Characterization and Prediction of Permanent Deformation Properties of Unbound Granular Materials for Pavement ME Design [1]

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Abstract

The objective of this study is to characterize and predict the permanent deformation properties of unbound granular materials (UGMs) for Pavement ME Design. First, laboratory repeated load triaxial (RLT) tests are conducted on the UGMs from 11 quarries in Texas to measure the permanent strain curves. The shakedown theory is applied to evaluate the permanent deformation behavior of the selected UGMs. It is found that using Werkmeister’s criteria to define the shakedown range boundaries is not suitable for the selected UGMs. Under this circumstance, new criteria are proposed to redefine the shakedown range boundaries for the flexible base materials in Texas. The new criteria are consistent with the current Texas flexible base specification in terms of aggregate classification. Second, the mechanistic-empirical design guide (MEPDG) model is used to determine the permanent deformation properties of the selected UGMs on the basis of the measured permanent strain curves. The determined permanent deformation properties are assigned as target values for the development of permanent deformation prediction models. Third, a series of performance-related base course properties are used to comprehensively characterize the UGMs, which include the dry density, moisture content, aggregate gradation, morphological properties, percent fines content, and methylene blue value. These performance-related base course properties are assigned as the inputs of the permanent deformation prediction models. Fourth, a multiple regression analysis is conducted to develop the prediction models for permanent deformation properties using these performance-related properties. The developed models are capable of accurately predicting the permanent deformation properties of UGMs. Compared to other prediction models (e.g., simple indicators-based models and Pavement ME Design models), the developed models have the highest prediction accuracy. It is also found that the Pavement ME model-predicted permanent strains are much lower than those measured from the RLT tests. This demonstrates that the current Pavement ME Design software substantially underestimates the rutting that occurs in base course. Finally, the developed prediction models are validated by comparing the predicted and measured permanent strains of other four base materials. The obtained R-squared value of 0.81 indicates that the developed models have a desirable accuracy in the prediction of permanent deformation properties of UGMs.

Keywords: Unbound Granular Material; Permanent Deformation; Performance Prediction; Pavement ME Design

Introduction

Unbound base layer is laid between asphalt concrete and subgrade in flexible pavements. Its main function is to provide the support for asphalt concrete and protect subgrade from severe permanent deformation (rutting) [1]. Pavements become prone to rutting when the unbound base can only poorly bear the stresses induced by the repeated traffic loads. Therefore, the permanent deformation behavior of unbound granular material (UGM) plays a significant role in the evaluation and prediction of the performance of unbound base layer in the field [2-3].

Currently, the most popular approach to determine the permanent deformation properties of UGM is by conducting the laboratory repeated load triaxial (RLT) test. The response of an UGM specimen under repeated loading is divided into a resilient (recoverable) strain and a permanent (unrecoverable) strain. The recoverable behavior is characterized by the resilient modulus of UGM. The permanent strain accumulated under load repetitions is used to describe the permanent deformation behavior [4]. To evaluate the permanent deformation properties of UGM, the shakedown theory has been widely used by pavement design practitioners [5-7]. According to this theory, the UGMs are categorized as three groups:

- Range A – plastic shakedown: the response is plastic only for a finite number of load repetitions, and becomes resilient after post-compaction;
- Range B – plastic creep: the level of permanent strain rate decreases to a low and nearly constant level during the primary stage; and
- Range C – incremental collapse: the permanent strain rate decreases slowly, and permanent strain accumulation does not cease.

In pavement design, the pavement must be able to resist permanent deformation. To ensure that pavement has desirable rutting resistance, the pavement design guide suggests to select the base materials from Range A and Range B, and avoid using the base materials from Range C [7]. To define the shakedown range boundaries, Werkmeister proposed the following criteria [8]:

- Range A: $\varepsilon_{p,5000} - \varepsilon_{p,3000} < 4.5\times10^{-5}$
- Range B: $4.5\times10^{-5} < \varepsilon_{p,5000} - \varepsilon_{p,3000} < 4.0\times10^{-4}$
- Range C: $\varepsilon_{p,5000} - \varepsilon_{p,3000} > 4.0\times10^{-4}$

where $\varepsilon_{p,5000}$ is the accumulated plastic strain at the 5000th load cycle, and $\varepsilon_{p,3000}$ is the accumulated plastic strain at the 3000th load cycle. However, these criteria are developed merely based on a limited number of RLT test results. Whether these criteria are suitable for other base materials are still unknown. Thus, the Werkmeister's criteria should be revisited and reevaluated for local base materials.

In order to characterize the permanent deformation properties of UGM, various models have been developed to determine the relationship between the accumulated permanent strain and the number of load cycles. The most commonly used model is the Tseng-Lytton model as shown in Equation 1 [9].

$$\varepsilon^{p} = \varepsilon_0 e^{-(\frac{\rho}{N})^{\beta}} \tag{1}$$

where ε^{p} is the permanent strain of the granular material; ε_0 is the maximum permanent strain; N is number of load cycles; ρ is a scale factor; and β is a shape factor. ε_0, ρ and β are the permanent deformation properties. However, in this form, it does not consider the stress effect, which significantly affects the permanent deformation behavior of UGM [10-11]. To consider the stress effect, the mechanistic-empirical design guide (MEPDG) modified the Tseng-Lytton model by converting the plastic strain measured from the laboratory to the field condition [12].

$$\varepsilon_p = \beta_s \left(\frac{\varepsilon_0}{\varepsilon_r} \right) e^{-\left(\frac{\rho}{N}\right)^{\beta}} \varepsilon_v \tag{2}$$

where β_s is a global calibration coefficient; ε_r is the resilient strain imposed in the laboratory test; and ε_v is the average vertical resilient strain in the base layer of the flexible pavements. As seen from Equation 2, the MEPDG model considers the effect of stress level on permanent deformation by linearly projecting the plastic deformation obtained from the laboratory tests to the plastic deformation of the pavement base layer in the field through vertical strains [13]. In this model, the permanent deformation properties (i.e., $\frac{\varepsilon_0}{\varepsilon_r}$, ρ and β) are determined through a regression analysis of the RLT test data. The RLT test method is accurate and reliable, but meanwhile such a test is complex and time-consuming, which requires experienced personnel to operate the test machine and analyze the data. These become major obstacles to applying the permanent deformation properties in quality control and quality assurance of base course construction [14].

