A Comparison between Static and Repeated Load Test to Predict Asphalt Concrete Rut Depth

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Abstract-Rutting has a significant impact on the pavements' performance. Rutting depth is often used as a parameter to assess the quality of pavements. The Asphalt Institute (AI) design method prescribes a maximum allowable rutting depth of 13mm, whereas the AASHTO design method stipulates a critical serviceability index of 2.5 which is equivalent to an average rutting depth of 15mm. In this research, static and repeated compression tests were performed to evaluate the permanent strain based on (1) the relationship between mix properties (asphalt content and type), and (2) testing temperature. The results indicated that the accumulated plastic strain was higher during the repeated load test than that during the static load tests. Notably, temperature played a major role. The power-law model was used to describe the relationship between the accumulated permanent strain and the number of load repetitions. Furthermore, graphical analysis was performed using VESYS 5W to predict the rut depth for the asphalt concrete layer. The α and μ parameters affected the predicted rut depth significantly. The results show a substantial difference between the two tests, indicating that the repeated load test is more adequate, useful, and accurate when compared with the static load test for the evaluation of the rut depth.

Keywords-asphalt concrete; rut depth; VESYS

I. INTRODUCTION

Rutting is a distress mechanism in flexible pavements. Recently, due to the increased truck tire pressures and the lack of maintenance that result in roadway deterioration [1], rutting has become the predominant mode of flexible pavement failures. Rutting is primarily caused by the accumulation of permanent deformations in the pavement or its layers. Furthermore, a major portion of rutting in the surface layer of flexible pavements is subjected to high tire pressures and heavy axle loads. High tire pressures decrease the contact area between the tire and the pavement, producing high stress, which aggravates deformation in flexible pavements. In addition, environmental conditions affect significantly the surface layer of the pavements [2].

The permanent deformation of the Asphalt Concrete (AC) mixture has been studied by several researchers for various materials using different testing procedures. Furthermore, various parameters and prediction models have been developed to measure rutting resistance. In this study, creep and uniaxial cyclic compression results of AC mixtures were estimated and compared based on various asphalt contents, asphalt types, and temperatures. Many studies have been performed to study the mechanism of rutting, and many methods have been proposed for predicting the Rut Depth (RD). Some of these methods are based on limiting the values of subgrade strain to levels that prevent rutting at the pavement surface. These methods were based on the assumption that when the maximum vertical compressive strain at the top of the subgrade is less than a critical value, rutting will be limited to an acceptable level for a specified number of load applications. However, this methodology does not essentially preclude the occurrence of rutting that might occur in the asphalt layer. Therefore, a layer-strain method was proposed to improve the above process by including additional analysis to evaluate the amount of rutting occurring in the asphalt layer [3]. It is reported [4] that excessive permanent deformation can lead to longitudinal depressions in wheel paths. This can be followed by longitudinal cracking. Subsequently, water can penetrate these cracks and deteriorate the roadway, causing it to lose its load-carrying capacity. Furthermore, excessive permanent deformation can reduce the driving comfort and can lead to icing or hydroplaning because of water getting collected in wheel paths.

AASHTO classified traffic control and environmental factors as the major causes of AC rutting. However, highway authorities have little control over these two factors. Furthermore, there are some limitations that prevent the redressing of problems that are within the control of highway agencies [5]. Several highway engineers focused on ascertaining the factors that can help address the problem of rutting to propose better mechanisms to reduce the RD. Authors in [6] performed several creep tests to study the permanent deformation of AC and developed a rutting prediction model based on a statistical method which considered factors such as stress, temperature, asphalt viscosity, effective asphalt content, air voids, and load repetition. To evaluate the parameters that affect the AC mix, authors in [7] evaluated the influencing factors and suggested variables such as the asphalt content, binder viscosity, air voids, and test temperature that affect the AC mix.

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Furthermore, additives were also used to improve the strength of asphalt materials, e.g. using rubber modified asphalt binder [8]. Most of the existing permanent deformation models for asphalt mixes have been empirically determined based on laboratory test results. As a simple performance test [9], a uniaxial repeated load test is generally used to characterize the permanent deformation response of asphalt mixes. Permanent deformation measured using repeated load tests, as depicted in Figure 1, is generally composed of three stages [10], primary, secondary, and tertiary. In the primary stage, the rate of permanent deformation accumulates quickly and tends to decrease, reaching a constant value in the secondary stage. Finally, the rate starts to increase rapidly and accumulates again in the tertiary stage [11]. The objective of these tests is to simulate the repeated load conditions that occur on the road. Authors in [12] compared the responses of 3 mixes consisting of conventional and modified binders under both creep and repeated loading. For creep loading at 37°C and confining pressure of 207KPa, the difference among the mixes was not discernible. The results of repeated load testing suggest that the repeated loading test may be more applicable than the creep test to calculate the permanent deformation characteristics of asphalt mixes. The results of Strategic Highway Research Program (SHRP) [13] also suggest that more deformation occurs in repeated loading than in creep loading for the same materials and other test conditions. Apart from the two conventional procedures used for repeated load tests, i.e. termination of the test at 10,000 loading cycles or 5% accumulated strain, regression coefficients *a* (intercept) and *b* (slope) were also used to determine the rutting susceptibility of AC mixtures [14]. Authors in [15] proposed a method based on repeated axial load tests to determine the flow number of bituminous mixtures. Static and repeated load tests were used to evaluate the rutting potential of asphalt mixtures, and the results indicated that the specimens of mixtures experienced a tertiary flow state in the repeated load test. However, no specimen achieved a tertiary flow state in the static load test. This can be attributed to the static pattern of loading that induces less strain when compared with that of repeated loading [16].
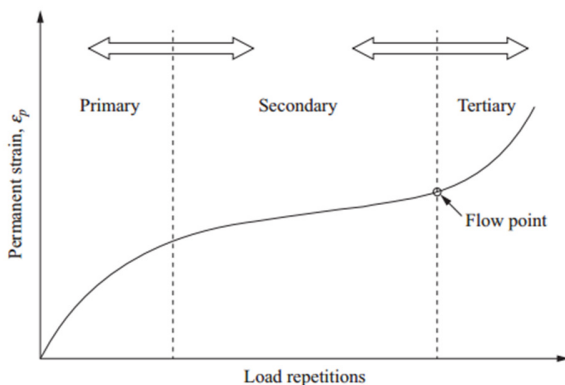
II. MATERIALS CHARACTERIZATION

