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Investigation of Resilience Characteristics of Unbound Granular Materials for Sustainable Pavements

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Abstract: In this study, a comprehensive laboratory testing program was designed to study the resilience characteristics of unbound granular materials (aggregate base coarse) using the repeated load triaxial test (RLTT). During the experimental program, the resilient modulus of unbound granular material was examined using different moisture content levels, material gradation using Fuller's equation, and stress levels. The results show that the moisture content, material gradation, and stress level have a major influence on the resilient modulus of unbound granular materials. Furthermore, a linear model has been developed between moisture content and the resilient modulus. The model significantly predicts the change in resilient modulus by changing moisture content. The study also aimed to improve the modified Uzan model by adding the effect of moisture content. An improved modified Uzan stress moisture model has been developed, which shows a strong relationship between the resilient modulus, stress, and moisture content. This study can be used as a benchmark for validating other numerical data.

Keywords: sustainable structure design; sustainable materials; resilient modulus; gradation coefficient; repeated load triaxial test; optimum moisture content; unbound granular material

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1. Introduction

The resilient modulus (M_r) is used in the designing process and selection of unbound granular materials (UGMs) for unbound pavement layers. There are many factors which affect the resilient modulus of unbound granular material, including stress level, moisture content, density, material gradation, aggregate type and shape, number of load cycles, load duration frequency, and load sequence. Among the other factors, moisture content, material gradations, and stress levels are the most important factors which affect the resilient modulus of unbound granular materials. Therefore, it is important to understand and quantify the changes that take place in the resilient modulus with changes in moisture content, material gradations, and stress levels, and to develop understanding of the relationship between these factors and resilient modulus of unbound granular material for indigenous material.

Moisture content affects the resilient modulus; many studies have observed that, with an increase in moisture content, the resilient modulus value decreases [1–4]. Lekarp reported that the resilient modulus of well-graded unbound granular tends to increase at the dry side of optimum moisture content (OMC), and vice versa, at the dry side of optimum moisture content, the materials behave more stiffly, resulting in an increase in the resilient modulus, and at the wet side of optimum moisture content the material becomes saturated and pore water pressure develops resulting in a reduction in the stiffness [5].

Haynes [4] reported a 50% reduction in resilient modulus in coarse aggregate when the saturation increases from 70% to 97%. Another study indicated that changes in fine and moisture content have a major influence on the permanent and resilient deformation of granular material [6]. Other researchers have observed that unbound granular material specimens samples soaked at a higher degree of saturation caused lower resilient modulus and had little resistance to heavy traffic [7]. Another study revealed that an increase in moisture content significantly decreases the resiliency of material [8]. However, it was also seen that the resilient modulus increases with increasing moisture content, but this only happens with a large amount of load applied and moisture content nearer to optimum; above optimum moisture content, the resilient modulus of unbound granular materials will always decrease [9]. Other researchers have also verified that the resilient modulus of aggregate of the base layer of pavement decreases with an increase in moisture content [10]. Tamrakar [11] concluded that the change in resilience modulus with increases in moisture content is dependent on the testing method and gradation. Moreover, it is noted that a 1% increase in moisture content causes the resilience modulus to decrease by 23%. Many researchers used the repeated load triaxial to study the influence of moisture content on the resilience of pavements. It was found that moisture affected the resilience deformation behavior of UGMs, and the resilient modulus of UGMs decreased with increased moisture content, even though it showed some increasing trend with increasing MC when a significant amount of permanent deformation took place post-compaction [12]. The moisture sensitivity of unbound graded aggregate material has been investigated, with the conclusion that, with an increase in saturation, the resiliency of aggregate decreases [13]. This is mostly due to groundwater table moisture increase in the pavement layers, which decreases the resilient modulus of pavement by 35% to 70% when the groundwater table is just 30 cm to 60 cm below the pavement surface [14]. Recent research indicates that the influence of water content on unbound granular aggregate material is strongly affected by the aggregate source and grain-size distribution [15]. Previous research also studied the influence of post-compaction on the effect of moisture content on the resilient modulus of unbound granular material. It is noted that the resilience of material decreases with the increase in moisture content when post-compaction is negligible and a slight increase was observed in the resilient modulus with post-compaction [16]. Most research confirms that the moisture content has a major influence on the resilient modulus of unbound granular materials [17]. Stolle et al. observed that the nature of fine content also influences the moisture sensitivity of the resilient modulus of aggregate [18]. Recent studies revealed that infiltration and gradation have significant effects on the bearing capacity, water retention, and mechanical behaviors of unbound granular material [19].

Material gradations also have a major impact on the resilient modulus of unbound granular materials. Gu et al. proposed a model for estimating the resilient modulus of aggregate, and concluded that the aggregate texture, particle size, shape, and percentage of fine content are key variables that affect the resilient modulus of aggregate [20]. Other studies have observed that the particle shape, aggregate source, compaction energy effort, and D_{max} significantly affect the mechanical properties of unbound granular aggregate for road base and sub-base material [21]. It is observed that the gradation type has a significant effect on the resilient modulus of unbound granular materials; coarser gradation gives high performance of resiliency as compared with finer gradation [22]. Previous studies also indicated that the lower limit of gradation gives more strength, and through using well-graded coarse-grained aggregate, one can increase the resilient modulus [23]. Recent studies showed that a 15% increase in stiffness was recorded with gradation D_{max} of 25 mm, and a 95% increase was recorded for gradation D_{max} of 37.5 mm when compared with the gradation D_{max} of 19 mm unbound granular material aggregate [24]. Material size distribution and fine content (particles passing through sieve no. 200) play an important role on resilient behavior of granular materials [1,25,26]. The stiffness of particles depends upon their size and distribution. Kolisoja determined that the value of resilient modulus increases with an increase in the maximum particle size at similar grain size distribution and the percentage of fine content [27]. Ekblad conducted tests on unbound granular aggregate for gradation coefficient values of 0.3, 0.4, 0.5, and 0.8. He reported that a 0.8 gradation coefficient containing coarser particles shows a high resilient modulus, whereas 0.3 values show lower resilient modulus values [25]. Barksdale observed a 60% reduction in resilient modulus values when the fine content increased from 0% to 10%. Barksdale also reported that angular and crushed materials with rough surfaces show higher resilient modulus values and load distribution properties than rounded particles with smooth surfaces [28]. Other researchers used additional materials as aggregates to improve the resilient behavior of the base layer of pavement. It is shown that the addition of coarse clay brick particles has minor impacts on the compressive resilient modulus of the mixture, and it can be significantly increased through the addition of fine particles [29]. Jaffar et al. added lime, sand, and marble waste to enhance the mechanical properties of subgrade soil. It was revealed that lime can improve the stiffness of the subgrade better than other modifiers. It was also concluded that optimum moisture content increases with an increasing lime percentage and decreases with increasing marble and sand percentages [30].