In order to overcome the limitations associated with the RLT test, using prediction models to estimate the permanent deformation properties of UGM has attracted more and more attention recently [2, 9, 15-17]. In this approach, the permanent deformation properties are usually correlated to a group of performance indicators which can be efficiently measured from other simple tests. Equations 3-5 present the prediction models that are recommended by Pavement ME Design [12].

$$\left(\frac{\varepsilon_0}{\varepsilon_r}\right)=\frac{\left(e^{(\rho)^{\beta}}\times 0.15\right)+\left(e^{\left(\rho/10^9\right)^{\beta}}\times 20\right)}{2} \tag{3}$$

$$\log\beta=-0.61119-0.017638\omega_c \tag{4}$$

$$\rho=10^9\times\left(\frac{-4.89285}{\left[1-\left(10^9\right)^{\beta}\right]}\right)^{1/\beta} \tag{5}$$

where ω_c is the moisture content of UGM (%). These prediction models correlate the permanent deformation behavior only to the moisture content of UGM, which do not take into account the physical properties of coarse and fine aggregates. However, the existing studies demonstrated that these physical properties of aggregates (e.g., gradation, angularity and shape) significantly affect the permanent deformation behavior of UGM [18-21]. Thus, new prediction models should be developed for Pavement ME Design in a manner that permanent deformation properties of UGMs are correlated to a series of performance-related base course properties.

To address the aforementioned research needs, this study aims to develop new models for predicting the permanent deformation properties of UGM. The performance-related base course properties are first identified. The laboratory triaxial tests and performance-related indicator tests are then performed on 14 types of UGMs. The shakedown theory is applied to evaluate the permanent deformation behavior of the selected UGMs. New criteria are proposed to define the shakedown range boundaries for flexible base materials in Texas. Subsequently, a statistical analysis is conducted to investigate the significant variables that are related to the permanent deformation properties of granular material. The prediction models are developed to estimate the permanent deformation properties of UGM using the identified significant variables. The developed prediction models are compared to other prediction models (e.g., Pavement ME Design models and simple indicator-based prediction models) in terms of the prediction accuracy. Finally, the prediction models are validated by comparing the model-predicted results to the laboratory-measured data of other four types of UGMs.

Selection of Performance-Related Base Course Properties

The selection of performance-related base course indicators is crucial to accurately estimate the permanent deformation properties of UGM. There are many property indicators used to characterize the flexible base materials. Typical properties used in Texas include particle size gradation, plasticity index, liquid limit, wet ball mill value, dry density and moisture content [14]. Other properties used by other specifying agencies include LA abrasion value and sand equivalent value. Among these properties, particle size gradation, dry density and moisture content are considered as basic performance indicators. Wet ball mill value and LA abrasion are used specially to evaluate the durability of coarse aggregates, while Atterberg limits and sand equivalent are applied to fine aggregates [22]. The existing studies focused on the prediction of the permanent deformation properties of UGM using these indicators [9, 15-16]. However, these indicators are usually empirical and not directly related to the performance of flexible base materials [14].

In recent years, many performance-related tests are investigated to evaluate flexible base materials, such as aggregate imaging system (AIMS) test, methylene blue test, and percent fines content (PFC) test. The AIMS test is used to characterize the shape, angularity and texture properties of aggregates [23-24]. The cubic-shaped aggregates were found to be more susceptible to permanent deformation than the crushed aggregates. The aggregate matrix specimens with lower angularity index and surface texture index correspond to a higher permanent strain in the base course [25-26]. Therefore, these aggregate morphological indices have potential to correlate to the engineering properties of UGM. The methylene blue test is used to measure the amount of moisture active clay particles in the aggregate matrix. It is proven that the methylene blue test has less variability compared to the plasticity index test [27]. The higher Methylene Blue Value (MBV) indicates that the fines in the base material have higher plasticity, which has a negative effect on the performance of the base course. For example, AASHTO T330 considers the expected performance of base course to be a failure, if its MBV is higher than 20 [28]. The PFC test is used to evaluate the total clay content in fine aggregates [29]. Clay is defined as the particles smaller than 2 microns according to the identification and classification of soils [29]. The clay content is a critical factor that controls moisture susceptibility, swelling, shrinkage, and plasticity of soils, which affects the performance of flexible bases.

Materials and Test Methods

This section presents the materials and laboratory test methods used to predict the permanent deformation properties of base courses.

Laboratory Experiments

The following laboratory tests were conducted in this study:

- RLT test that was used to determine the permanent deformation properties of UGMs;
- Tests to measure performance-related base course properties, including AIMS test for coarse aggregates, methylene blue test and PFC test for fine aggregates.

The RLT test was conducted on the cylindrical UGM specimens through the Material Testing System (MTS). The sample fabrication and testing procedure followed the standard AASHTO T 307 [30]. The permanent deformation test was conducted at a level of 137.9 kPa deviatoric stress with 48.3 kPa confining pressure. This recommended stress state was determined according to the finite element calculation of the stress response of the middle of an aggregate layer in a typical pavement structure under a standard traffic load when considering the nonlinear cross-anisotropic behavior of the base course. The static confining pressure and haversine-shaped deviator stress with 0.1 second load period and 0.9 second rest period were applied to the specimen for 10,000 cycles. During each test, two Linear Variable Differential Transformers (LVDTs) mounted on the middle-half of the specimen were used to measure the vertical deformation of the specimen. The test data were used to determine the permanent deformation properties of UGMs.

The tests to measure the performance-related base course properties were detailed described at Gu et al. [4]. These required tests were simpler, lower cost, and more efficient than the RLT test.

Materials

Base materials used in this study are selected from different quarries in Texas. These quarries are selected in attempts to capture the geographic, mineralogical, and production volume diversity of typical sources used for Texas Department of Transportation (TxDOT) projects. In this study, 14 types of base materials are used to develop the permanent deformation prediction models, and other 4 types of base materials are selected to validate the prediction accuracy of the developed models. Most of the selected base materials are tested at their optimum moisture contents. To investigate the influence of moisture content, 3 types of base material are fabricated at three different moisture contents.

