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Issam I. A. Qamhia
University of Illinois at Urbana-Champaign

Liang Chern Chow
American Engineering Testing, Inc.

Debakanta Mishra
Boise State University

Erol Tutumluer
University of Illinois at Urbana-Champaign

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By

Issam I. A. Qamhia, Ph.D. Student, Graduate Research Assistant
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
205 North Mathews, Urbana, IL 61801, USA
Phone: (414) 687-5947 / Email: qamhia2@illinois.edu

Liang Chern Chow, Geotechnical Engineer
American Engineering Testing, Inc.,
550 Cleveland Ave N, St. Paul, MN 55114, USA
Phone: (612) 532-2145 / Email: lchow@amengtest.com

Debakanta Mishra, Ph.D., Assistant Professor
Department of Civil Engineering
Boise State University
1910 University, Boise, ID 83725, USA
Phone: (208) 426-3710 / Email: debmishra@boisestate.edu

Erol Tutumluer, Ph.D., Professor (Corresponding Author)
Paul F. Kent Endowed Faculty Scholar
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
205 North Mathews, Urbana, IL 61801, USA
Phone: (217) 333-8637 / Fax: (217) 333-1924 / Email: tutumlue@illinois.edu

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[1] Issam Qamhia – Graduate Research Assistant
[2] Liang Chern Chow – Geotechnical Engineer
[3] Debakanta Mishra – Assistant Professor
[1] Erol Tutumluer – Professor, Paul F. Kent Endowed Faculty Scholar

[1] University of Illinois at Urbana-Champaign
[2] American Engineering Testing, Inc.
[3] Boise State University

Abstract

This paper presents findings from an ongoing research study at the University of Illinois focused on developing and calibrating an improved permanent deformation model for unbound aggregate materials through laboratory testing and characterization. The project scope included testing sixteen aggregate materials, commonly used in the state of North Carolina for pavement base courses, in the laboratory through monotonic and repeated load triaxial testing. This paper primarily focuses on quantifying effects of aggregate gradation on permanent deformation behavior. To accomplish this, four materials were tested at both: (1) "source gradations," i.e. original gradations from quarry, and (2) an "engineered gradation," i.e., standard reference gradation at which aggregate specimens were prepared for testing. Predictive rutting models were developed to consider the influences of shear strength and applied stress states on permanent deformation accumulation. Rutting model parameters obtained from testing aggregate specimen at one gradation could be used to reasonably predict the permanent deformation accumulation in another sample given the shear strength properties did not show notable differences. For specimens corresponding to significantly different amounts and/or plastic nature of fines, the permanent strain levels predicted using one set of model parameters differed significantly from those predicted using another set of model parameters developed for another gradation. Moreover, the effects of gradation on permanent strain accumulation were significantly more pronounced at the higher shear stress ratios (e.g. 0.75), compared to lower shear stress ratios; which is defined as the ratio between the shear stress applied to a specimen during repeated load triaxial testing compared to the corresponding shear strength under the same confinement.

Key Words: Aggregate Gradation, Permanent Deformation, Repeated Load Triaxial Testing, Shear Strength, Shear Stress Ratio, Rutting Model Development

INTRODUCTION

Rutting is the main performance indicator for unbound aggregate base/subbase layers in flexible pavements. Several of the widely used rutting models, such as the one used in the Pavement ME Design software by AASHTO, predict the permanent deformation accumulation in unbound aggregate layers based on resilient strains levels without giving any consideration to aggregate shear strength. However, several research studies in the past [1, 2] have established that aggregate shear strength plays a significant role in governing the rutting potential under loading. Unbound aggregate materials with relatively high shear strength properties often exhibit lower tendencies for lateral and vertical deformations under similar loading conditions compared to aggregate materials with relatively low shear strength. The following factors have been identified to significantly affect the permanent deformation accumulation in unbound aggregate materials: moisture content or degree of saturation, dry density, fines content and plasticity, mineralogy, grain size distribution, principal stress orientation under moving wheel, and stress history [3-6].

Grain size distribution or gradation has been identified as one of the main factors that influence the permanent deformation accumulation in unbound aggregate materials. Cunningham et al. [7] studied the effects of particle size distribution on aggregate mechanical behavior by testing the same unbound materials at five different gradations satisfying typical gradation bands specified by the North Carolina Department of Transportation (NCDOT). Conducting a wide variety of laboratory tests, they observed that the Optimum Moisture Content (OMC), Maximum Dry Density (MDD), and index properties such as Atterberg limits were not significantly influenced by changes in the well-graded aggregate gradations that were considered in their work. However, mechanical responses of the specimens changed significantly as the fines content (material finer than 0.075 mm or passing No. 200 sieve) approached 8% to12%. Ghabchi et al. [8] performed a similar study by testing different aggregate types at gradations corresponding to the upper and lower limits of a specified gradation band. They observed that the specimens blended at gradations that correspond to the upper limit (finer gradations) had higher densities and OMC values when compared to the specimens blended at gradations near the lower limit (coarser gradations) of the specification band. However, they observed that specimens blended at lower limit gradations exhibited higher stability and resilient moduli due to better packing, and the more interlocking of the larger-sized particles. Recent research efforts at the University of Illinois [9-11] compared relative impacts of moisture content, fines content, and type of fines (plastic vs. nonplastic) on the permanent deformation behavior of both crushed and uncrushed aggregate materials. A drastic reduction in aggregate shear strength and resistance to permanent deformation was observed when excess moisture was introduced in uncrushed gravel specimens comprising high amounts of plastic fines.

Many predictive models have been proposed by researchers to predict the permanent deformation accumulation in unbound aggregate base/subbase layers. They traditionally relate permanent strain accumulation to the number of load applications. Barksdale [6] proposed a linear relationship between permanent strain and the logarithm of number of load applications. Monismith et al. [12] proposed the widely-used log-log relationship between permanent strain and number of load applications (also known as the phenomenological model). Other common models developed in the 1970s and 1980s include those proposed by Pappin [13], El-Mitiny [14], Khedr [15], and Tseng and Lytton [16]. Several additional models proposed in the 1990s also include those developed by Wolff [17], Thompson and Nauman [18], van Niekerk and Huurman [19], Paute et al. [20], Huurman [21], and Ullidtz [22]. Lekarp and Dawson [23] state that the failure of granular materials under repeated loading is a gradual process dependent on applied stress states and number of load applications. Gidel et al. [24] also proposed a stress dependent permanent deformation model based on the laboratory data. Recently, Chow et al. [25-27] proposed a framework for predicting permanent deformation (also known as the UIUC Rutting Model) as a function of applied wheel load stress levels and aggregate shear strength under applied confinement (or ratio of the two defined as the shear stress ratio) along with the number of load applications.