Another previous finding is that under less load cycle, the resilient modulus dominates the permanent deformation [31]. The results of a recent study suggested that axial load, material type, and the maximum particle size are required to be considered for the investigation of confining stress and resilient modulus [32]. Furthermore, experimental research showed that the confining stresses favor the resilient modulus. As confining stresses increased, the resilient modulus increased [33]. Gu et al. concluded that the cyclic shear stress has a significant effect on resilient stiffness; with low shear stress, the resilient modulus is affected less by principal stresses [34]. The increase in cyclic major principal stress leads to the progress of resilient modulus, and the growing frequency generally decreases with the increasing initial stress ratio [35]. The variation in resilient modulus of unbound granular materials is observed with the rise in cyclic amplitude stress involving two phases, the first phase of rapid linear increase and the second phase of the steady and gradual rise [36]. Resilient modulus is measured on 240 kPa axial stress. It was observed that the resilient modulus increases with an increase in loading frequency at different loading frequencies, showing the same variation: rapid increase initially and then a steady and stable rise [37]. Plastic strain and resilient strain were predicted under the influence of loading repetitions, axial stresses, and other factors [38]. A very prominent experimental model showed that the dynamic stresses (σ_{cri}) nearly linearly increase with increasing confining stresses (σ_3) [39]. Other researchers have investigated the effect of confining stress on the resilient modulus of unbound granular materials, and stated that confining stresses of unbound granular materials rise with the rise in axial stresses and decline with material density [32]. Previous studies showed that the resilient modulus is influenced mostly by the level of applied stresses and increases significantly with an increase in confining pressure [2,3,5,40]. Monismith [3] stated that the resilient modulus value increases up to 500% by increasing the confining stress from 20 kPa to 200 kPa. Smith and Nair reported that the value of resilient modulus increases up to 50% when the sum of principle stresses increases from 70 kPa to 200 kPa [2]. It is reported that the resilient modulus generally increases with an increase in density [27,41,42]. Very recent research has suggested the use of different polymers to improve the stiffness of unbound granular materials to withstand heavy vehicle loading [43].

The stress level is the most prominent factor that affects the resilient modulus values of unbound granular materials. It is essential that the relationship between stress and strain be accurately modeled. Many researchers have developed regression models relating resilient modulus and stress level, and a few have been reported in Table 1, presented below.

Table 1. Models based on resilient modulus and stress level.

Model	Author	Equation	Variable	Remarks
(Uzan Model) [44]	Uzan	$M_r = k_1\ \mathrm{P_a}\ (\theta/\mathrm{P_a})^{k2} * (\sigma_d/\mathrm{P_a})^{k3}$	k_1, k_2 = Material constants Pa = Atmospheric pressure	More precisely models the nonlinearity of granular soils
AASHTO Model [5]		$M_r = k_1 \sigma_d{}^{k2}$	k_1, k_2 = Material constants	Uses least square regression analysis
Universal Model (Modified Uzan model) (Uzan et al. 1992) [45]	Uzan	$M_r = k_1 \mathrm{P_a}\ (\theta/\mathrm{P_a})^{k2} * (\tau_{oct}/\mathrm{P_a})^{k3}$	k_1, k_2 = Material constants Pa = Atmospheric pressure	Bulk stress and deviator stress effects are considered
K-Θ Model [44]	Uzan	$M_r = A(3p_{max})^B$	A,B = Material constants Pmax = Max atmospheric pressure	Poisson's ratio is assumed to be constant. No effect of dev. stress is considered
Boyce Model [5]	Boyce (1980)	$\varepsilon_v = p^A*(1/k_1)\ [1 - \beta\ (q^2/p^2)]$ $\varepsilon_s = (p^B/3C)*(q/p)$	A, C = Material constants controlled by B	The model is nonlinear elastic and isotropic

Ekblad tested many models on granular materials with different gradation coefficients and presented that the best-fitting model is the modified Uzan (K-θ) model [25]. Uzan used bulk stress, which is the change in volume of a body due to deforming force, and deviator stress, which is the difference between the major and minor principal stresses, to predict M_r. It successfully predicts the M_r with changes in stresses, but is not sensitive to moisture change. Stress and moisture are the key elements affecting the resilient modulus. The effect of moisture on the resilient modulus is not yet quantifiable. This study focused on improving the modified Uzan model (as shown in Table 1) by including the effect of moisture content. Consequently, the improved modified Uzan stress–moisture model has been developed, which reasonably shows the relationship between the resilient modulus, stress, and moisture content. It is proven that a linear relationship satisfactorily defines the change in M_r due to variation in moisture.

2. Experimental Program

Aggregates were collected from a local limestone quarry, and gradations were prepared using Fuller's equation [46]. Samples were prepared according to AASHTO T-307, and conventional aggregate tests and repeated load triaxial tests were performed. Different stress levels were applied to samples, as per AASHTO T-307 and TP-46 standards. Effects of stress, moisture, and gradations on resilient modulus have been discussed. The results obtained were then fitted in the modified Uzan stress–moisture model.

2.1. Materials and Samples

Aggregates were collected from a local limestone quarry mostly used for unbound pavement materials in the Northern and Central regions of Pakistan. The maximum aggregate size selected for the tests was 19 mm. Particle size distributions were selected according to Fuller's equation [46]:

$$P = \left(\frac{d}{D_{max}}\right)^n \tag{1}$$

where P is the percentage of aggregates smaller than sieve size 'd', 'd' sieve size being considered, D_{max} is the maximum particle size, and 'n' is the grading coefficient, describing the shape of the curve. Four types of gradation were selected on the basis of the grading coefficient (n). Gradation coefficient values of 0.6, 0.5, 0.4, and 0.3 were selected for this study to find the effect of variation in gradation on the resilient behavior of UGM. Figure 1 shows gradation curves for different gradation coefficients.

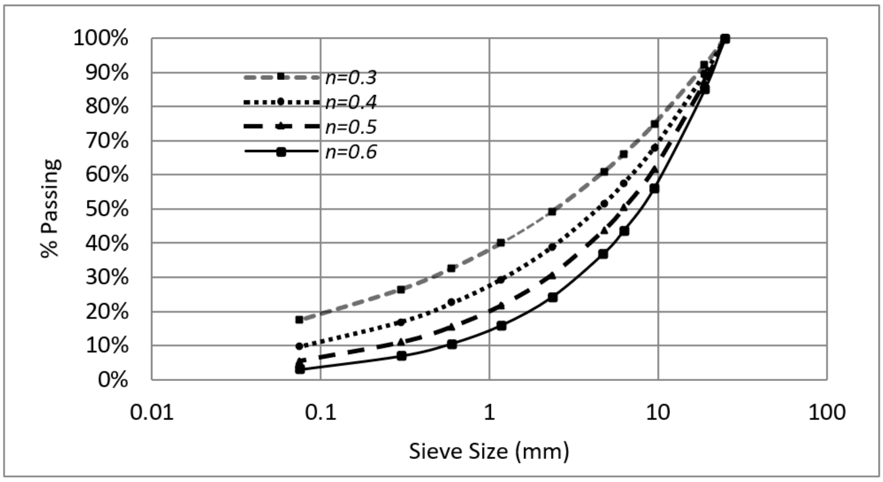


Figure 1. Aggregate gradation with varying gradation coefficient.

As the (n) values increase the gradation becomes coarser. These gradations contain different percentages of fine content; with a decrease in (n) value, the percentage of fine content increases. For gradation constant of n = 0.6, 0.5, 0.4 and 0.3, the fine contents of total weight of the sample were 3%, 5%, 10% and 18%, respectively. Optimum moisture content (OMC) and maximum dry density of these gradations were determined by conducting a modified compaction test as per ASTM D1557-09 [47], and are reported in Table 2.

Table 2. Densities and optimum moisture contents for various gradation coefficients.

Gradation Coefficients (n)	Max Dry Density kg/m^3	Optimum Moisture Content %
0.6	2432.40	4.03
0.5	2406.93	4.3
0.4	2395.72	4.8
0.3	2381.46	5.42

Five levels of moisture contents were selected to check the dry and wet effect of moisture on these gradations. These gradations were compacted at OMC (% of the total mc = Ww/Wd, where mc is the moisture content, Ww is the weight of water, and Wd is the dry weight of solids/gradation), (OMC + 1%), (OMC − 1%), (OMC − 2%) and oven-dry condition to investigate the resilient modulus at different moisture and gradation levels. Repeated load triaxial tests (RLTTs) [48] were conducted to determine the resilient modulus of these aggregates gradations. Table 3 shows the moisture contents of selected gradations of the samples for RLTT.