Results and Discussion

Determination of Permanent Deformation Properties of UGM

Figure 1 presents the relationship between the accumulated plastic strain of the selected UGMs and the number of load cycles. In the legend of Figure 1, the letter represents the different source of the selected UGM, the number represents the number of times that the material is obtained, the symbol "+" indicates the specimen is compacted above the optimum moisture content, and the symbol "-" means that the specimen is fabricated below the optimum moisture content. For instance, "B02" stands for the material from the quarry B that is picked up at the second time. In this study, the base materials "B02", "E01", and "H01" are selected to fabricate at three different moisture contents (i.e., optimum, above the optimum, and below the optimum moisture content). As seen from Figure 1, most of the selected base materials only experience the primary stage and secondary stage under the current load protocol. The primary stage has a high initial permanent deformation, with a decreasing rate of change of plastic strains. The secondary stage has a constant rate of change of plastic strain. The accumulated plastic strain of "B02+" exceeds the measurement upper limit during the test.

The measured plastic strain curves are used to determine the permanent deformation properties in Equation 1. Table 1 presents the determined permanent deformation properties of the selected UGMs. The resilient strains corresponding to the 500th load cycle are also recorded and shown in Table 1. By inputting these data into the MEPDG model, the rutting behavior of unbound base can be predicted at any given pavement structure and number of load repetitions. These determined permanent deformation properties will be assigned as target values to develop the permanent deformation prediction models.

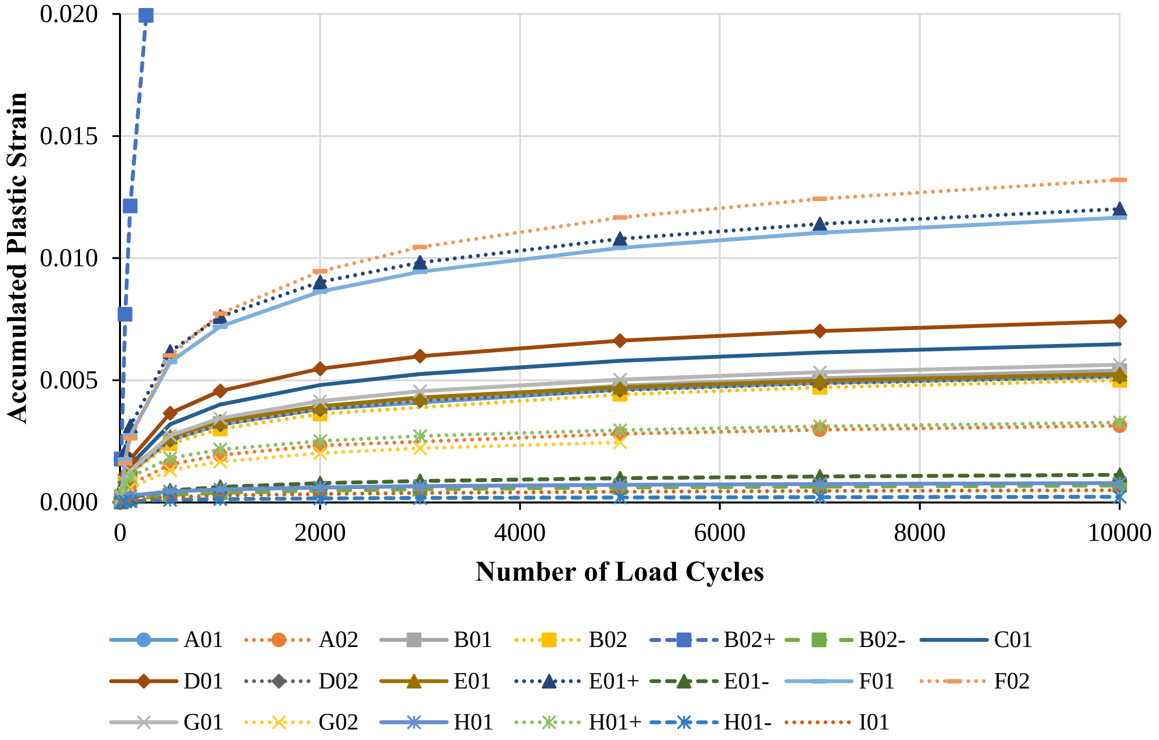

Figure 1. RLT Test Results of the Selected Unbound Granular Materials

Table 1. Determined Permanent Deformation Properties of Unbound Granular Materials

Source Type	ε_0	ρ	β	ε_r at 500th load cycle
A01	8.38E-03	890	0.301	3.89E-04
A02	5.04E-03	860	0.305	3.07E-04
B01	9.32E-03	940	0.287	3.59E-04
B02	1.28E-02	1500	0.246	4.06E-04
B02+	2.00E-02	1570	0.303	3.58E-03
B02-	1.24E-03	1520	0.302	2.23E-04
C01	1.04E-02	860	0.305	8.81E-04
D01	1.23E-02	970	0.293	3.85E-04
D02	4.86E-03	940	0.292	3.25E-04
E01	1.98E-03	820	0.31	3.12E-04
E01+	1.21E-02	810	0.289	4.36E-04
E01-	1.08E-03	1560	0.303	2.26E-04
F01	2.19E-02	900	0.3	4.23E-04
F02	2.24E-02	1230	0.304	4.82E-04
G01	9.19E-03	950	0.302	3.61E-04
G02	4.50E-03	980	0.31	2.28E-04
H01	1.42E-03	980	0.1	1.92E-04
H01+	1.21E-02	810	0.289	2.26E-04
H01-	1.08E-03	1560	0.303	8.36E-05
I01	8.57E-04	1530	0.305	3.95E-04

Characterization of Permanent Deformation Behavior of UGM

In this study, the shakedown range criteria are reevaluated for flexible base materials in Texas. Table 2 presents the grading results of the tested base materials based on the Werkmeister's criteria and the TxDOT's specification (i.e., Item-247). According to Item-247, the flexible base materials are classified as 4 grades in terms of aggregate gradation, Atterberg limits, wet ball mill value, and unconfined and confined compressive strength [31]. The Grade 1 and Grade 2 aggregates are preferred to use in the base course construction. As seen from Table 2, most of the UGMs used in this study are in Range C (i.e., incremental collapse) according to Werkmeister's criteria. This implies that these base materials should be avoided using in base course. However, according to the TxDOT's specification Item-247, most of these materials are in Grade 2, which is recommended to base course construction. This contradiction demonstrates that the Werkmeister's criteria needs to be adjusted for the base materials in Texas. In order to be accordance with the TxDOT's specification, new criteria are needed to define the shakedown range boundaries, which are presented as follows.