The research described in this paper builds on the Chow et al. [25-27] framework study with the goal to develop and calibrate a new rutting model to better predict rutting performance of in-service unbound aggregate pavement layers. Sixteen different aggregate materials commonly used in the state of North Carolina for pavement base/subbase applications were tested in the laboratory for shear strength and permanent deformation behavior. The first phase of the project [25-27] involved testing the sixteen aggregate materials at one common engineered gradation to eliminate the effects of particle size distribution on aggregate behavior. The improved rutting model developed adequately captured the effects of applied stress states and aggregate shear strength while predicting the permanent strain accumulation in unbound aggregate layers.

Although the first phase of the study successfully developed an improved rutting model for better rut prediction, all test results and corresponding rutting model parameters were developed for the fixed engineered gradation. The ability of the newly developed rutting model to accurately predict permanent strain accumulation at different gradations was not verified during the first phase. This is particularly important as aggregate materials used for constructing pavement base and subbase layers are usually placed at their respective source gradations. These gradations may fall anywhere within the upper and lower bounds specified by state and local agencies. Since significant differences in the particle size distribution can be observed for two aggregate materials satisfying the gradation specifications, it is important to re-evaluate the performance of the newly developed rutting model at different aggregate source gradations.

This paper presents four aggregate materials, selected based on their permanent deformation trends at a fixed engineered gradation and further investigated for the effects of the differences among the source and engineered (controlled) gradations, e,g., amount of fines present, on permanent deformation behavior. Triaxial shear strength tests were first conducted to determine the shear strength properties of the aggregates at their respective source gradations. Mohr-Coulomb failure envelopes were established, and the concept of Shear Stress Ratio (SSR) was used to evaluate the permanent deformation behavior at different stress states. Rutting model parameters established from the laboratory data at the source gradations are compared with those established at the engineered gradations to assess their sensitivity to gradation changes.

OBJECTIVE AND SCOPE

The primary objective of this paper is to present a detailed discussion on the effects of varying grain size distribution on unbound aggregate shear strength and permanent deformation behavior. Results for four different aggregate materials are presented; and their shear strength properties and permanent deformation trends at the quarry source gradations are compared with the results obtained at the engineered gradations. Rutting model parameters corresponding to the source gradations have been established by fitting the UIUC Rutting Model to the repeated load triaxial test results. The effects of aggregate gradation on the rutting model parameters are discussed in detail.

AGGREGATE MATERIALS TESTED

Four aggregate materials, denoted as M1, M2, M3 and M4 were tested during this phase of the research study. Each material was tested for shear strength and permanent deformation behavior at its original (or source) gradation. The first step in the test matrix involved sieving each aggregate material to establish the "as received" gradation curve. Figure 1 presents the gradation curves for the four materials along with the NCDOT base course material specification bands. The fixed engineered gradation used during the first phase of the study is also shown in Figure 1. The source gradation for M1 closely resembled the engineered gradation, whereas certain portions of the source gradation curves for M2 and M4 differed significantly from the engineered gradation curve. It should also be noted that although materials M2 and M4 are commonly used by NCDOT for pavement base/subbase applications, parts of the source gradation curves lie outside the agency-specified gradation band.

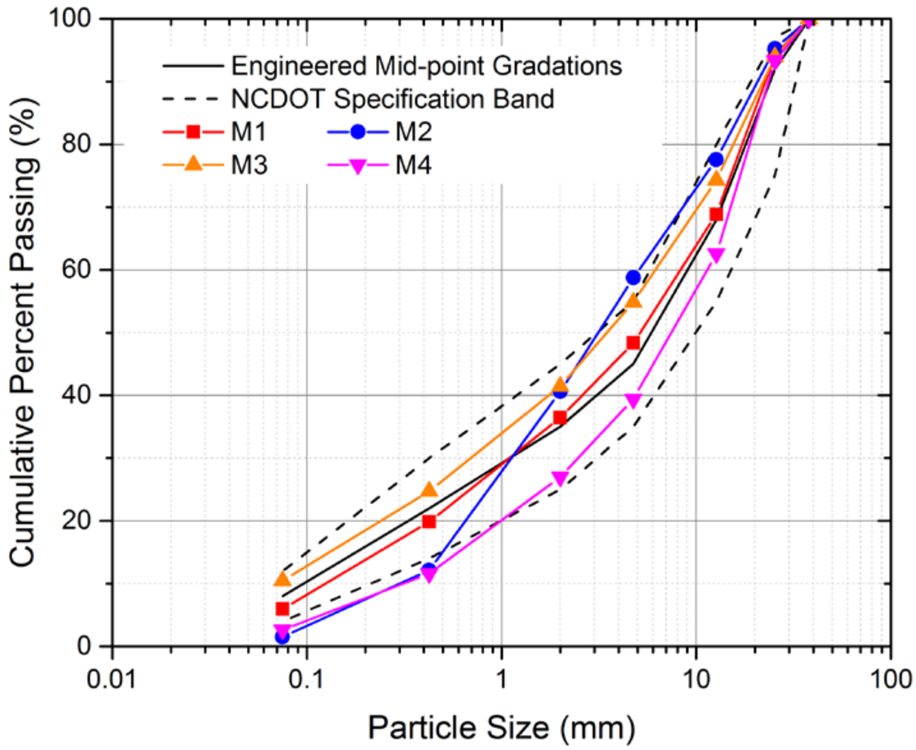


Figure 1: Engineered and Source Gradations for the Tested Aggregate Materials

The aggregate materials were tested by the NCDOT Materials Division in Raleigh, NC for certain index properties such as Atterberg limits. Compaction (moisture-density) curves for the four materials were established following the NCDOT compaction procedure, which is similar to the modified compaction method (AASHTO T180), but involves the application of 86 blows per layer, instead of 56. In addition, the aggregate type was visually classified based on its basic lithology. The relevant properties are summarized in Table 1. Three of the aggregate materials (M1, M3 and M4) were geologically classified as granite, whereas material M2 fell under rhyolite category. Moreover, M2 was the only aggregate material included in this study that comprised plastic fines (Plasticity Index, or PI = 6%). The OMC values for the four materials ranged from 5.7% to 6.1%, and the MDD values ranged from 22.2 kN/m^3 (141.6 pcf) to 22.7 kN/m^3 (144.7 pcf).

