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A Framework to Utilize Shear Strength Properties for Evaluating Rutting Potentials of Unbound Aggregate Materials

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Abstract

This paper presents shear strength and permanent deformation trends of four unbound aggregate materials, commonly used for base and subbase layers in the state of North Carolina, USA, studied through repeated load triaxial testing, using the University of Illinois FastCell equipment. A testing and modeling framework has been established to develop a proper permanent deformation prediction model, referred to herein as the UIUC rutting model, with number of load applications. According to the framework, the unbound aggregate shear strength properties are incorporated into the model using the ratio of the applied wheel load shear stress to the mobilized shear strength, i.e., the Shear Stress Ratio (SSR). This requires conducting repeated load permanent deformation tests at SSR values of 0.25, 0.5 and 0.75 to determine the trends in permanent deformation accumulation. The prediction ability of the developed UIUC rutting model is evaluated in this paper for the four materials tested at both an engineered target gradation and source gradations.

Keywords: Aggregate Gradation, Unbound Aggregate Testing, Permanent Deformation, Repeated Load Triaxial Testing, Triaxial Shear Strength Testing, Shear Stress Ratio, Aggregate Rutting Model

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1 Introduction

Rutting is the main performance indicator of 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 (PD) accumulation in unbound aggregate layers based on resilient strain levels without giving any consideration to aggregate shear strength. However, several research studies in the past (Tao, et al., 2010; Thompson, 1998) have established that aggregate shear strength plays a significant role in governing the base/subbase rutting

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potential under wheel loading.

Several predictive models for unbound aggregate base/subbase rutting have been proposed by researchers to predict permanent deformation accumulation with wheel load applications. Most of these models relate axial resilient strain in a specimen, or mid-layer vertical strain in a granular base/subbase, to the number of load repetitions. In 1975, Monismith et al. proposed the widely used log-log relationship between permanent strain and number of load cycles (Monismith, et al., 1975). Several commonly used unbound aggregate rutting models were proposed after 1990; such as, Wolff (Wolff, 1992), Thompson and Nauman (Thompson & Nauman, 1993), van Niekerk and Huurman (van Neekerk & Huurman, 1995) and Ullidtz (Ullidtz, 1997). Many of them were based on accelerated pavement testing or field tests, while others were based on repeated load triaxial testing as well as analytical discrete element solutions. Several researcher also studied stress state dependency of permanent deformation in granular materials. Lekarp and Dawson reported that failure of unbound aggregates under repeated loading was a gradual process and the applied stress states significantly affected the accumulation of permanent deformation (Lekarp & Dawson, 1998). Gidel proposed a stress dependent permanent deformation model based on the laboratory studies (Gidel, et al., 2001). Most recently Chow et al. proposed a permanent deformation model based on repeated load triaxial testing, and the model incorporated stress levels and shear stress ratios to predict the accumulation of permanent strain (Chow, et al., 2014a).

The research described in this paper builds on the Chow et al. (Chow, et al., 2014a; Chow, 2014b; Chow, et al., 2014c) study, which was intended to develop an unbound aggregate permanent deformation model for improved predictions of the field observed rutting trends of in-service unbound aggregate pavement layers. Totally, sixteen unbound materials, commonly used in the State of North Carolina (NC), USA for aggregate base/subbase layers, were tested at one fixed engineered gradation during this first phase of the study. The second and recently initiated phase was to also evaluate four of the materials studied next for the permanent deformation trends at their source gradations. The goal was to investigate the applicability of the developed rutting model to accurately predict permanent strain accumulations at different source gradations. Realistically, these were the size distributions of as received aggregate materials used in the construction of unbound base/subbase layers.