- Range A: $\varepsilon_{p,5000} - \varepsilon_{p,3000} < 6.0\times10^{-5}$
- Range B: $6.0\times10^{-5} < \varepsilon_{p,5000} - \varepsilon_{p,3000} < 6.0\times10^{-4}$
- Range C: $\varepsilon_{p,5000} - \varepsilon_{p,3000} > 6.0\times10^{-4}$

Table 2 also presents the classification results of the selected UGMs using the new criteria. It is shown that the new criteria are in good agreement with Tex-247 in terms of these classification results.

Table 2. Grading Results of Tested Base Materials Using Werkmeister's Criteria, New Criteria and Tex-247

Source Type	$\varepsilon_{p,5000} - \varepsilon_{p,3000}$	Werkmeister's Criteria	New Criteria	TX Item-247 Grade
A01	4.34E-04	C	B	2
A02	2.63E-04	B	B	2
B01	4.80E-04	C	B	2
B02	4.43E-04	C	B	2
C01	5.44E-04	C	B	2
D01	6.29E-04	C	C	3
D02	4.32E-04	C	B	2
E01	4.25E-04	C	B	2
F01	9.83E-04	C	C	3
F02	1.21E-03	C	C	3
G01	4.83E-04	C	B	2

G02	2.42E-04	B	B	2
H01	5.75E-05	B	A	1
I01	4.80E-05	B	B	2

Characterization of Performance-Related Base Course Properties

Aggregate Gradation

In order to quantify the aggregate gradation, a known statistical distribution is used to fit the gradation curve. The cumulative Weibull distribution is adopted in this study, which is shown in Equation 6.

$$F\left(x;a,\lambda\right)=1-e^{-\left(x/\lambda\right)^{a}} \tag{6}$$

where $F\left(x;a,\lambda\right)$ is the cumulative probability; x is the aggregate size; λ is the scale parameter; and a is the shape parameter [32]. The determined shape parameter a and scale parameter λ are used to quantify the aggregate gradation. The determined gradation parameters are presented at the 6th and 7th columns in Table 3.

AIMS Test

The AIMS test is used to characterize the angularity, shape and texture properties of aggregates. Angularity index is related to the corner sharpness of aggregate particle. The AIMS software calculates the angularity index of aggregate using the gradient method, which is shown in Equation 7.

$$AI=\frac{1}{\frac{N}{3}-1}\sum_{i=1}^{N-3}\left|\theta_i-\theta_{i+3}\right| \tag{7}$$

where AI is the angularity index, θ is the edge directional angle, the subscript i denotes the ith point on the boundary of a particle, and N is the total number of points on the boundary. A higher angularity index represents that the aggregate particle has more sharp corners.

Shape index is related to the sphericity of aggregate particle, which is calculated using Equation 8.

$$SI=\sum_{\theta=0}^{\theta=360-\Delta\theta}\frac{\left|R_{\theta+\Delta\theta}-R_{\theta}\right|}{R_{\theta}} \tag{8}$$

where SI is the shape index, θ is the directional angle, and R is the radius in different directions. The shape index less than 6.5 indicates that the particle shape is circular, the shape index between 6.5 and 8.0 indicates that the particle shape is semi-circular, the shape index between 8.0 and 10.5 represents that the particle shape is semi-elongated, and the shape index greater than 10.5 represents that the particle shape is elongated.

Texture index describes the relative surface smoothness of aggregate particle. The AIMS software calculates the texture index of aggregate using the wavelet method, which is presented in Equation 9.

$$TI = \frac{1}{3N}\sum_{i=1}^{3}\sum_{j=1}^{N}\left(D_{i,j}\left(x,y\right)\right)^{2} \tag{9}$$

where TI is the texture index, N denotes the level of decomposition, and i takes a value 1, 2 or 3, for the three detailed images of texture, j is the wavelet coefficient index, and $D_{i,j}\left(x,y\right)$ is the detail coefficient at location (x, y) for the Nth level of decomposition [33]. A higher texture index indicates the aggregate particle has a rougher surface.

Since the aggregate matrix is composed of the different sizes of aggregates, the composite angularity, shape and surface texture indices are used to characterize the morphologies of coarse aggregate blend. The calculation of composite angularity, shape and surface texture indices are shown in Equation 10.

$$\text{Composite Index} = \frac{\sum_{i=1}^{n}\left[\left(a_i\right)\left(\text{index}_i\right)\right]}{\sum_{i=1}^{n}\left(a_i\right)} \tag{10}$$

where Composite Index is the composite angularity, shape, or surface texture index for a certain aggregate blend, respectively; a_i is the volume percentage of the i^{th} size aggregate blended in the aggregate matrix; and index_i is the angularity, shape, or surface texture indices for a given size of aggregate [26]. The AIMS test results are presented from the 8th to 10th column in Table 3. The subscripts in these columns denote the following: A is for angularity; S is for shape; and T is for texture.

Figures 2 – 4 present the correlations of morphological properties (i.e., angularity, shape and texture indices) of coarse aggregates to the accumulated plastic strain at the 10,000th load cycle. As seen from these figures, increasing the angularity, texture and shape indices tends to reduce the accumulated plastic strain. This demonstrates that the UGM with more sharp corners and rougher surfaces has a higher rutting resistance. The shape index of the selected UGMs ranges from 7.1 to 8.1, which indicates that most of the selected aggregates are semi-circular. In this range, the aggregates oriented to elongation is slightly better than those oriented to circle to resist the permanent deformation. Note that the shape index of the selected UGMs is in a relatively narrow range. This might not sufficiently reflect the impact of aggregate shape on permanent deformation behavior of UGM.