Table 3. Different combinations of moisture contents and gradation coefficients.

Gradation Coefficient	OMC%	OMC + 1%	OMC − 1%	OMC − 2%	Dry
0.6	4.03	5.03	3.03	2.03	mc = 0
0.5	4.3	5.3	3.3	2.3	mc = 0
0.4	4.8	5.8	3.8	2.8	mc = 0
0.3	5.42	6.42	4.42	3.42	mc = 0

2.2. Material Properties

Aggregate conventional tests were performed on aggregates to determine the physical properties of the material, and are tabulated in Table 4; it can be observed that the values fall well within the prescribed allowable values.

Table 4. Aggregate conventional test results.

S. No	Description	Designation	Result	Allowable Limits
1	Aggregate Abrasion Value % [49]	C 131	21	<40
2	Aggregate Impact Value % [50]	BS 812–112	14	<40
3	Water Absorption of Coarse Aggregates % [51]	C 128	0.57	<2
4	Specific Gravity of Coarse Aggregate [52]	C 127	2.63	2.5–2.9

2.3. Specimen Preparation

AASHTO T-307 [53] specifies the diameter of the triaxial sample based on the maximum particle size of the material. The diameter-to-height ratio should be 1:2. AASHTO recommended that for unbound granular material, the sample should have a diameter greater than five times the maximum particle size of that material. NCHRP (2004) [54] recommended that for untreated granular material, a sample size of 4 in (100 mm) diameter and 8 in (200 mm) height for unbound granular material with a maximum particle size of 0.75 in (19 mm) or below 0.75 in should be used. In this study, a 4 in (100 mm) diameter and 8 in (200 mm) height sample was prepared with a maximum particle size of 0.75 in (19 mm), as shown in Figure 2. Materials were compacted using a vibratory compactor in 4 layers; each layer was 2 in (50 mm) in height. Compaction was carried out at 98% relative density.

(**a**) (**b**) (**c**)

Figure 2. Specimen compaction apparatus.(**a**) vibratory compactor (**b**) assembly (**c**) prepared sample.

2.4. Resilient Modulus Test

Repeated load triaxial testing was carried out using the long-term pavement performance protocol (LTPP) [55] and AASHTO T-307 [53], as shown in Figure 3. Specimens were subjected to repeated load triaxial testing in a pneumatic triaxial chamber. Deformation was measured externally with two linear variable differential transducers (LVDTs). The top loading device was used with close loop electrohydraulic testing, which applies a repeated load cycle of haversine shape load pulse with 0.1 s loading duration and 0.9 s rest period. Each sample was conditioned at 103.7 kPa confining stress and 93.1 kPa deviator stress for 500 cycles. After conditioning, the sample was subjected to 15 loading sequences for repeated 100 loading cycles with different combinations of confining and deviator stresses, as tabulated in Table 5. The last five cycles were recorded to report the values of resilient modulus for each sequence.

Figure 3. Repeated load triaxial test assembly.

Table 5. Test sequence for base/subbase material.

Sequence Number	Confining Pressure, σ_3 (kPa)	Maximum Axial Stress, σ_d (kPa)	Cyclic Stress, σ_{cd} (kPa)	Contact Stress, $\sigma_{contact}$ (kPa)	Number of Load Applications
Conditioning	103.4	103.4	93.1	1.5	500–1000
1	20.7	20.7	18.6	2.1	100
2	20.7	41.4	37.3	4.1	100
3	20.7	62.1	55.9	6.2	100
4	34.5	34.5	31.0	3.5	100
5	34.5	68.9	62.0	6.9	100
6	34.5	103.4	93.1	10.3	100
7	68.9	68.9	62.0	6.9	100
8	68.9	137.9	124.1	13.8	100
9	68.9	206.8	186.1	20.7	100
10	103.4	68.9	62.0	6.9	100
11	103.4	103.4	93.1	10.3	100
12	103.4	206.8	186.1	20.7	100
13	137.9	103.4	93.1	10.3	100
14	137.8	137.9	124.1	13.8	100
15	137.9	275.8	248.2	27.6	100

2.5. Results and Discussion

2.5.1. Effect of Moisture Content on the Resilient Modulus

The M_r values shown in Figure 4 were at gradation coefficient n = 0.6 compacted at a moisture contents of 5.03%, 4.03%, 3.03%, 2.03%, and oven-dry conditions, i.e., (mc%). It can be observed that M_r at an OMC of 4.03% shows significantly lower values than at 3.03%, 2.03%, and oven-dry conditions, and the value of M_r at 5.03% moisture content is lower than that at OMC 4.03%. Thus, increasing the percentage moisture content at the wet side of OMC significantly reduces the M_r.

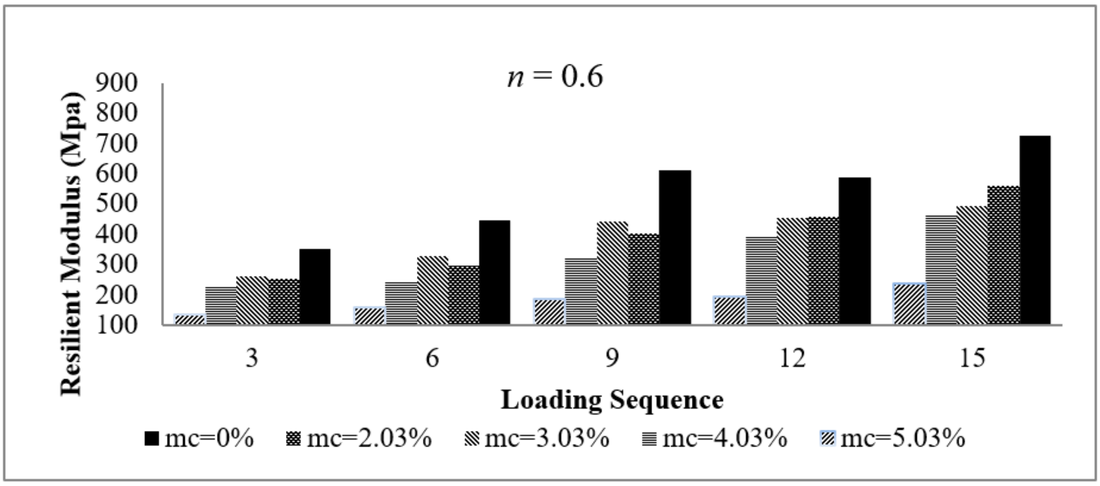


Figure 4. Resilient modulus for gradation n = 0.6 compacted at five different moisture contents.

Resilient modulus results at higher stress levels 3, 6, 9, 12, and 15 are presented in the graphs.

M_r values shown in Figure 5 were measured at a gradation coefficient (n) of 0.5 and compacted at moisture contents of 5.30%, 4.30%, 3.30%, 2.30%, and oven-dry conditions, i.e., (mc%). It can be observed that the M_r at an OMC of 4.30% showed significantly lower values than at 3.30%, 2.30%, and oven-dry condition, and the value of Mr at 5.30% moisture content was lower than at OMC 4.30%. Thus, increasing the moisture content at the wet side of OMC significantly reduces the M_r.