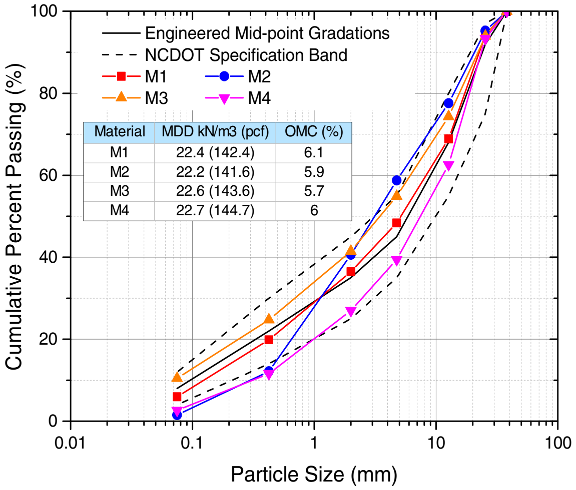
This paper presents the testing and modeling results of the four NC aggregate materials studied at both an engineered (controlled) target gradation and the source gradations. The shear strength properties of each material were determined through monotonic triaxial shear tests at both source gradations and the engineered gradation. The Mohr-Coulomb failure envelopes were established, then the permanent deformation accumulation behavior at different stress states (three different shear stress ratios) were evaluated. Rutting model parameters established from the laboratory data at source gradations are compared with those established at the engineered gradation to assess their sensitivity to grain size distribution changes.

2 Material Description

Four aggregate materials, denoted here as M1, M2, M3 and M4, were tested. Each material was tested for shear strength and permanent deformation behavior at both the engineered gradation and source gradations. The first step in the test matrix involved carrying out sieve analysis for each aggregate material to determine the source gradation curve.

Figure 1 shows the source gradation curves for the four materials as well as the fixed engineered gradation used during the first phase of the study. The engineered gradation was chosen as the mid-range of the gradation band permitted by NC Department of Transportation (DOT) for typical base/subbase unbound aggregate materials. The source gradation for M1 closely resembles the engineered gradation, while some portions of the source gradation curves for M2 and M4 differ significantly from the engineered gradation curve.

The aggregate materials were visually classified for rock type: materials M1, M3 and M4 are geologically classified as granite, whereas material M2 is rhyolite. Moisture-density curves were also established for the four materials following the NCDOT compaction procedure, which follows the AASHTO modified compaction method (AASHTO T180), but applies 86 blows per layer, instead of 56. The optimum moisture content (OMC) values for the four materials ranged from 5.7% to 6.1%, and the maximum dry density (MDD) values ranged from 22.2 kN/m^3 (141.6 pcf) to 22.7 kN/m^3 (144.7 pcf), as shown in Figure 1. Additionally, material M2 is the only aggregate material in this study that has plastic fines, with a plasticity index of 6.



Material	MDD kN/m3 (pcf)	OMC (%)
M1	22.4 (142.4)	6.1
M2	22.2 (141.6)	5.9
M3	22.6 (143.6)	5.7
M4	22.7 (144.7)	6

Figure 1: Engineered Mid-range Gradation and Source Gradations for the Tested Aggregate Materials

3 Shear Strength Test Results

Monotonic triaxial shear tests were performed on each material at the source gradation (SG) and the mid-range engineered gradation (EG) to establish the shear strength properties: friction angle and cohesion intercept; defining the Mohr-Coulomb failure envelope. Test specimens, 152 mm (6 in.) in diameter and 305 mm (12 in.) tall, were compacted under OMC and MDD conditions 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. Each material was tested at the SG and EG with a minimum of three tests conducted at the confining pressure levels of 35 kPa (5 psi), 69 kPa (10 psi), and 103 kPa (15 psi).

Table 1 summarizes the shear strength properties (c and ϕ) for the four materials at the source and engineered gradations. Material M1 has a significantly lower cohesion intercept (c) at the SG compared to the value at the EG. However, the friction angles for the two gradations are very close. This discrepancy in the shear strength properties might have been caused by the higher fines content (percent passing the No. 200 sieve or smaller than 0.075 mm) for the EG (8%) compared to the SG (6%). The slightly higher fines content at the EG for M1 may have contributed to the higher shear strength values. Note that previous studies have observed that dense graded aggregates achieve the maximum shear strength at approximately 8% fines content (Seyhan & Tutumluer, 2002). Similar trends are shown for material M3. The largest change in friction angle between the two gradations was found for material M2 (40.3° at SG; 37.7° at EG). M2 is the only material with plastic fines. The presence of 8% plastic fines at EG make the matrix significantly weaker compared to 1.5% plastic fines at the SG. Material M4, on the other hand, has 2.6% fines at SG, but no significant change in the c and ϕ values for this material were observed at the two gradations.