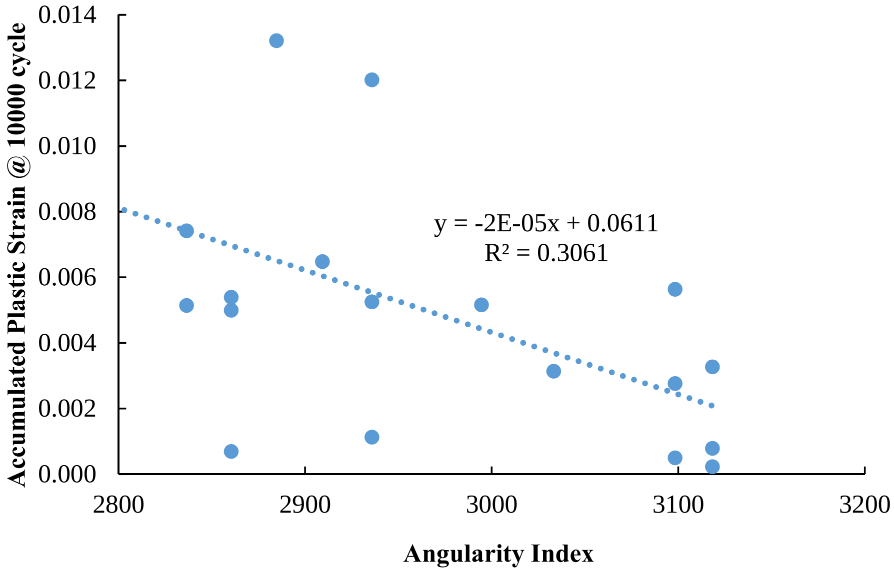

Figure 2. Correlation between Angularity Index and Accumulated Plastic Strain

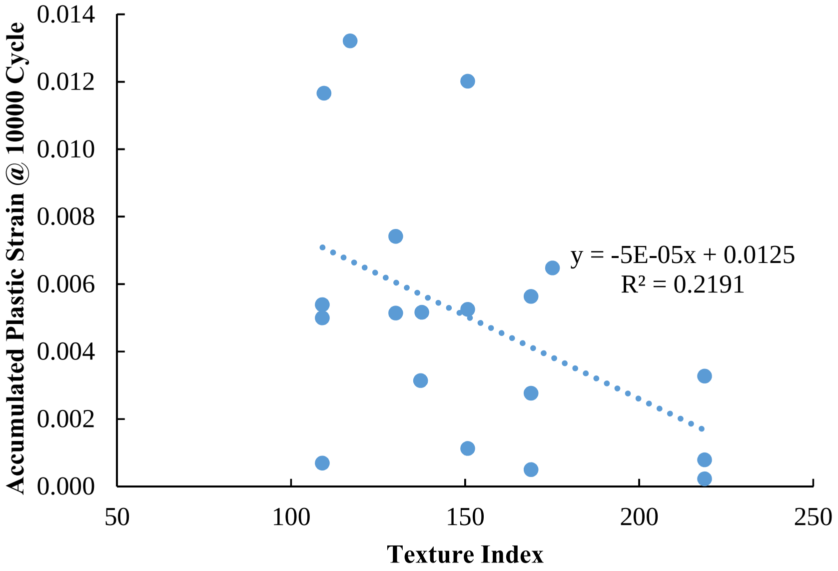

Figure 3. Correlation between Texture Index and Accumulated Plastic Strain

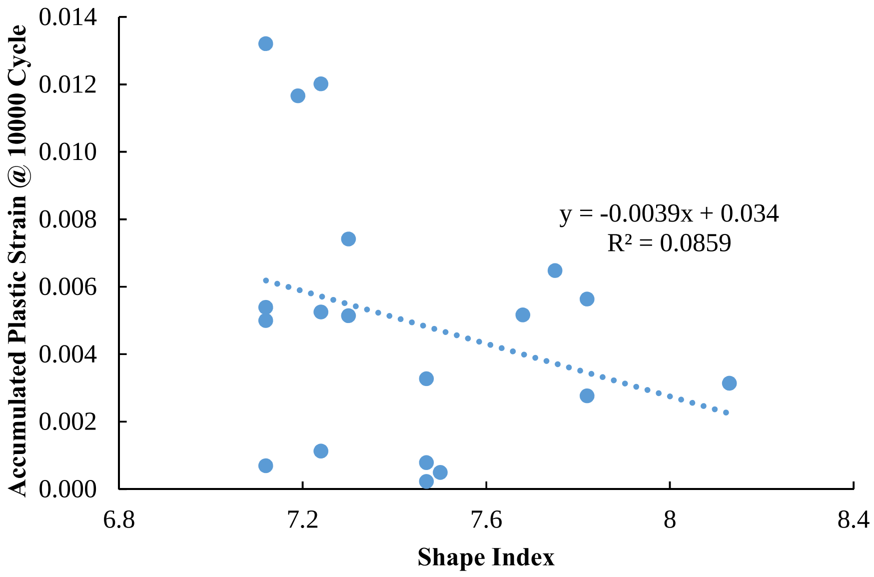

Figure 4. Correlation between Shape Index and Accumulated Plastic Strain

Percent Fines Content and Methylene Blue Tests

Percent fines content and methylene blue tests are used to characterize the amount and quality of moisture active clay in fine aggregates. The percent fines content is calculated using Equation 11.

$$\text{Percent Fines Content }(pfc) = \frac{m_{2\mu m}}{m_{75\mu m}} \qquad (11)$$

where $m_{2\mu m}$ is the mass of aggregate smaller than 2 microns; $m_{75\mu m}$ is the mass of aggregate smaller than 75 microns. The 5th column of Table 3 lists the results of percent fines content test. The MBV is calculated using Equation 12 [27].

$$MBV = S_c \times \left(MBV_{reading} + C \right) \qquad (12)$$

where MBV is the real methylene blue value of fine aggregates, $MBV_{reading}$ is the reading value from the colorimeter device (mg/g); C is the correction factor for the concentration of the solution, and S_c is the adjusting factor for sample size. The methylene blue test results are listed in the 4th column of Table 3. The performance-related base course properties listed in Table 3 will be assigned as input variables to develop the permanent deformation prediction models in the next section.