Table 1: Aggregate Source Properties and Compaction Characteristics

Material	**Aggregate Type**	**MDD** $\gamma_{d,max}$	**OMC** ω_{opt}	**Liquid Limit** ***LL***	**Plasticity Index** ***PI***
		kN/m^3 (pcf)	(%)	(%)	(%)
M1	Granite	22.4 (142.4)	6.1	19	Nonplastic
M2	Rhyolite	22.2 (141.6)	5.9	23	6
M3	Granite	22.6 (143.6)	5.7	18	Nonplastic
M4	Granite	22.7 (144.7)	6.0	18	Nonplastic

TRIAXIAL MONOTONIC SHEAR STRENGTH TESTS

The first step involved testing the four aggregate materials for shear strength properties at their source gradations (SG), and comparing the results with those corresponding to the engineered gradations (EG) established during the first phase of the study. Drained triaxial monotonic shear strength tests were performed to establish the shear strength properties (friction angle, ϕ; and cohesion intercept, c) for each aggregate material. Cylindrical test specimens, 152 mm (6 in.) in diameter by 305 mm (12 in.) height, were prepared under OMC and MDD conditions by compacting in six equal lifts. An axial strain rate of 1% per minute (3 mm/min or 0.12 in./min) was applied to shear the specimens. A minimum of three tests were conducted for each material corresponding to confining pressure levels of 35 kPa (5 psi), 69 kPa (10 psi), and 103 kPa (15 psi) to establish the Mohr-Coulomb failure envelopes.

Table 2 summarizes the shear strength properties (c and ϕ) for the four materials at the source and engineered gradations. In addition to the friction angle (ϕ), the secant friction angle (ϕ_s) values corresponding to a confining pressure level of 35 kPa (5 psi) have also been presented in Table 2. The secant friction angles were determined from the peak deviator stress levels achieved during triaxial shear strength tests assuming passive state of Mohr-Coulomb failure criteria with zero cohesion intercept ($c = 0$). This value can be seen as the peak drained friction angle in granular soils. All values reported in this paper are based on the triaxial shear strength test results at 5 psi (34.5 kPa) confining pressure, which is also the stress state all permanent deformation tests were conducted at. Note that the ratio between major and minor principal stresses in a cohesionless material cannot exceed the value:

$$\tan^2\left(45 + \frac{\phi_s}{2}\right) = \frac{\sigma_{1,f}}{\sigma_3}$$

where $\sigma_{1,f}$ is peak normal stress at major principal direction and σ_3 is minor principal stress or confining pressure of 5 psi (34.5 kPa) from laboratory shear strength tests.

As listed in Table 2, material M1 has a significantly lower cohesion intercept (*c*) at the SG (55.1 kPa) compared to the value at the EG (160.6 kPa). However, the friction angles for the two gradations are very close to each other (39.4° for SG; 39.3° for EG). This means, for a given confining stress, the shear strength for the EG will be significantly higher than the SG owing to the significantly larger *c* value. Although the two gradation curves (SG and EG) for material M1 are reasonably close to each other, this discrepancy in the shear strength behavior may be a manifestation of slightly higher fines content for the EG (8%) compared to the SG (6%). Note that previous research studies have observed that dense graded aggregates achieve the maximum shear strength at approximately 8% fines content [28, 29]. The slightly higher fines content at the EG for M1 may have contributed to the higher shear strength values.

The largest change in friction angle between the two gradations was found for material M2 (40.3° at SG; 37.7° at EG). As already mentioned, M2 was the only material that comprised plastic fines. The presence of 8% plastic fines at EG make the matrix significantly weaker compared to the presence of 1.5% plastic fines at the SG. Material M3 with 10.5% fines content at SG had a lower friction angle and a slightly higher cohesion intercept compared to the EG. This too can potentially be attributed to the fact that aggregate matrices with crushed particles achieve the "most stable" condition at around 8% fines. This finding from previous researchers [28,29] can also be corroborated by comparing the ϕ_s values for the SG and EG for material M3. Table 2 lists the ϕ_s value for EG (8% fines), which is higher than that for the SG (10.5% fines). Although material M4 comprised only 2.6% fines at SG, no significant change in ϕ value for this material was observed as the gradation was changed from SG to EG.

Table 2: Shear Strength Properties of the Four Different Materials at Source and Engineered Gradations

Material	Source Gradation				Engineered Gradation			
	Fines Content, P_{200}*	Secant Friction Angle, ϕ_s	Friction Angle, ϕ	Cohesion, *c*	Fines Content, P_{200}*	Secant Friction Angle, ϕ_s	Friction Angle, ϕ	Cohesion, *c*
	(%)	(Degree)	(Degree)	kPa (psi)	(%)	(Degree)	(Degree)	kPa (psi)
M1	6.0	56.9	39.4	55.1 (8.0)	8.0	66.9	39.3	160.6 (23.3)
M2	1.5	56.2	40.3	48.9 (7.1)	8.0	50.5	37.7	43.4 (6.3)
M3	10.5	50.8	40.0	21.4 (3.1)	8.0	51.2	41.4	19.3 (2.8)
M4	2.6	55.8	48.1	13.1 (1.9)	8.0	51.3	48.8	3.4 (0.5)