The shear strength test results presented in Table 1 indicate that one of the major factors having significant influence on the shear strength properties is the fines content (percent passing the No. 200 sieve or smaller than 0.075 mm). Crushed aggregate materials with approximately 8% fines are often more stable from the shear strength tests when compared to those with significantly lower or higher fines contents. This is generally valid as long as the fines are nonplastic in nature. Plastic fines commonly have more drastic effects on the shear strength behavior of unbound aggregate materials.

	Source Gradations (SGs)			**Engineered Gradation (EG)**		
Material	P_{200} (%)	Friction Angle, ϕ (degrees)	Cohesion, c kPa (psi)	P_{200} (%)	Friction Angle, ϕ (degrees)	Cohesion, c kPa (psi)
M1	6.0	39.4	55.1 (8.0)	8.0	39.3	160.6 (23.3)
M2	1.5	40.3	48.9 (7.1)	8.0	37.7	43.4 (6.3)
M3	10.5	40.0	21.4 (3.1)	8.0	41.4	19.3 (2.8)
M4	2.6	48.1	13.1 (1.9)	8.0	48.8	3.4 (0.5)

Table 1: Shear Strength Properties of the Four NCDOT Materials at Source and Engineered Gradation

4 Evaluating Unbound Aggregate Rutting Models for Dynamic Stress States

Repeated load triaxial tests were carried out to monitor the permanent deformation accumulation trends of each of the four aggregate materials at the two different gradations. Each material was tested at stress levels corresponding to SSR values of 0.25, 0.50 and 0.75, which correspond to the ratios of applied shear stress magnitudes mobilized on the failure plane to the shear strength properties of the material achieved under the same confining pressure. Detailed discussions on the concept of SSR have been presented elsewhere (Chow, et al., 2014c). 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 using the University of Illinois FastCell (UI-FastCell) advanced triaxial equipment at a confining pressure of 34.5 kPa (5 psi). Typically 10,000 load cycles were applied at each stress level, using a haversine-shaped load pulse with a 0.1s pulse time, and 0.9s rest period.

Figure 2 shows the permanent strains accumulated at 10,000 loading cycles for the four materials having the two different gradations tested at the corresponding stress states and SSR values. An example for the accumulation of permanent deformation at different SSRs is shown in Figure 3. The higher SSR levels consistently resulted in higher permanent strain accumulations for all material types and gradations.

As shown in Figure 2, material M2 accumulated the highest permanent strain (>5%) at the EG for the 0.75 SSR test. This can be closely linked to the plasticity of materials passing the No. 40 sieve present in this material. At the EG, the material M2 comprised 22% of plastic materials passing the No. 40 sieve (0.425 mm); while at the SG, it comprised only 12% materials finer than No. 40. The same material (M2) accumulated significantly lower amounts of permanent strain at the SG. A similar trend was also observed for material M4, for which the lower percentage passing the No. 40 sieve at the SG (11.5 % vs. 22% finer than 0.425 mm) led to lower permanent strains. On the other hand, material M3 showed only a slightly opposite trend of percent passing the No. 40 sieve and permanent strain.

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 of 0.75, and lowest at SSR of 0.25. Thus, the effects of gradation on aggregate permanent deformation behavior becomes more significant as the applied stress levels approach closer to the shear strength failure values of the materials. Additionally, permanent strain accumulated after 10,000 load cycles appears to vary linearly with applied deviator stress levels, and exponentially with SSR. This linear trend was also previously seen for other aggregate materials by Chow et al. (Chow, et al., 2014a).

