted the experimental work and data compilation, literature review, set the study layout and reviewed and wrote the final version of the paper; RSA analyzed the data and helped write the draft version of the paper; … all authors had approved the final version.

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