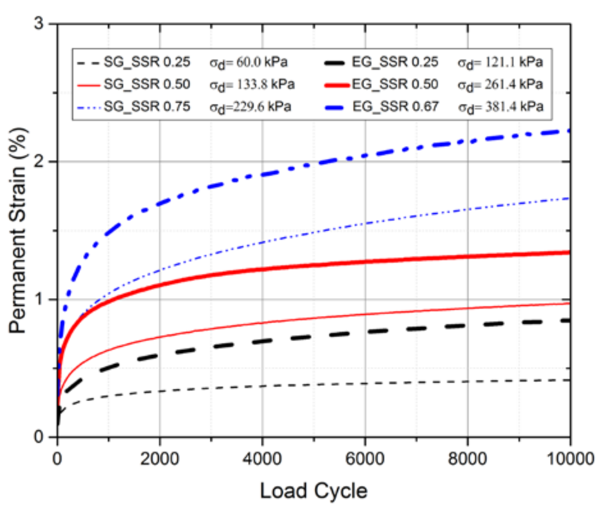
* P200: Passing sieve No. 200 (0.075 mm)

Close inspection of the test results presented in Table 2 indicates that fines content have a significant effect on the shear strength properties of unbound aggregate materials. Crushed aggregate matrices comprising 8% fines often exhibit more stable behavior compared to those with lower or higher fines contents as long as the fines are nonplastic in nature. Presence of plastic fines in the aggregate matrix has a drastic adverse effect on the shear strength behavior.

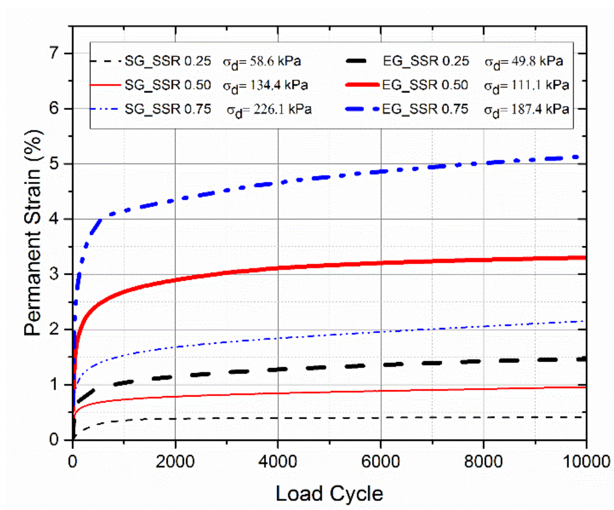
REPEATED LOAD TRIAXIAL TESTING FOR PERMANENT DEFORMATION

Repeated load triaxial tests were carried out to compare the rutting trends of each of the four aggregate materials at the two different gradation levels. Each material was tested at stress levels corresponding to Shear Stress Ratio (SSR) values of 0.25, 0.50 and 0.75; conducting one test at each stress state for each gradation. The SSR value represents the ratio between the shear stress induced to a specimen during repeated load triaxial testing compared to the corresponding shear strength under the same confinement. Detailed discussions on the concept of SSR have been presented elsewhere [26]. The selected SSR levels correspond to aggregate layers subjected to low, medium and high wheel load stress levels, respectively. All the permanent deformation tests were performed at a confining pressure of 34.5 kPa (5 psi), which closely simulates typical confining pressure levels in the field including the residual compaction stresses locked-in the granular base. Totally 10,000 load cycles were applied at each stress level using a haversine-shaped load pulse with a 0.1 second pulse width, and 0.9 second rest period, similar to AASHTO T307. This loading configuration and number of cycles are believed to capture the first two stages in the shakedown of unbound materials, namely: the plastic shakedown and the plastic creep stages that were identified by Werkmeister et al. [30]. All repeated load triaxial tests were performed using the University of Illinois FastCell (UI-FastCell) loading device.

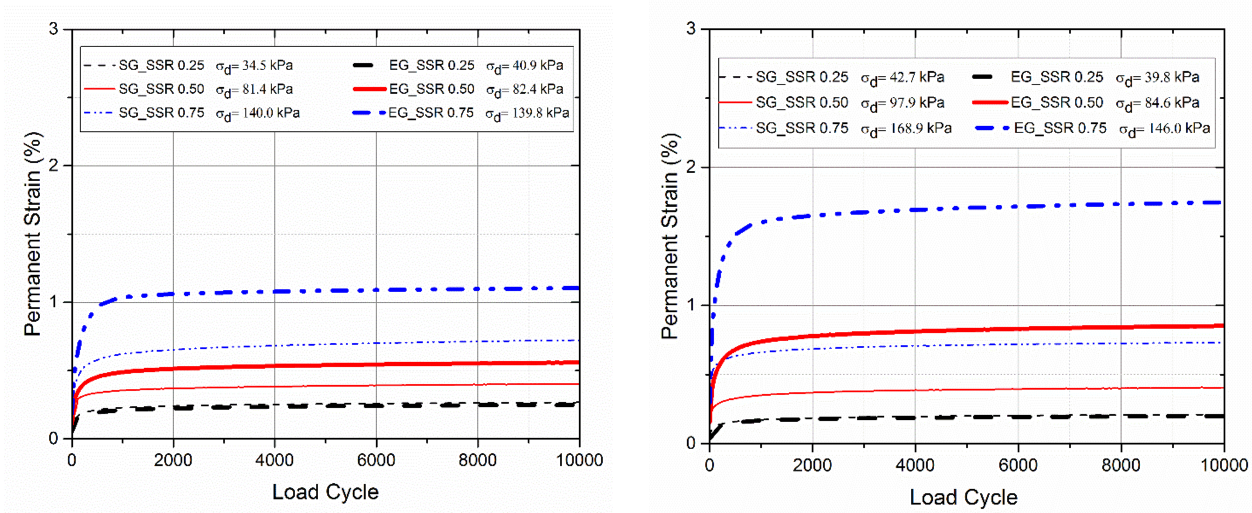
Results from the permanent deformation testing of the four materials at the two different gradations are presented in Figure 2. Those results corresponding to the EG are plotted using thick lines. The applied deviator stress (σ_d) levels to achieve different SSR values for different materials and gradations are also listed. For material M1, the highest SSR level that could be achieved for the EG was 0.67 (instead of 0.75) due to the high shear strength of this material and limiting equipment capacity. Higher SSR levels consistently resulted in higher permanent strain accumulations for all material types and gradations.