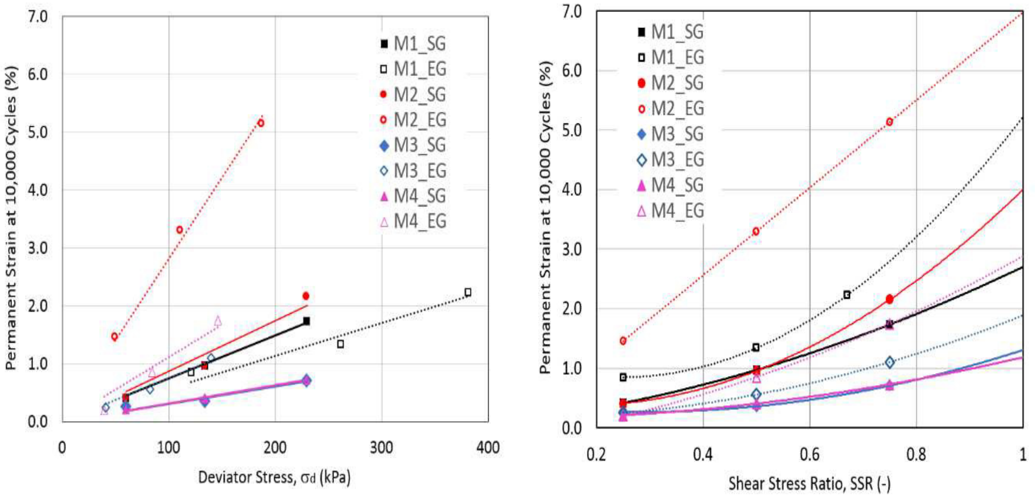


Figure 2: Permanent Strain Values after 10,000 cycles for the four materials graphed with applied deviator stress levels and SSR values (σ_3 = 34.5 kPa = 5 psi)

5 UIUC Rutting Model

Following the comprehensive laboratory characterization of the materials, the following step involved fitting the permanent deformation accumulation trends of the four materials with the previously developed UIUC rutting model by Chow (Chow, 2014b). The formulation of the model is presented in equation 1 below.

$$\varepsilon_p(N) = AN^B {\sigma_d}^C SSR^D \tag{1}$$

where

SSR Shear Stress Ratio = $\frac{\tau_f}{\tau_{max}} = \frac{\tau_f}{c+\sigma_f tan\emptyset}$;
$\varepsilon_p(N)$ 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 Apparent cohesion intercept;
ϕ Friction angle;

σ_f	Normal stress acting on specimen failure plane; and
A, B, C, D	Regression parameters.

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

Table 2: UIUC Rutting Model Parameters for the Four Aggregate Materials at the Source and Engineered Gradations

Table 2 lists the regression model parameters (*A* through *D*) for the four aggregate materials established from the repeated load triaxial testing at EG and SG. Note that 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) and as seen in Figure 3 for materials M1 and M2, where the solid lines indicate laboratory conducted tests at different SSR values and the dashed lines are for the corresponding model predictions. Chow et al. (Chow, et al., 2014c) 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. This work is currently underway and will be presented elsewhere.

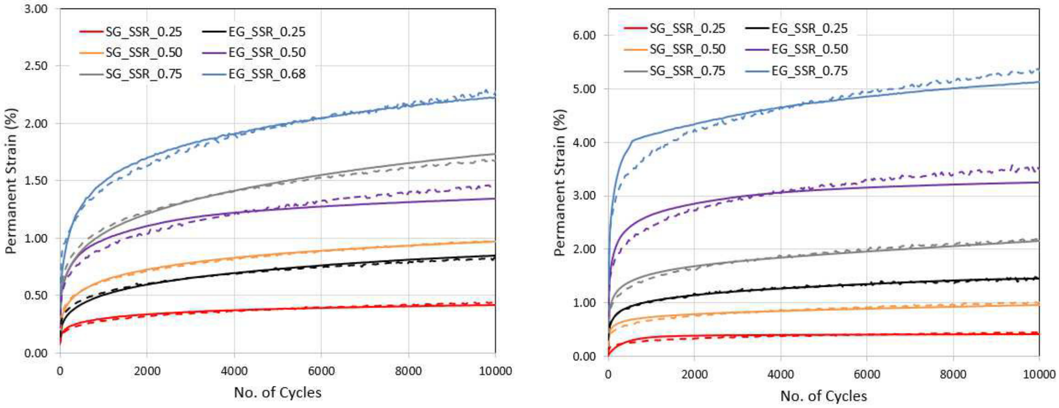
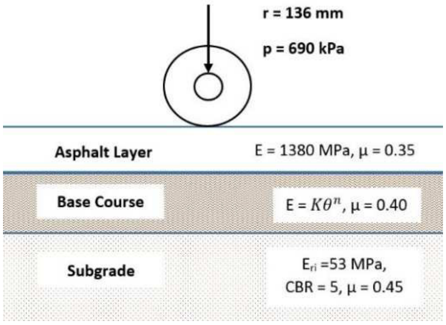