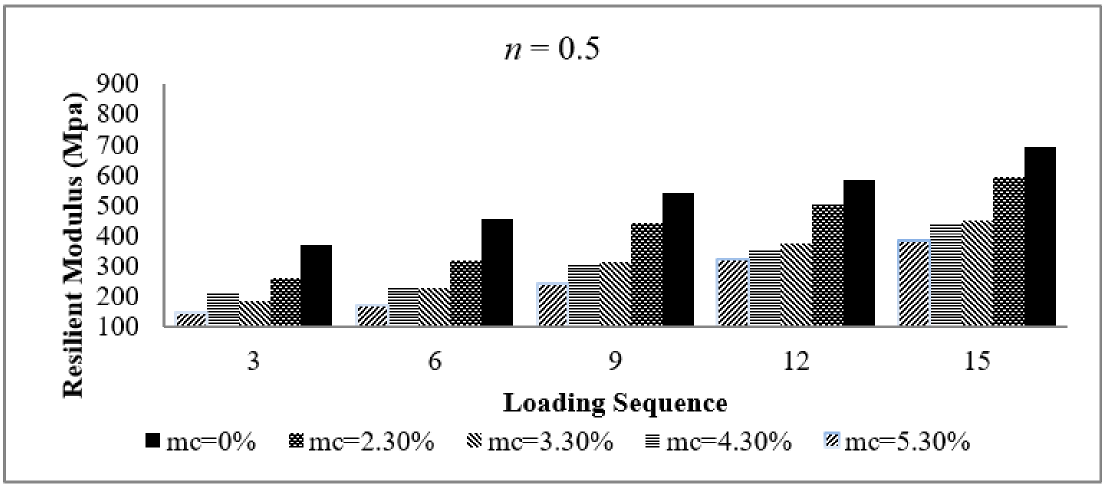


Figure 5. Resilient modulus for gradation n = 0.5 compacted at five different moisture contents.

M_r values shown in Figure 6 were measured at a gradation coefficient (n) of 0.4 and compacted at moisture contents of 5.80%, 4.80%, 3.80%, 2.80%, and oven-dry conditions, i.e., (mc%). It can be observed that M_r at an OMC of 4.80% shows significantly lower values than at 3.80%, 2.80%, and oven-dry conditions, and the value of M_r at 5.80% moisture content is lower than at an OMC of 4.80%. Thus, increasing the moisture content at the wet side of OMC significantly reduces the M_r.

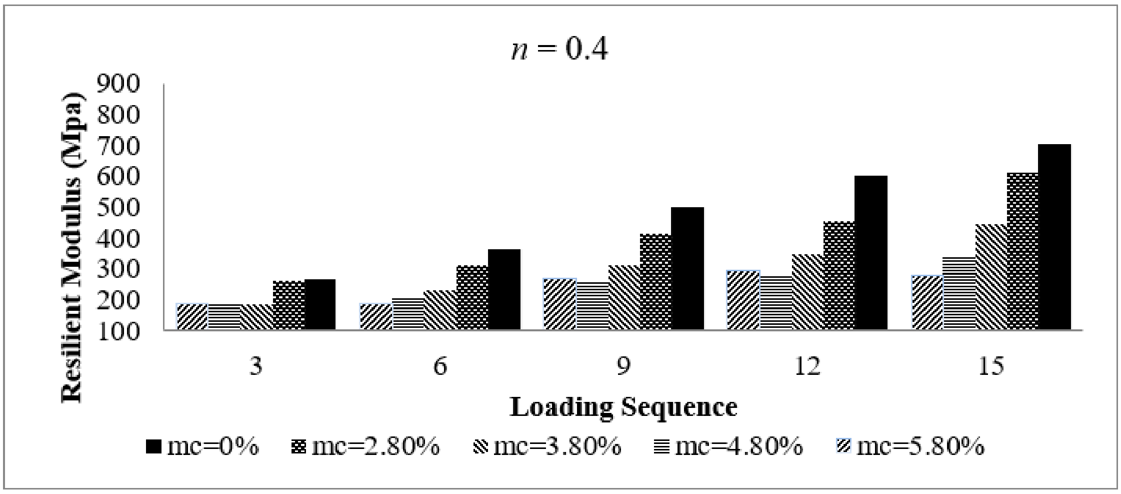


Figure 6. Resilient modulus for gradation n = 0.4 compacted at five different moisture contents.

M_r values shown in Figure 7 were measured at a gradation coefficient (n) of 0.3 and compacted at moisture contents of 6.42%, 5.42%, 4.42%, 3.42%, and oven-dry conditions, i.e., (mc%). It can be observed that M_r at an OMC of 5.42% shows significantly lower values than at 4.42%, 3.42%, and oven-dry conditions, and the value of Mr at a 6.42% moisture content is lower than at an OMC of 5.42%. Thus, increasing the moisture content at the wet side of OMC significantly reduces the Mr.

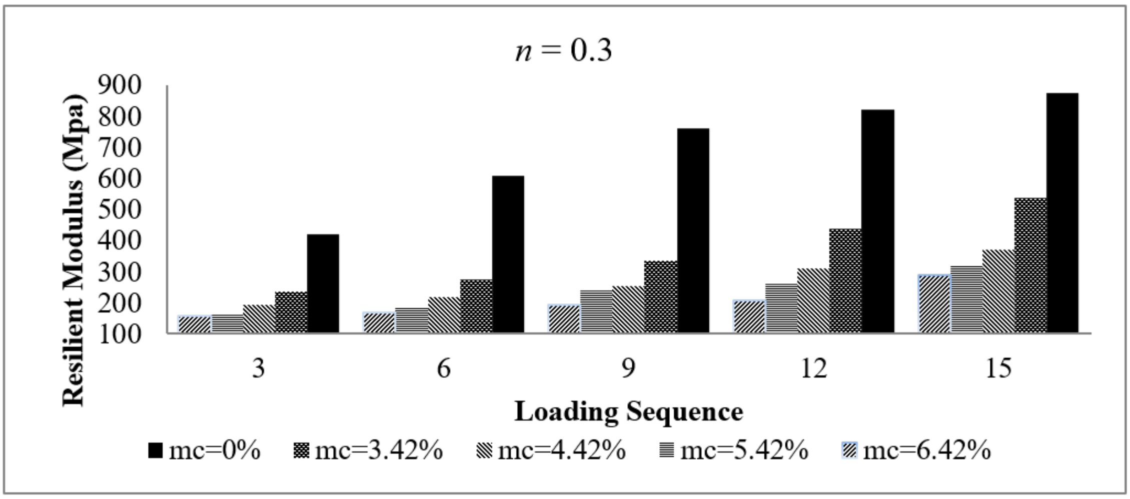


Figure 7. Resilient modulus for gradation n = 0.3 compacted at five different moisture contents.

The M_r at high moisture decreases because with a lower water content, the material becomes stiffer and rigid, which gives a higher M_r. By increasing the water content, the friction between the particles reduces, which reduces the rigidity and stiffness of the particles. Moisture works as a lubricant between aggregate particles, making it easier for the particles to relatively slide/roll; thus, M_r decreases.

The relationship between resilient modulus and gradation coefficient at different moisture contents is shown in Figure 8. Each gradation was compacted at different moisture contents to investigate which gradation gave excellent M_r with respect to moisture. It was also investigated that with increasing moisture for different gradations, the gradation behaves differently.