Material M1



Material M2



Material M3 Material M4

Figure 2: Permanent Strain Accumulations in the Four Aggregate Materials at Different SSR Levels and Gradations (note the change in y-axis scale for material M2)

As shown in Figure 2, material M2 accumulated the highest permanent strain, with the permanent strain level at the 0.75 SSR exceeding 5% at the EG. This can be attributed to the plasticity of fines present in this material. At the EG, the material M2 comprised 22% of plastic materials passing No. 40 sieve (0.425 mm); while at the SG, it comprised only 12.1% materials finer than 0.425 mm. Presence of the plastic fines weakened the aggregate matrix significantly; leading to high permanent strain accumulations. It is important to note that the same material (M2) accumulated significantly lower amounts of permanent strain at the SG. A similar trend was also seen for material M4, for which the lower fines content at the SG (11.5 % vs. 22% finer than 0.425 mm) led to lower permanent strain accumulations. Comparing the results for M2 and M4, the detrimental effect of plastic fines on aggregate behavior is quite apparent. Interestingly, the trends of permanent strain accumulation for material M3 were opposite to those for M2 and M4. The source gradation for M3 was finer than the engineered gradation (10.5% fines for SG; 8% fines for the EG) and the SG specimen showed slightly lower permanent strain accumulation than the EG one.

Variations in the permanent deformation behavior between EG and SG specimens for material M1 can be primarily attributed to the large variations in the applied stress levels to achieve the different SSR values during permanent deformation testing. Note that the particle size distribution curves for EG and SG specimens for material M1 closely resemble each other. Overall, the effects of gradation on rutting characteristics are more pronounced at the higher SSR values. This is clearly seen for materials M2, M3 and M4, where the differences in accumulated permanent strains between the EG and SG specimens were the highest for SSR = 0.75, and lowest at SSR = 0.25. This indicates that the effects of gradation on aggregate permanent deformation behavior becomes more significant as the applied stress levels approach the corresponding shear strength values of the materials.

Although SSR values are a good indicator of aggregate behavior at different stress levels compared to the corresponding shear strengths, looking at SSR by itself can be misleading when comparing the rutting potential of different aggregate materials. A better practice therefore is to consider both SSR and the deviator stress level at the same time. Figure 3 illustrates the effects of the applied deviator stress levels on the permanent strain accumulation in each aggregate material after 10,000 load applications. As shown in Figure 3, permanent strain accumulated after 10,000 load cycles appears to vary linearly with applied deviator stress levels. This linear trend was also previously seen for other aggregate materials by Chow et al. [26]. A closer look at the slope of the individual lines can shed some light on how material behavior changes at different stress levels. For example, the slopes of the SG lines for both materials M2 and M4 are significantly lower than the slopes of the corresponding EG lines. In other words, the rate of increase in permanent strain with increasing deviator stress levels for these two materials is much higher for EG specimens compared to the SG specimens. This can be directly correlated to the difference between the fines contents for the EG and SG gradations for a given material. Materials M2 and M4 with P_{200} difference of 6.5% and 5.4%, respectively, ($P_{200,EG}$ - $P_{200,SG}$ = 6.5% for M2) show large divergence between the SG and EG lines with increasing deviator stress levels. The P_{200} difference for materials M1 and M3 are 2.0% and 2.5% respectively, and the corresponding EG and SG lines do not diverge significantly with increasing deviator stress levels (refer to Figure 3).

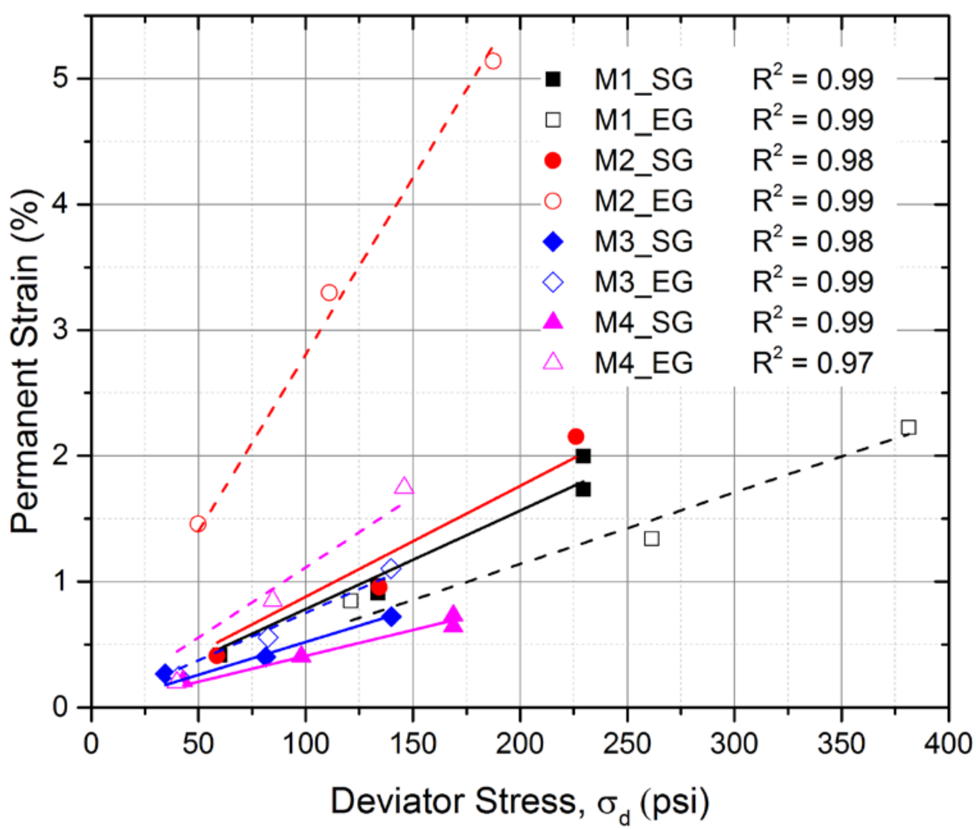


Figure 3: Permanent Strain Values after 10,000 cycles for the Four Material Types Graphed with Applied Deviator Stress Levels (σ_3 = 34.5 kPa)