Figure 3: Permanent Strain Accumulations in Aggregate Materials M1 (Left) and M2 (Right) at Different SSR Levels and Gradations. *Solid lines represent experimental data and dashed lines represent UIUC rutting model predictions*

6 Implementing the UIUC Rutting Model in Pavement Design

The following discussion presents a recommended implementation of the UIUC permanent deformation model to predict the in-service rutting trends of unbound aggregate materials used in flexible pavement base and subbase layers. Three different road scenarios of conventional flexible pavement road sections carrying low, moderate and high volumes of traffic were considered for analysis using ILLI-PAVE 2000 software. The typical thicknesses and material properties for each road scenario are shown in Figure 4. ILLI-Pave 2000 software was used to analyze 6 different cases for each material at both SG and EG; for SSR values of 0.25, 0.50 and 0.75 for each gradation. The mid-depth stress states in the unbound base layers were computed under the center line of the wheel.

For the base coarse (BC) layer, the stress dependent resilient modulus properties of the four unbound materials were used as inputs. These were obtained from laboratory resilient modulus tests at the source gradation following the AASHTO T307 test procedure. The resilient modulus test results were fitted with the K-θ model; $M_R = K(\theta/p_0)^n$ (Hicks & Monismith, 1972) to account for stress-dependent resilient modulus behavior. The K values for materials M1 through M4 were 17 MPa (2.5 ksi), 13.9 MPa (2.0 ksi), 11.8 MPa (1.7 ksi), and 15.2 MPa (2.2 ksi) respectively, whereas the corresponding n values were 0.59, 0.60, 0.68, and 0.62, respectively.



Road Scenario	***AC Thickness***	***BC Thickness***
	mm (in.)	mm (in.)
Low Volume	76 (3)	203 (8)
Moderate Volume	152 (6)	203 (8)
High Volume	229 (9)	254 (10)

Figure 4: Geometry and Layer Properties for the Conventional Flexible Pavement Scenarios Analyzed

Figure 5 presents the predicted permanent strains computed from the UIUC rutting model. The permanent strains were predicted at 10,000 load repetitions. The SSR values were calculated from the shear strength properties determined for each aggregate material at the SG and EG from the laboratory study. The SSR was computed with an assumption of a 34.5 kPa (5 psi) confining pressure, although the values computed from ILLI-PAVE were different for each case; and ranged from below 6.9 kPa (1 psi) to 48.3 kPa (7 psi). The 34.5 kPa (5 psi) confining pressure assumption closely simulates typical confining pressure levels in the field considering typical residual compaction stresses locked-in the granular base during pavement construction and subsequent trafficking.

Different levels of permanent deformation were accumulated in each material tested at the engineered and source gradations. The highest permanent deformation accumulation was for the case of low volume roads, where the deviator stress calculated for the unbound layer at mid-depth and the corresponding SSR values were the highest. Additionally, the shear strength properties (cohesion and friction angle) and the change of shear properties with gradation are also affecting the computed SSR and the rate of rutting accumulation. For example, material M4 will experience a shear stress higher than its shear strength (SSR = 1.03) at the EG for the low volume road, indicating premature failure, while in the case of the SG, the SSR of 0.88 indicates that the material can survive many more load repetitions. Thus, given similar stress states, design alternatives with different materials will require estimating the SSR levels to evaluate field rutting accumulation to prevent premature failure. The accumulated permanent strains might be low, but the higher SSR may result in a premature movement into the incremental collapse (Zone C) of the material according to the theory of shakedown of unbound materials (Werkmeister, et al., 2004).