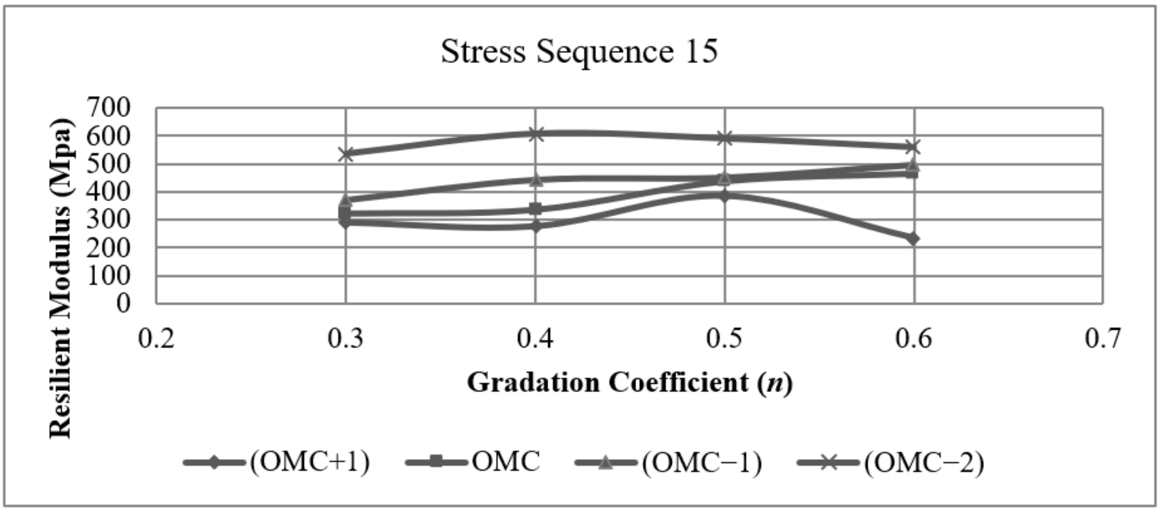


Figure 8. Resilient modulus and gradations at different moisture and stress levels.

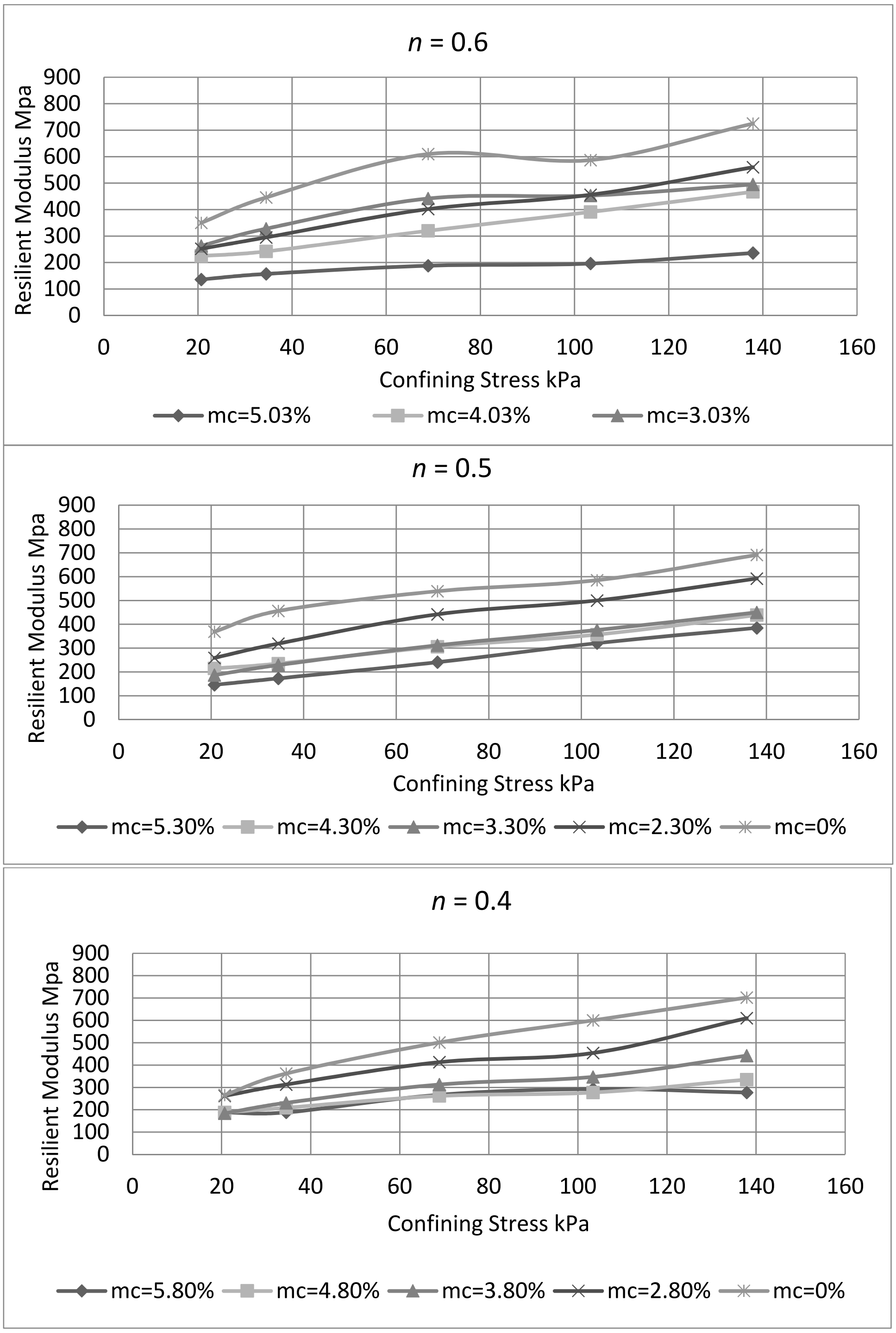
Higher M_r has been observed at a gradation of 0.5 at moisture (OMC + 1) %, as shown in Figure 8. Fine and very coarse gradation at a higher moisture content, above OMC, shows a smaller resilient modulus. Gradation n = 0.6 contain 3% fine content. Gradation mboxemphn = 0.6 at (OMC + 1) % shows the smallest M_r, which is because of the instability of the sample, compromising the resilience and rigidity of the material. The other factor is due to the small number of fine particles in n = 0.6: the pore water pressure is so high that the material just starts to flow, and the friction between the aggregates is reduced. Increasing water with less fine content, the erosion of particles has been observed, which decreases the rigidity. The finer gradation becomes softer when additional moisture is added above OMC.

At OMC, an increasing trend in M_r has been observed from 0.3 to 0.6. This shows that by increasing the gradation coefficient at moisture OMC%, the resilient modulus has been observed to increase. The maximum dry density from the proctor test was also observed to increase, from 0.3 to 0.6. This is because at OMC, the gradation of 0.6 has the maximum dry density. At (OMC − 1), gradation 0.6 shows a higher M_r than other gradations. In dry conditions, the material becomes stiffer, which increases the resilient modulus. At moisture (OMC − 2), the graph shows that gradation between 0.4 and 0.5 shows higher M_r than the other gradations.

2.5.2. Effect of Moisture Stresses on Resilient Modulus

The resilient modulus test results conducted on unbound granular materials with different gradations (varying gradation coefficient) and moisture content are illustrated in Figure 9a–d.

Figure 9a–d shows the effect of confining stress and moisture content on the resilient modulus. The graph shows that by increasing the confining stress, the resilient modulus significantly increases. This is because confining stress gives stability to the sample and prevents the sample from prior failure. Higher confining stress shows more stability. At constant confining stress, the resilient modulus increases with an increase in deviator stress.

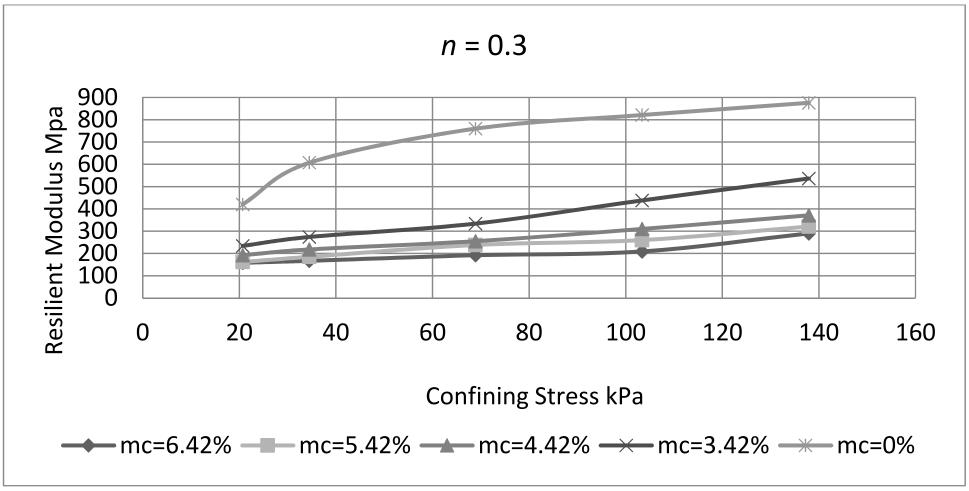


(**a**)

(**b**)

(**c**)

Figure 9. *Cont.*



(**d**)

Figure 9. Resilient modulus and confining stress values at different moisture contents. (**a**) $n = 0.6$ (**b**) $n = 0.5$ (**c**) $n = 0.4$ (**d**) $n = 0.3$.