GRADATION CHANGES AFFECTING RUTTING MODEL PARAMETERS

The next step in this research effort involved analyzing the permanent deformation accumulation trends of the four materials tested at the source and engineered gradations in light of the rutting model framework (UIUC Rutting Model) proposed by Chow et al. [26]. Equation (1) presents the formulation of the UIUC Rutting Model.

$$\varepsilon_p(N) = AN^B {\sigma_d}^C \left(\frac{\tau_f}{\tau_{max}}\right)^D = AN^B {\sigma_d}^C \left(\frac{\tau_f}{c+\sigma_f tan\emptyset}\right)^D = AN^B {\sigma_d}^C SSR^D \qquad (1)$$

where

$\varepsilon_p(N)$ = Permanent strain (in %) corresponding to N-load application;
σ_d = Applied deviator stress;
τ_f = Shear stress acting on failure plane;
τ_{max} = Available shear strength at a normal stress (confinement);
c = Cohesion intercept;
ϕ = Friction angle;
σ_f = Normal stress acting on specimen failure plane; and
A, B, C, D = Regression parameters.

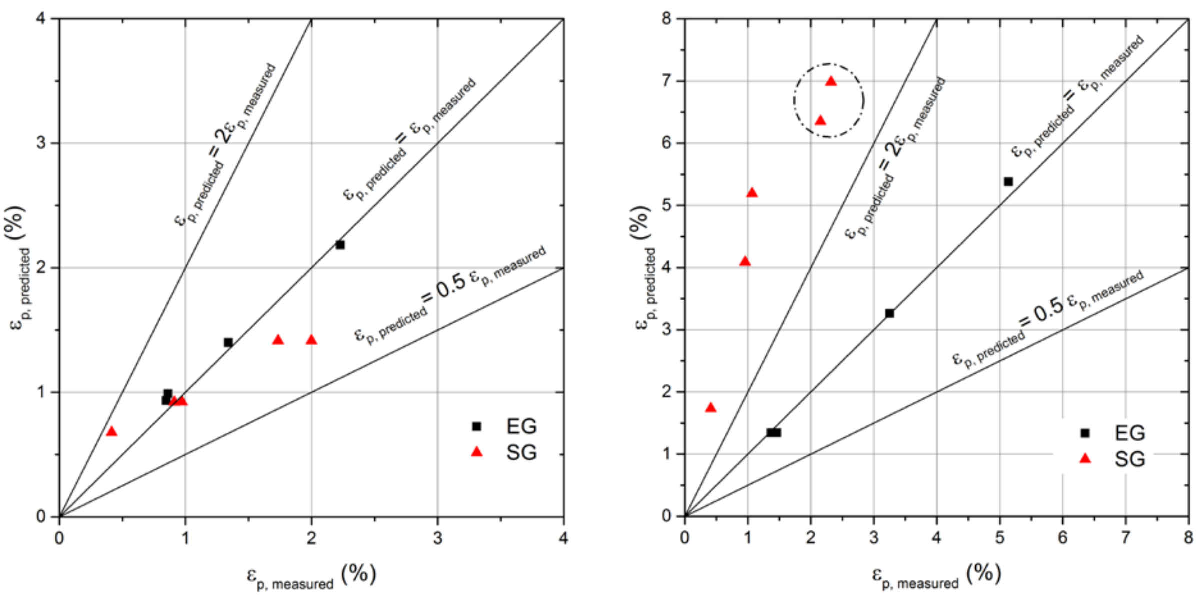
Table 3 lists the regression model parameters (*A* through *D*) for the four aggregate materials established from repeated load triaxial testing at EG and SG configurations. According to Table 3, the model parameters vary over a wide range as they are essentially coefficients corresponding to the least square errors between measured and predicted values of permanent strains. Detailed discussions and interpretations of individual model parameters are beyond the scope of the current paper. Nevertheless, the computed model parameters predict permanent deformations reasonably well as indicated by the high coefficient of determination (R^2) values given in Table 3. Chow et al. [25-27] present several recommendations to improve the engineering significance of these model parameters. For example, one suggested improvement involves forcing these regression model parameters to assume values within appropriate ranges that correspond to commonly observed aggregate behavior trends.

Table 3: UIUC Rutting Model Parameters for the Four Aggregate Materials Under Both the Source and Engineered Gradations

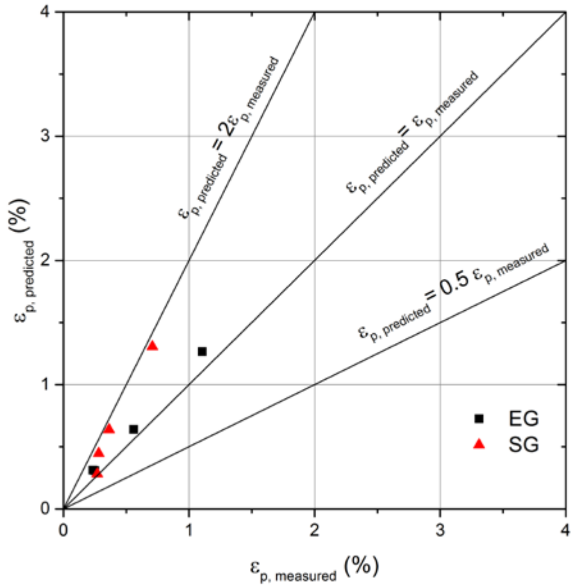
Material	Gradation	A	B	C	D	R^2
M1	SG	4.187E-3	0.1954	1.1840	(-0.2034)	0.998
	EG	3.778E-14	0.1959	6.7787	(-6.9203)	0.991
M2	SG	8.1828E-10	0.17715	5.3655	(-5.1513)	0.974
	EG	5.551E+00	0.1659	(-0.3291)	1.6501	0.982
M3	SG	5.1081E-12	0.0967	7.4817	(-8.2813)	0.981
	EG	2.838E-06	0.1045	3.7036	(-3.1253)	0.990
M4	SG	2.1531E-6	0.0857	3.4715	(-3.1729)	0.996
	EG	2.771E+02	0.1250	(-1.6669)	4.1391	0.994