Table 3. Performance-Related Base Course Properties of Selected Base Materials for Model Development

Material Type	γ_d (kg/m^3)	w (%)	MBV	pfc	Gradation		Angularity	Shape	Texture
					a_G	λ_G	AI	SI	TI
A01	2414	5.4	7.1	13.2	0.73	10.6	2994.6	7.68	137.6
A02	2409	5.6	6.4	12.3	0.67	9.6	3033.3	8.13	137.2
B01	2267	6	2.1	20	0.72	10.4	2860.5	7.12	109.0
B02	2254	6.4	2.7	21.5	0.72	10.4	2860.5	7.12	109.0
B03	2210	7.5	2.7	21.5	0.72	10.4	2860.5	7.12	109.0
B04	2230	4.9	2.7	21.5	0.72	10.4	2860.5	7.12	109.0
C01	2196	7.1	5.3	11.4	0.87	14.6	2909.3	7.75	175.1
D01	2246	6.2	16.4	12.7	0.93	10.3	2836.6	7.30	130.1
D02	2276	6	10.6	12.3	0.93	12.7	2836.6	7.30	130.1
E01	2185	7.9	3.1	14.3	0.90	11.3	2935.9	7.24	150.8
E02	2110	9.4	3.1	14.3	0.90	11.3	2935.9	7.24	150.8
E03	2120	6.4	3.1	14.3	0.90	11.3	2935.9	7.24	150.8
F01	2206	7.4	7.0	15.5	0.85	12.7	2797.1	7.19	109.5
F02	2233	7.1	7.6	15.8	0.85	13.1	2884.7	7.12	117.0
G01	2335	6.5	6.8	13.6	0.88	10.8	3098.3	7.82	169.0
G02	2249	6.5	2.8	15.0	1.02	13.1	3098.3	7.82	169.0
H01	2291	6.3	5.0	16.1	0.89	8.3	3118.4	7.47	218.8
H02	2240	7.8	5.0	16.1	0.89	8.3	3118.4	7.47	218.8
H03	2180	4.8	6.1	11.2	0.89	8.3	3118.4	7.47	218.8
I01	2092	7.7	18.5	22.8	0.75	9.9	3098.3	7.50	169.0

Development of Prediction Models for Permanent Deformation Properties of UGM

Based on the permanent deformation properties and performance-related base course properties determined above, multiple regression analysis is performed using JMP software to investigate the correlation between them [34]. As listed in Table 3, the base course properties used in the model development include the dry density, moisture content, aggregate gradation in terms of Weibull distribution parameters, MBV, pfc, and angularity, shape and texture indices. A stepwise regression analysis is performed to identify the significant performance-related properties of the base course for predicting $\frac{\varepsilon_0}{\varepsilon_r}$, ρ and β in the permanent deformation models [35]. The analysis mixes the forward and backward stepwise regression methods. The p-value obtained from the t-test is used to identify the significant variables in the model. A p-value less than 0.05 indicates that the variable is significant at a 95 percent confidence level. Initially, all of the variables are inputted into the model. When running the analysis, the variables are removed or entered on the basis of the p-value threshold stopping rule. That is, if the p-value of the variable is larger than 0.25, the variable will be removed from the model, and vice versa. Finally, the one with largest F-test value is chosen as the best regression model.

Table 4 presents the results produced by the JMP software. The t-ratio is a ratio of the departure of an estimated parameter from its notional value and its standard error. A higher absolute value of t-ratio corresponds to a smaller obtained p-value. Equations 13 to 15 list the prediction models for $\frac{\varepsilon_0}{\varepsilon_r}$, ρ and β, respectively. Figures 5—7 compare the permanent deformation properties (i.e., $\frac{\varepsilon_0}{\varepsilon_r}$, ρ and β) predicted by Equations 13 through 15 against those determined from the RLT tests. It is shown that the predicted permanent deformation properties are in good agreement with those laboratory measured results. This indicates that the developed prediction models can accurately estimate the permanent deformation behavior of UGM.

$$\begin{aligned}\frac{\varepsilon_0}{\varepsilon_r} = &-2511.78 + 156.40\ln(\gamma_d) + 9.65w - 2.70pfc + 225.57\ln(AI) \\ &-30.86SI - 53.77\ln(TI)\end{aligned} \tag{13}$$

$$\ln(\rho) = 42.83 - 4.56\ln(\gamma_d) - 0.19w + 0.038pfc \tag{14}$$

$$\begin{aligned}\beta = &\ 0.29 - 0.52\ln(\gamma_d) - 0.0058w - 0.0036pfc + 0.56\ln(AI) + 0.037SI \\ &-0.148\ln(TI) + 0.0039\lambda_G\end{aligned} \tag{15}$$

Table 4. Results of Multiple Regression Analysis

	Variables	DF	Parameter Estimate	Standard Error	T- ratio	P-value
Prediction Model of $\varepsilon_0/\varepsilon_r$	Intercept	1	-2511.78	726.60	-3.46	0.0043
	$\ln(\gamma_d)$	1	156.40	51.87	3.02	0.0099
	w	1	9.65	1.34	7.18	<0.0001
	pfc	1	2.70	0.58	-4.68	0.0004
	$\ln(AI)$	1	225.57	102.66	2.20	0.0467
	SI	1	-30.86	8.07	-3.82	0.0021
	$\ln(TI)$	1	-53.77	15.67	-3.43	0.0045
Prediction Model of $\ln(\rho)$	Intercept	1	42.83	5.97	7.17	<0.0001
	$\ln(\gamma_d)$	1	-4.56	0.76	-6.00	<0.0001
	w	1	-0.19	0.025	-7.61	<0.0001
	pfc	1	0.038	0.0066	5.76	<0.0001
Prediction Model of β	Intercept	1	0.29	1.37	0.21	0.8337
	$\ln(\gamma_d)$	1	-0.52	0.090	-5.72	<0.0001
	w	1	-0.0058	0.0023	-2.58	0.024
	pfc	1	-0.0036	0.00097	-3.68	0.0031
	$\ln(AI)$	1	0.56	0.18	3.19	0.0078
	SI	1	0.037	0.015	2.46	0.0298
	$\ln(TI)$	1	-0.15	0.026	-5.74	<0.0001
	λ_G	1	0.0039	0.0018	2.10	0.0574

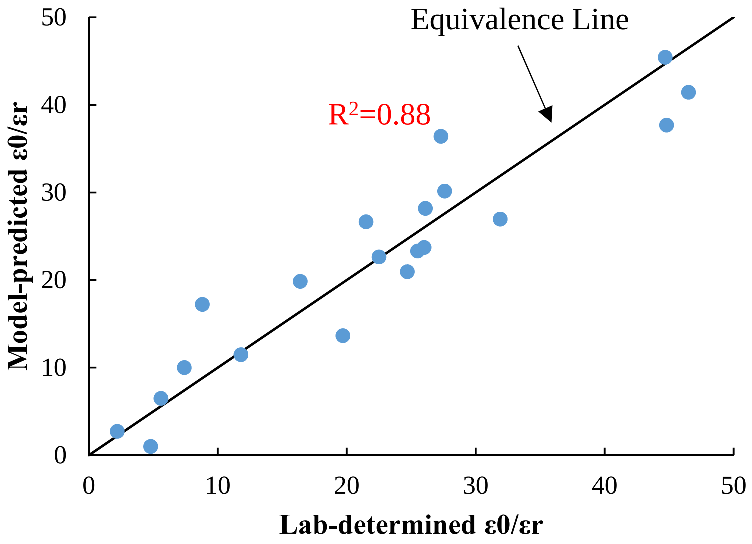

Figure 5. Comparison of Model-predicted $\varepsilon_0/\varepsilon_r$ against Laboratory-determined $\varepsilon_0/\varepsilon_r$