2.5.3. Effect of Material Gradation on the Resilient Modulus

Material gradation is another key factor that affects the resilient modulus of unbound granular material. Figure 10 shows the effect of four different gradations on the resilient modulus at optimum moisture content.

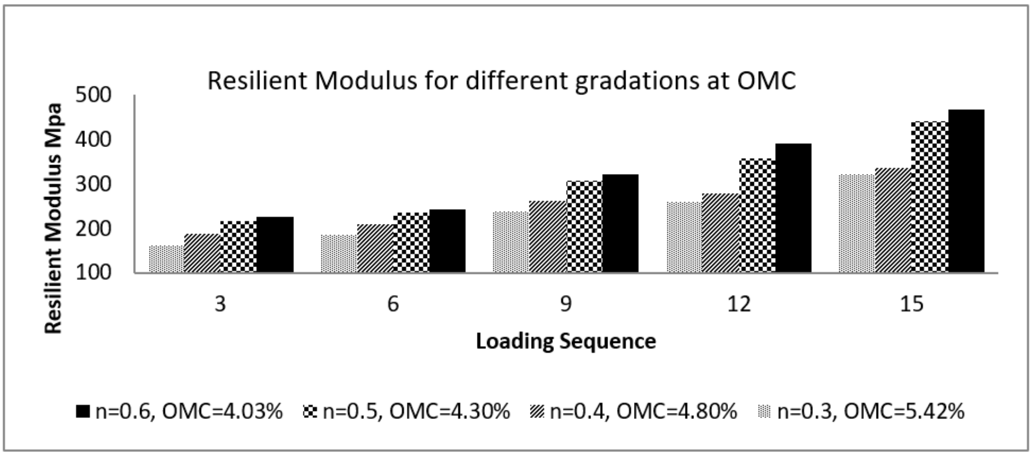


Figure 10. Resilient modulus and gradation at OMC.

Figure 10 shows that $n = 0.6$ has the maximum M_r and 0.3 shows the smallest M_r value; therefore, it has been observed from testing that a coarser gradation shows higher M_r than finer gradation. When the gradation becomes coarser, the workability of the material decreases, increasing the rigidity and stiffness in the sample. This has been observed in the literature [24–27], that the coarser gradations exhibit better pavement performance characteristics.

The other factor which affects the rigidity and stiffness of the granular materials is the percentage of fine content in the gradation curve. It was observed from the results that by increasing the percentage of fine particles in the gradation, the resilient modulus decreases. Fine content has high plasticity; thus, the material becomes weaker and more susceptible to moisture. An increasing percentage of fine content increases the plasticity of material, and material does not drain well. At higher percentages of fine content, the larger particles float in a sea of fine particles; therefore, more fine particles produce soft gradation and reduce the specimen stiffness.

Figure 11 shows the stress and strain relationship of unbound granular material under repeated load triaxial testing. As the stress increases, the strain gradually increases, but at some point, the strain continues to increase significantly with small changes in stress, which shows that the material no longer bears the stress.

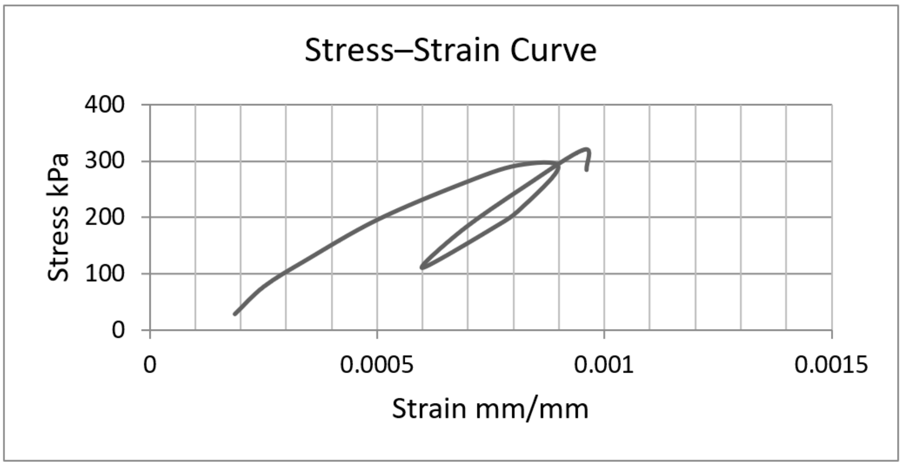


Figure 11. Stress and strain curve of unbound granular material under repeated load triaxial testing.

3. Statistical Model

3.1. Statistical Model Evaluation

To check the goodness-of-fit and adequacy of the statistical model, various statistical indices, such as R^2, p-value, F-value, and RMSE, were calculated and are presented in Tables 6–8. The p-value is used for assessing the predictive capability of the regression model, i.e., whether the proposed model fits the data well. The p statistic is a ratio of the variance explained by the regression model (regression mean square) to the unexplained variance (residuals mean square). It is frequently thought of as a refinement of the more general likelihood ratio test (LR). The p-value is employed to determine whether all the predictors are jointly significant.

R^2 is a measure of how much variance in the dependent variable is explained by the model's explanatory (independent) variables. It is calculated by multiplying the "cumulative difference in the total sum of squares (TSS) and residual sum of squares (RSS) by the total sum of squares (TSS)". An R^2 of 0.8 and above shows a strong correlation between predicted and observed values.

The adjusted R-squared is another fundamental model evaluation metric, which takes into consideration the number of independent predictors/explanatory variables utilized for predicting the dependent (target) variable. By doing so, it may be determined if the addition of new predictors to the model will affect the model fit. When comparing models with varying numbers of variables, adjusted R^2 is better and commonly preferred. For calculating the adjusted R^2, the estimated variance (MST) and residuals (MSE) are determined by dividing the respective sum of squares by the degree of freedom.

Root mean square error (RMSE) indicates the standard deviation of residuals. Residuals indicate how far the data points are from the regression line. RMSE is a measure of how tightly the data are clustered around the regression line of best-fit. It is simply taking the square-root of model MSE values.

The F-value statistic is obtained by dividing the "regression mean square (MSR)" and the model "mean square error (MSE)" as shown in Table 6.

Table 6. Regression constants and goodness-of-fit test results for the moisture model (Equation (2)).