A simple comparison of how accurately the model parameters established for one gradation can predict the permanent strain at a different gradation can be made to evaluate the sensitivity and reliability of the model parameters. First, the SSR values in the UIUC Rutting Model formulation (Equations 1 and 2) were adjusted to reflect the effects of different *c* and ϕ values. Since the SSR term in Equations (1) and (2) corresponds to a given set of *c* and ϕ values, which in turn correspond to a given grain size distribution for a particular material type, it is necessary to correct the SSR values when comparing the permanent deformation predictions for engineered and source gradations. For instance, model parameters *A*, *B*, *C* and *D* used in Figure 4(b) for material M2 were determined based on EG shear strength test results (ϕ = 37.7°; *c* = 43.4 kPa). When evaluating the predicted vs. measured results using SG data, the actual applied stresses are used to recalculate the SSR values and are used along with the EG model parameters (instead of using the predetermined SSR values of 0.25, 0.50 and 0.75 based on ϕ = 40.3° and *c* = 21.4 kPa corresponding to the SG). In other words, assuming 10,000 load cycles, the permanent strain values in Figure 4 were calculated based on SSR of applied deviator stress (σ_d) to the shear strength ($\tau_{max,\ EG}$) of the engineered gradation. The opposite is shown in Figure 5, where the SG model parameters are used for comparison. This facilitates analyzing the effects of applied stress states on permanent strain accumulation under consistent shear strength conditions.

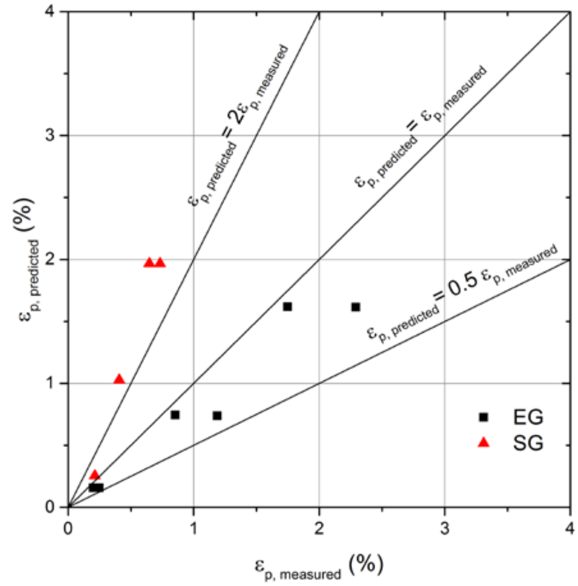
Figure 4 shows the predicted versus measured permanent strain values for each aggregate material. Overall, the predicted permanent strain values reasonably agree with the measured values for materials M1 and M3. On the other hand, the measured permanent strain values for materials M2 and M4 are highly overestimated for the source gradation (overestimation by nearly 200%). This is primarily due to the significant difference between the fines content at SG and EG configurations for these two materials; the model parameters in these cases are only valid for the engineered gradation. The circled data points correspond to SSR of 0.9, which is approaching the ultimate strength of material M2. This has reflected the model's capability to predict high deformations on heavily loaded specimens.



(a) (b)



(c)



(d)

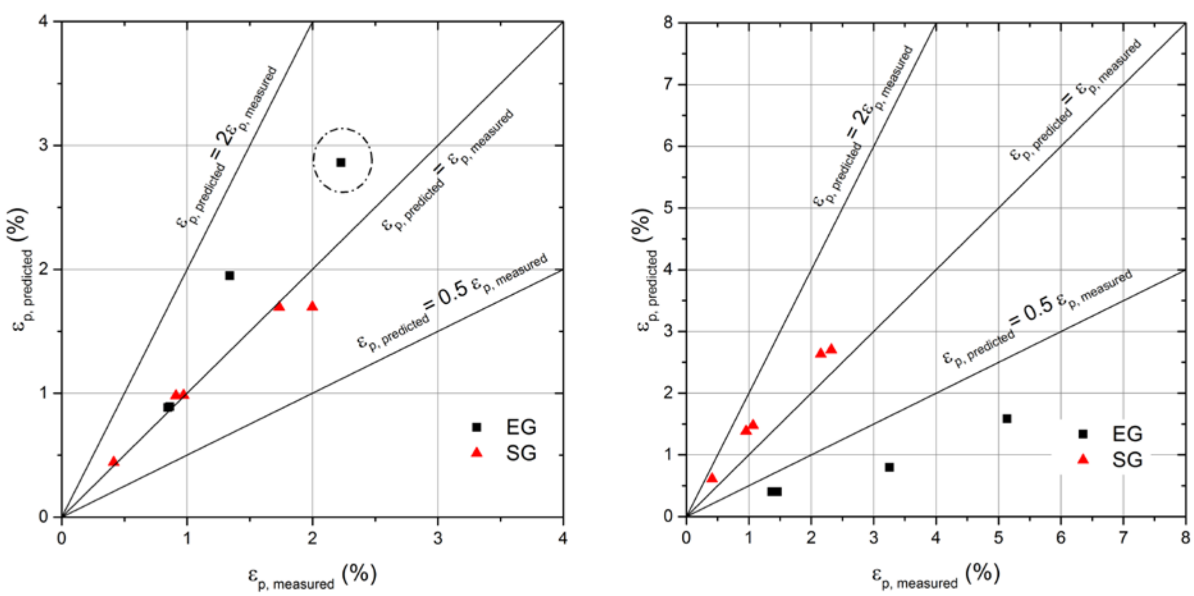
Figure 4: Predicted versus Measured Permanent Strains for All Repeated Load Triaxial Test Results based on Engineered Gradation Regressed Parameters: (a) Material M1; (b) M2; (c) M3 and (d) M4 *(note the change in axis scale for material M2)*

Figure 5 compares the predicted and measured results from the model parameters determined for source gradations. Once again, the predicted permanent strains of material M1 and M3 are reasonably accurate although the shear strength properties are notably different from the two gradations. The SSR computed for the data point circled in Figure 5(a) is over 1.0, which represents shear failure of the specimen under this particular applied stress state. A further investigation into the stress-strain relationship from the 34.5 kPa (5 psi) confinement shear strength test revealed that the strain at peak stress was roughly 2.5%. Clearly, the predicted value of 2.9% strain has reflected the measured 2.3% strain (see Figure 3) that was approaching failure. As expected, material M2 predicted permanent strain values were underestimated because the weaker engineered aggregate material with high plastic fines accumulated extremely high permanent strains. Based on the above observations, the model parameters as obtained through multiple linear regression method *work reasonably well given the shear strength properties are similar regardless of gradation variations*. This conclusion is most obviously drawn from the material M3 ϕ_s values listed in Table 2. When SSR is set to 0.5-0.75 of maximum, it is possible to determine an allowable stress based on ϕ and *c* to properly characterize viable range of permanent deformation accumulations without specimen failure.