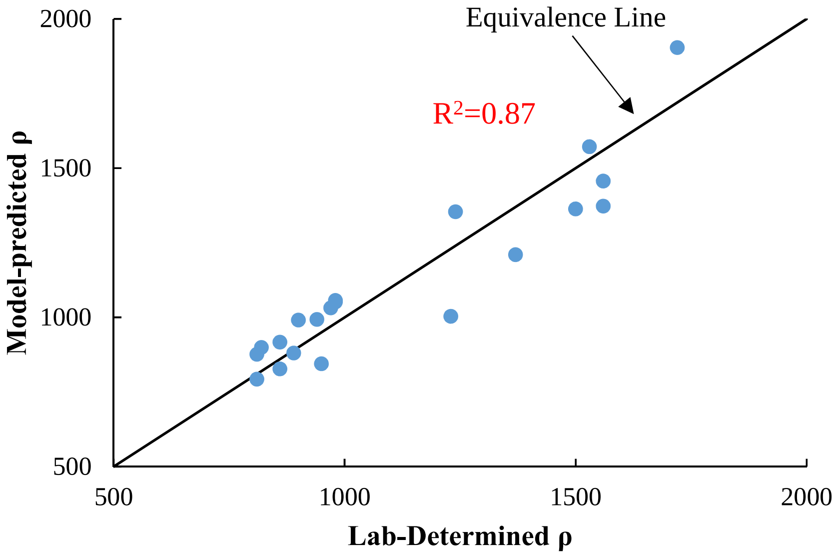

Figure 6. Comparison of Model-predicted ρ against Laboratory-determined ρ

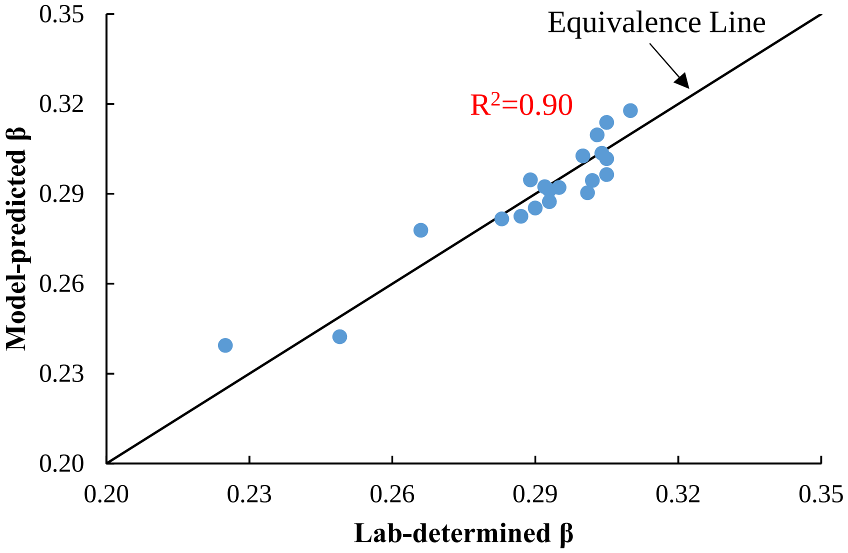

Figure 7. Comparison of Model-predicted β against Laboratory-determined β

To further examine the model accuracy, the developed permanent deformation prediction models (i.e., performance-related properties-based models) are compared against the other two types of prediction models shown below.

- Simple indicators-based models, which are the regression models based on the simple indicators including, the liquid limit, plasticity index, aggregate percent of passing sieve No. 4, and aggregate percent of passing sieve No. 200; and
- Pavement ME models, which are described in Equations 3—5.

Figure 8 compares the model prediction accuracy among the above three models. The model-predicted permanent strains are compared against the laboratory-measured results for all the selected base materials. As seen from Figure 8, the performance-related properties-based prediction models outperform the other two types of models at the prediction accuracy. Among these prediction models, the current Pavement ME Design models have the lowest prediction accuracy. It is shown that the Pavement ME model-predicted permanent strains are much lower than those measured from the RLT tests. This demonstrates that the current Pavement ME Design software substantially underestimates the rutting that occurs in base course.