Effect of Moisture on UGM by Changing Theta and Gradation							
Theta	n	k_1	k_2	R^2 $(1-\frac{MSE}{MST})$	p-Value = $(1-\frac{RSS}{TSS})$	F-Value = MSR/MSE	RMSE = $\sqrt{\frac{\sum_{i=1}^{N} \lVert y(i)-\hat{y}(i) \rVert^2}{N}}$
196.5	0.3	5705.8	−712.35	0.94	0	0.94	41,092
392.7	0.3	7128.4	−907.1	0.93	0	0.93	53,360
496.2	0.3	7956.9	−986.01	0.98	0	0.98	33,749
661.7	0.3	8581.4	−963.76	0.97	0	0.97	37,130
196.5	0.4	3709.3	−319.99	0.93	0	0.93	17,324
392.7	0.4	5057.3	−448.19	0.93	0	0.93	23,958
496.2	0.4	5961.9	−585.82	0.94	0	0.94	28,193
661.7	0.4	7404	−774.95	0.92	0	0.92	45,509
196.5	0.5	4433.8	−528.15	0.95	0	0.95	20,986
392.7	0.5	5434	−575.46	0.95	0	0.95	23,711
496.2	0.5	5886.9	−527.86	0.94	0	0.94	23,396
661.7	0.5	6949.2	−602.11	0.94	0	0.94	26,509
196.5	0.6	4422.6	−526.41	0.91	0	0.91	29,166
392.7	0.6	6093.8	−768.35	0.91	0	0.91	41,358
496.2	0.6	6095.1	−683.1	0.86	0	0.86	47,719
661.7	0.6	7430.4	−872.65	0.91	0	0.91	46,875

Table 7. Regression parameters and coefficients of determination for training dataset.

Model Training Regression Parameters and Goodness-of-Fit Tests									
n	k_1	k_2	k_3	k_4	R^2	adj R^2	p-Value	F-Value	RMSE
0.3	5191.7	0.0691	0.1652	−714.36	0.89	0.88	0.00	0.89	73,667
0.4	3687.7	0.1530	0.1654	−410.53	0.80	0.78	0.00	0.81	64,009
0.5	3448.6	0.0616	0.2667	−433.28	0.91	0.91	0.00	0.93	39,910
0.6	4918.6	0.2397	−0.0061	−551.76	0.78	0.76	0.00	0.79	71,683

Table 8. Regression parameters and coefficients of determination for testing dataset.

Model Testing Regression Parameters and Goodness-of-Fit Tests									
n	k_1	k_2	k_3	k_4	R^2	adj R^2	p-Value	F-Value	RMSE
0.3	5191.7	0.0691	0.1652	−714.36	0.76	0.73	0.00	1.23	50,008
0.4	3687.7	0.1530	0.1654	−410.53	0.76	0.72	0.00	0.90	48,587
0.5	3448.6	0.0616	0.2667	−433.28	0.88	0.86	0.00	0.93	36,376
0.6	4918.6	0.2397	−0.0061	−551.76	0.55	0.47	0.00	0.90	65,674

3.2. Relationship of Resilient Modulus and Moisture Content

The values of resilient modulus from repeated load triaxial tests were plotted against different moisture levels. Various curves were obtained, and the linear model best fitted the data. The linear model is shown in Equation (2).

$$M_r = p_o(k_1 + k_2 m) \quad (2)$$

where 'M_r' (kPa) is the resilient modulus, 'p_o' (kPa) is the atmospheric pressure, k_1 and k_2 are regression constants, and m is the moisture content.

Figure 12 shows the representative graphs between moisture and resilient modulus for gradation constant n = 0.5 and principal stresses (theta), which is the sum of the confining stress (σ_3), axial stress (σ_1), and mean normal stress (p). The experimental data points are shown in red, and the black line shows the model fit. From Figure 12, it can be observed that the model fits appropriately. Moreover, the coefficient of determination 'R^2' is shown in the table for specified stresses (theta) and also advocates the results.

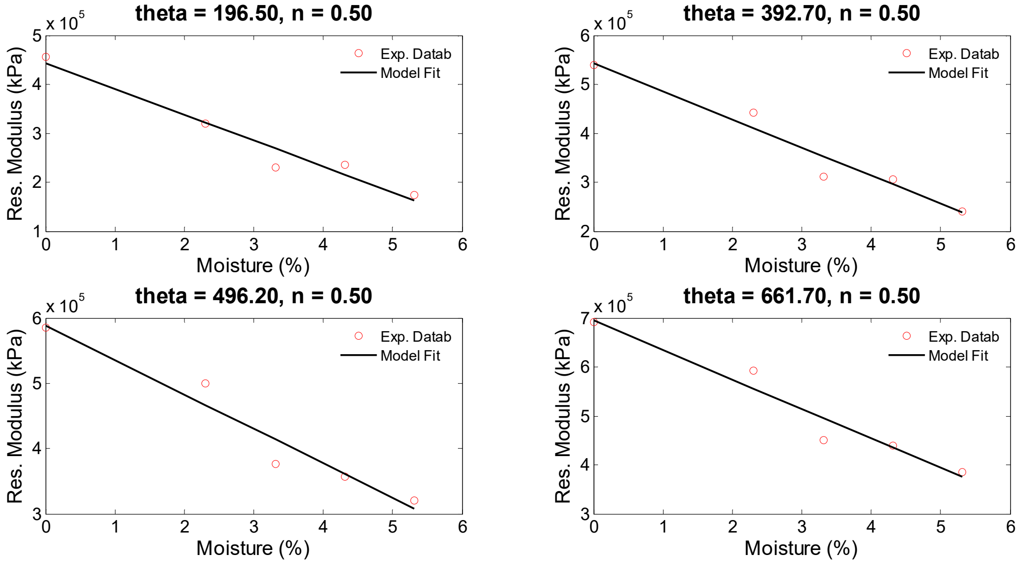


Figure 12. Graphs showing the moisture model fit for stresses (theta).

The coefficient of determination and graphical fit of the model in experimental data show that the new linear relationship in Equation (2) appropriately represents the resilient modulus variation with changes in the moisture content. Data obtained from the tests and regression model were statistically analyzed using F-tests [56]. The basic purpose was to estimate the accuracy and validity of the model. The p-value hypothesis is that two independent samples, experimental and predicted M_r values, come from normal distributions with the same variance. A p-value of '0' shows that null hypothesis (variances are equal) cannot be rejected at the 5% significance level; a p-value of '1' shows that the null hypothesis can be rejected at the 5% level. To say that our model is a good fit, the p-value should be equal to '0'. From Table 6, all p-values are '0' showing a good fit.

3.3. Improved Relationship for Resilient Modulus, Stresses, and Moisture

Ekblad tested various K-θ models (stress-based) and reported that the modified Uzan model was the best one. The Uzan model was fitted to the research data, and the model result showed substantial agreement with the test data. Therefore, the modified Uzan model was selected for further modifications for moisture contents.

A new relationship is suggested here that includes the effects of stress and moisture variations. The new relationship is shown in Equation (3).

$$M_r = p_o[(k_1(^{\theta}/_{p_o})^{k_2}(^{\sigma_d}/_{p_o})^{k_3}) + (k_4 m)] \quad (3)$$

where 'M_r' (kPa) is the resilient modulus, 'p_o' (kPa) is the atmospheric pressure (100 kPa), and k_1, k_2, k_3, and k_4 are regression constants, θ is the sum of confining and deviator stress, and d is the deviator stress.

The regression model in Equation (2) shows that a linear relationship can successfully predict the resilient modulus with changing moisture contents. The modified Uzan model the changes in the resilient modulus with changing stresses. Therefore, this new relationship, Equation (3), modifies both Equation (2) and the modified Uzan model, such that it predicts the resilient modulus with changing stresses and moisture content. The new model was fitted in the resilient modulus data for repeated load triaxial testing using the least-square fit technique.

The model in Equation (3) was trained on three-fifths of the dataset of resilient modulus obtained from repeated load triaxial tests, and two-fifths of the data were used for fitting that model. Figures 13 and 14 show the training and testing of the regression model in the data. The fit of the model in Figures 12 and 13 shows that the new relationship is in agreement with the resilient modulus data.