SUMMARY AND CONCLUSIONS

This paper presented findings from an on ongoing research study at the University of Illinois aimed at developing and calibrating an improved permanent deformation model for unbound aggregate materials. The primary focus of this paper was to present a detailed discussion on the effects of varying grain size distribution on unbound aggregate shear strength and permanent deformation behavior. Results for four different aggregate materials were presented; and their shear strength properties and permanent deformation (PD) trends at the quarry source gradations (SG) were compared with the results obtained at the engineered gradations (EG). The study also looked at the effects of shear strength and shear stress ratio, SSR, (ratio between the shear stress applied to a specimen during repeated load triaxial testing compared to the corresponding shear strength under the same confinement) on the accumulation trends of permanent strain and the effect of changing the gradation on the accumulated rutting levels. The primary observations are as follows:

- The effects of varying grain size distribution on shear strength of aggregate materials were primarily dominated by the amount of fines passing No. 200 sieve. Material M2 with higher fines content, especially with plastic fines (i.e. PI = 6), was significantly weaker than the same material with lower fines content.
- Overall, the effects of gradation on permanent deformation accumulation were more noticeable at the higher shear stress ratio values. This was seen for materials M2 to M4, where the differences in accumulated permanent strains between samples tested at the source and engineered gradations were the highest for the SSR of 0.75 and the lowest for the SSR of 0.25.
- A very good correlation was obtained between the measured and the predicted permanent strain values with the UIUC predictive rutting model that considered both the SSR and the applied deviator stress levels along with the number of load applications.



(a) (b)

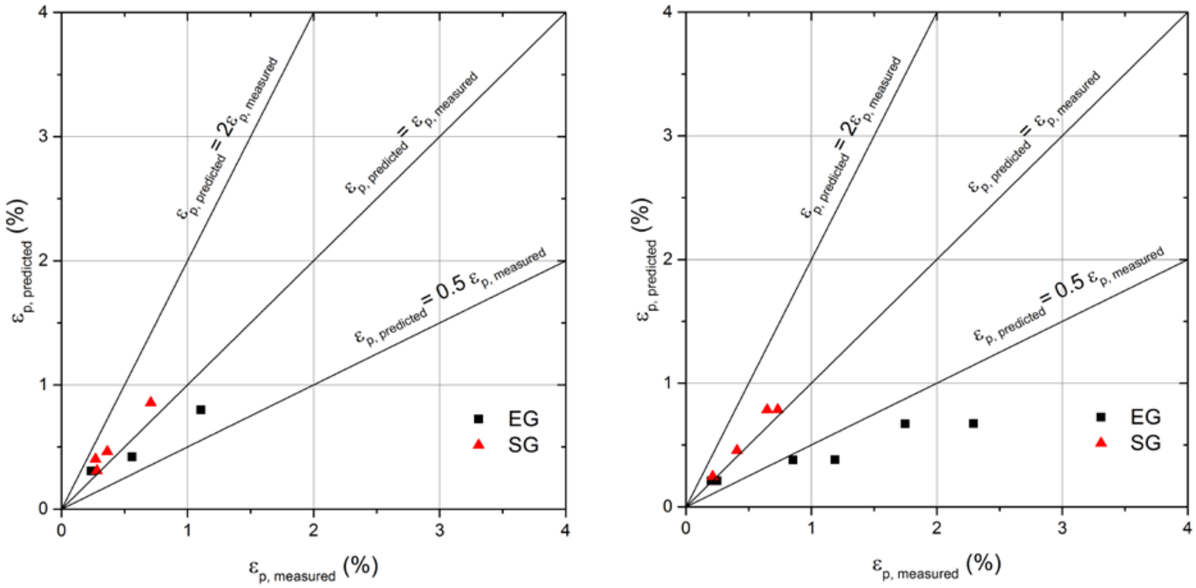


Figure 5: Plots of Predicted versus Measured Permanent Strain for All Repeated Load Triaxial Test Results based on Source Gradation Regressed Parameters: (a) Material M1; (b) M2; (c) M3 and (d) M4 *(note the change in axis scale for material M2)*

- For materials with similar EG and SG, for example, with similar fines content (e.g. M1 and M3); either the SG or EG rutting model parameters can be reasonably used to predict permanent deformation accumulation. On the other hand, if the gradations and fines contents are significantly different (M2 and M4), then high errors will result from using one set of model parameters at one gradation to predict the PD at a different gradation due to differences in shear strength properties. Whereas, the model parameters obtained from different gradations were found to work reasonably well given the shear strength properties are similar regardless of gradation variations.
- Shear strength properties (ultimately used in the calculation of SSR) and the applied stress levels clearly dictate the permanent deformation accumulation trends in aggregate materials. Gradation is also an important material property that contributes the permanent deformation accumulated at a certain level of mobilized shear loading.
- There is a definite need for more accurate mechanistic models to estimate the permanent deformation characteristics of unbound aggregate materials. This paper presented the effect of shear strength on the accumulation of permanent deformation in unbound materials, and the influences of gradation variability on the UIUC rutting model predictions. Certainly improvements are needed for adopting more physically relevant and consistent model parameters (A, B, C, and D), for example, for different gradations. Additional testing at different gradations will expand the current database and enhance the reliability and accuracy of the permanent deformation model predictions. When a large enough laboratory database is established, the model parameters assigned in the UIUC rutting model can be more confidently correlated to aggregate material types and characteristics, such as index properties, gradation, and shape properties.

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