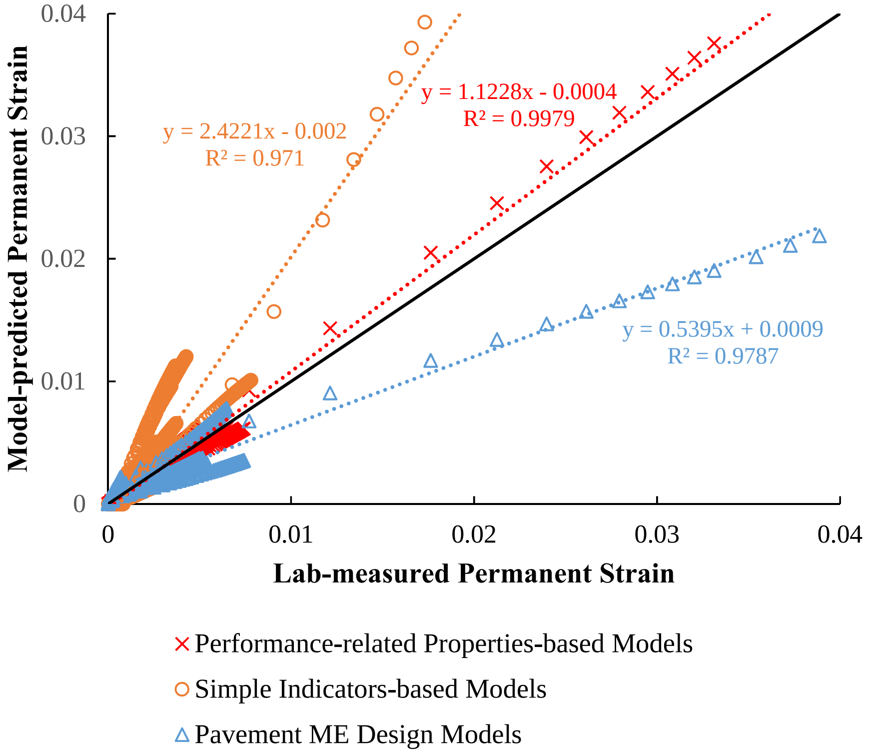

Figure 8. Prediction Accuracy of Various Permanent Deformation Prediction Models

In this study, other 4 types of base materials are selected for model validation. Table 5 presents the measured performance-related base course properties of these base materials (i.e., J01, J02, K01, and K02). These properties are inputted into Equations 13—15 to predict the permanent deformation properties of base materials. Meanwhile, the RLT tests are also performed on these base materials. The measured permanent strains of base materials are then compared to those predicted by the developed models. The detailed comparison results are shown in Figure 9. As illustrated, the model-predicted permanent strains are comparable to those measured from the RLT tests. The obtained R-squared value of 0.81 indicates that the developed models have a desirable accuracy in the prediction of permanent deformation properties of UGM.

Table 5. Performance-Related Base Course Properties of Selected Base Materials for Model Validation

Material Type	γ_d (kg/m^3)	w (%)	MBV	pfc	Gradation		Angularity	Shape	Texture
					a_G	λ_G	AI	SI	TI
J01	2174	6.7	4.1	12.4	0.75	10.2	3015.1	7.32	162.5
J02	2192	6.9	4.5	14.1	0.77	10.3	3015.1	7.32	162.5
K01	2321	6.2	4.5	15.3	0.85	12.6	3120.4	7.61	140.45
K02	2345	6.0	5.7	16.4	0.82	12.8	3120.4	7.61	140.45

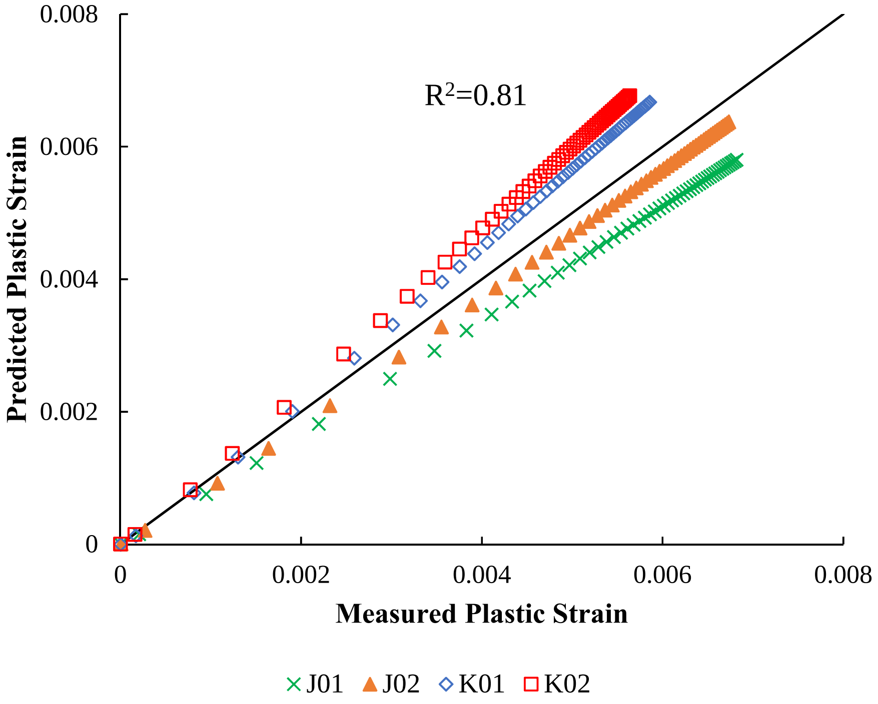

Figure 9. Validation of Model Prediction Accuracy

Conclusion

This study focused on the characterization and prediction of the permanent deformation properties of unbound granular materials (UGM) for Pavement ME Design. A comprehensive laboratory testing program was performed on a total of 18 types of base materials, which included both the repeated load triaxial tests and other performance-related indicator tests. The relationship was established between the permanent deformation behavior of UGMs and their performance-related properties. The major findings of this paper were summarized as follows.

- The shakedown theory was used to evaluate the permanent deformation behavior of the selected UGM. The Werkmeister's criteria to shakedown range boundaries were not suitable to the flexible base materials in Texas. New criteria were proposed to redefine the shakedown range boundaries, which are $\varepsilon_{p,5000} - \varepsilon_{p,3000} < 6.0 \times 10^{-5}$ for Range A; $6.0 \times 10^{-5} < \varepsilon_{p,5000} - \varepsilon_{p,3000} < 6.0 \times 10^{-4}$ for Range B; and $\varepsilon_{p,5000} - \varepsilon_{p,3000} > 6.0 \times 10^{-4}$ for Range C. These new criteria were consistent with the TxDOT's flexible base specification Item-247 in terms of aggregate classification.
- Aggregate morphological properties, such as angularity, shape, and texture indices, were correlated to the permanent deformation behavior of UGM. Increasing the angularity, texture and shape indices tends to reduce the accumulated plastic strain.
- A series of performance-related base course properties were identified, which included the dry density, moisture content, aggregate gradation in terms of Weibull distribution parameters, methylene blue value, percent fines content, and angularity, shape and texture indices. These properties were then used to develop regression models to predict the permanent deformation properties of UGM. It was found that the developed performance-related properties-based prediction models were capable of accurately predicting the permanent deformation properties of UGM.
- Compared to the simple indicators-based models and Pavement ME Design models, the performance-related properties-based model has the highest prediction accuracy. It was also found that the Pavement ME model-predicted permanent strains are much lower than those measured from the RLT tests. This demonstrated that the current Pavement ME Design software substantially underestimates the rutting that occurs in base course.

- The developed prediction models were validated by comparing the predicted and measured permanent strains of other four base materials. The obtained R-squared value of 0.81 indicated that the developed models have a desirable accuracy in the prediction of permanent deformation properties of UGMs.

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