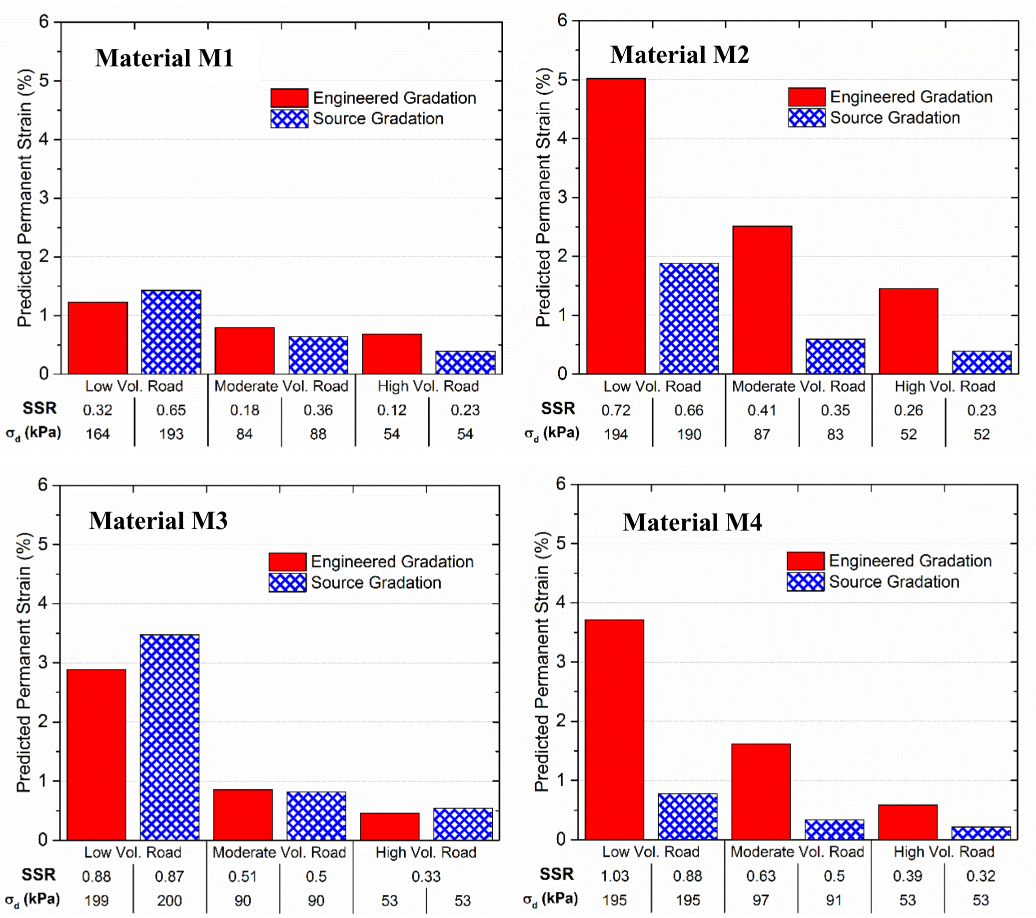


Figure 5: Model predicted permanent deformations for the three road scenarios at the engineered and source gradations (N = 10,000 load cycles)

7 Summary and Conclusions

This paper presented findings from an on ongoing study aimed at developing an improved permanent deformation model for unbound materials. The model takes into account the effects of stress states, shear strength, number of load applications, and varying grain size distribution on unbound aggregate permanent deformation behavior. Results of the shear strength and permanent deformation tests were presented for four different aggregate materials both at the quarry source gradations (SG) and a controlled engineered gradation (EG). The primary observations are as follows:

- The effects of varying grain size distribution on shear strength properties of aggregate materials were primarily dominated by the amount of fines passing No. 200 sieve. Material M2, with higher plastic materials passing No. 40 sieve at the EG, was significantly weaker than the same material with lower plastic material content at the SG.

- Overall, the effects of grain size distribution on permanent deformation accumulation were more noticeable at the higher shear stress ratio (SSR) values. This trend was seen for materials M2, M3, and M4, where the differences in accumulated permanent strains between samples tested at the SG and EG were the highest at the SSR of 0.75 and the lowest at the SSR of 0.25.
- Close predictions of the laboratory measured permanent strains were obtained from the UIUC predictive rutting model, which considers the SSR, stress state (the applied deviator stress levels) and the number of load applications.
- Shear strength properties (ultimately used in the calculation of SSR) and the applied stress levels clearly dictated the permanent deformation accumulation trends in aggregate materials. Gradation was also a major material property that contributed to the permanent deformation accumulated at a certain SSR.

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