The coefficients of determination R^2, adjusted R^2, F-test, F-test values, and RMSE values for training and testing data are shown in Tables 7 and 8. The coefficient of determination, R^2, along with adjusted R^2, shows that the model predicts the trained values well and also performs well with the testing data. All p-values show that the null hypothesis is true, exhibiting a '0' value. The higher values of F and lower relative values of RMSE also show that the model fitness is acceptable.

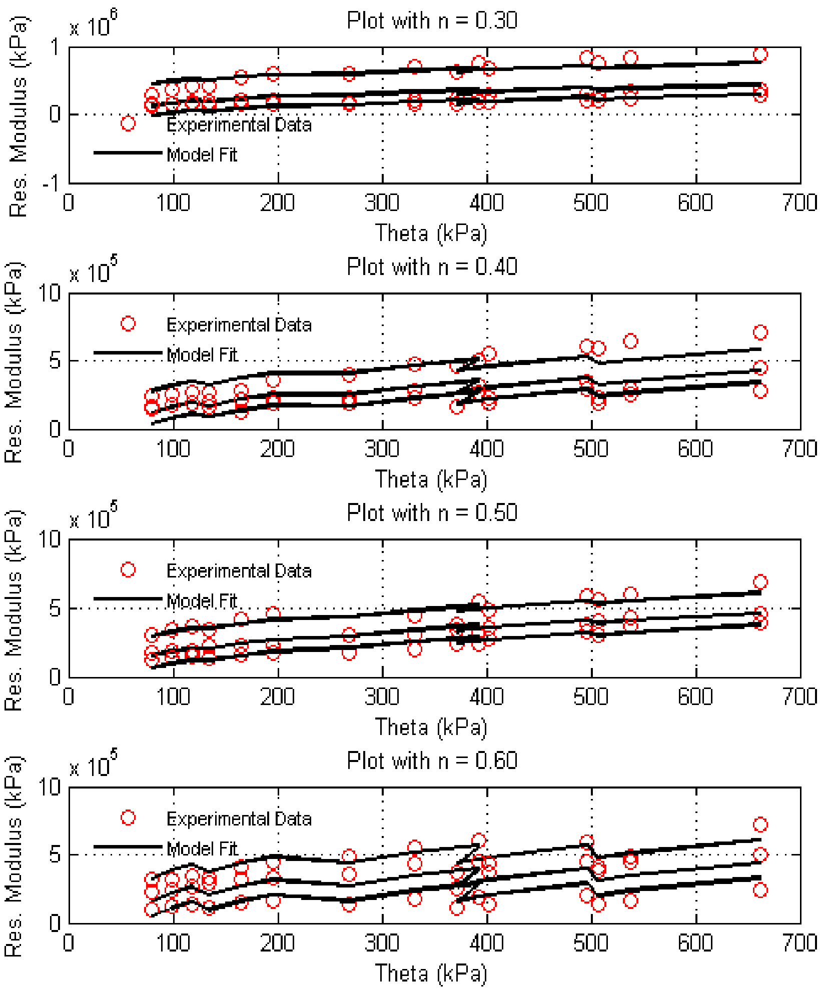


Figure 13. Training a new model for the resilient modulus data.

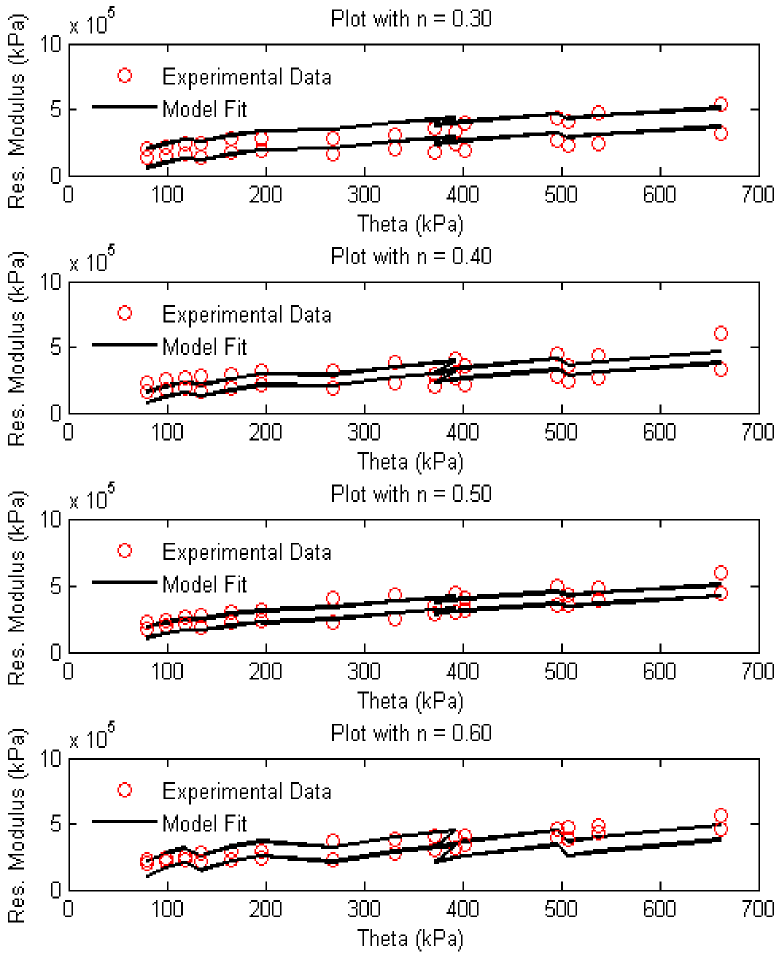


Figure 14. Testing a new model for the resilient modulus data.

4. Conclusions

An effort has been made to investigate the resilient modulus of unbound granular material under repeated load triaxial testing by changing the moisture content, material gradation, and stress level. The following main conclusions have been drawn from this study:

- The resilient modulus decreases with an increase in the moisture content of unbound granular material, and vice versa. This is because at the dry side of optimum moisture content, the materials behave more stiffly, resulting in an increase in the resilient modulus, and at the wet side of optimum moisture content, the material becomes saturated and pore water pressure develops, resulting in a reduction in the stiffness.
- The resilient modulus increases significantly with the increase in both deviator and confining stresses of unbound granular material. It is shown in Figure 9b that by increasing the confining stress from 103 kPa to 137 kPa, the resilient modulus increases from 585 Mpa to 691 Mpa.
- The resilient modulus also decreases with an increase in finer gradation and increases with an increase in coarser gradation in unbound granular materials. A lower resilient modulus value is observed at (n) 0.3 and 0.4, and a higher resilient modulus value is seen at (n) 0.5 and 0.6. This is because the coarser gradations are stiffer than the finer gradation.
- A new relationship has been proposed in Equation (2), which depicts that the moisture content and resilient modulus of unbound granular material can be predicted through a linear relationship. However, the accuracy is better if Equation (3) is applied.

- The new relationship has been trained on three-fifth of the dataset, and regression parameters were calculated. The model was tested on the rest of the data with the trained parameters. It can be concluded that resilient modulus values predicted by the new relationship are in good agreement with repeated load triaxial test data. Therefore, new relationships can be used in the design process with greater confidence compared with the previous relationships, which only consider the stress tensors for the prediction of resilient modulus.

From the experimental data, it is concluded that unbound granular material shows higher resilient modulus at coarser gradations, lower moisture contents, and higher stress levels, and vice versa. Higher M_r values are indicative of greater stiffness and strength of unbound granular materials, as well as their increased resistance to shear failure under traffic loading, thereby improving pavement durability. To conclude, the structural behavior of the pavement against traffic loading can be reliably determined by knowing the resilient modulus of various pavement materials. The resilient modulus of unbound granular material obtained in this study can be helpful for engineers and scientists for sustainable pavement design.

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