A. Asphalt Cement

To characterize the properties of the base bitumen, conventional tests such as the penetration test, softening point test, flash point test, and penetration and ductility after the thin-film oven test were performed. These tests were performed in conformity with the relevant test parameters listed in Table I.

TABLE I.   PROPERTIES OF ASPHALT CEMENT

Property	ASTM design ation	Penetration grade 40–50		Penetration grade 60-70	
		Test results	SCRB specification	Test results	SCRB specific
Penetration at 25°C, 100gm, 5s (0.1mm)	D-5	42	40-50	67	60-70
Softening point (°C)	D-36	51	……	45	…..
Ductility at 25°C, 5cm/min (cm)	D-113	>100	>100	….	>100
Flash point (°C)	D-92	289	Min. 232	292	Min. 232
Specific gravity	D-70	1.041	……	1.028	……
Residue from thin-film oven test:	D-1754				
-Retained penetration (% of original)	D-5	59.5	55+	64.1	52+
-Ductility at 25°C, 5cm/min (cm)	D-113	80	25+	100+	50+

B. Aggregates

Coarse and fine aggregates were chosen and mixed in appropriate proportions to meet the wearing course gradation prescribed by the SCRB specification (SCRB, R/9 2003). The gradation curve of the aggregates is depicted in Figure 2. To obtain the properties of the coarse and fine aggregates used in the mixture, conventional tests, such as the specific gravity test, Los Angeles abrasion resistance test, sodium sulfate soundness test, and sand equivalent test were performed. The results, along with the specification limits set by the SCRB, are listed in Table II.
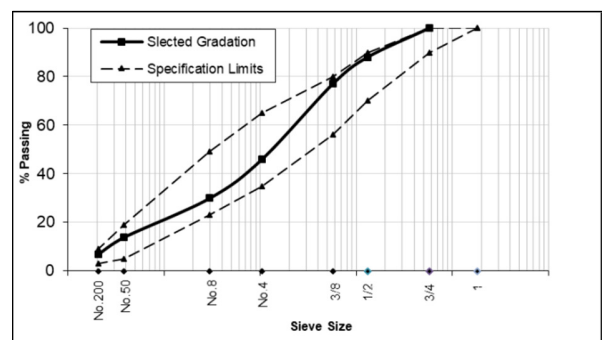

Fig. 1.   Typical permanent deformation behavior of asphalt mixture.

Fig. 2.   Aggregate gradation curve.

C. Mineral Filler

The filler is a non-plastic material that must pass through sieve No. 200 (0.075mm). The physical properties of the filler used in this study are listed in Table III.

TABLE II.   PHYSICAL PROPERTIES OF AGGREGATES

Property	ASTM designation	Test results	SCRB specification
Coarse aggregates:			
1. Bulk specific gravity	C-127	2.611	.....
2. Apparent specific gravity		2.689	.....
3. Water absorption (%)		0.443	.....
4. Wear by Los Angeles abrasion (%)	C-131	18.7	30 max.
5. Soundness loss by sodium sulfate solution (%)	C-88	3.1	10 max.
6. Fractured pieces (%)		96	95 min.
Fine aggregates:			
1. Bulk specific gravity	C-127	2.663	
2. Apparent specific gravity		2.697	
3. Water absorption (%)		0.727	
4. Sand equivalent (%)	2419	55	45 min.

TABLE III.   PHYSICAL PROPERTIES OF THE MINERAL FILLER (LIMESTONE DUST)

Property	Test results
Specific gravity	2.794
Passing sieve No. 200 (0.075mm)	94

D. Specimen Preparation

The cylindrical specimens used in this study were 101.6mm (4in) in diameter and 203.2mm (8in) in height. The fractions of the aggregates were separated into groups and the aggregates retained on the pan were discarded and replaced by the mineral filler (limestone dust). Based on the graduation specifications depicted in Figure 2, the aggregates were mixed into a batch of 3800g on the mixing bowl and heated to 150°C in a temperature-controlled oven. Asphalt was also heated in a container to a temperature in the range of 135–140°C for 2min, and the contents of the bowel were thoroughly mixed manually on a hot plate. To ensure a uniform compaction temperature, the bowel with its contents was transferred to an oven and stored for 10min at 140°C. A preheated to 100°C compaction mold was prepared and a 4-in paper disk was inserted to cover the mold base plate. The interior edge of the mold was lubricated using a brush to facilitate the specimen extraction. The specimen was compacted by the double plunger method with a load of 65000lb (29491kg) applied using a hydraulic compression machine at the Material Laboratory of the Civil Engineering Department of the University of Baghdad. The load was applied to each end of the specimen for 1min. Finally, 36 specimens were carefully transferred to a smooth, flat surface and allowed to cool overnight at 25ºC and then were removed from the mold using a hydraulic extractor. The specimens were then numbered and stored in a bag.

III.   EVALUATION OF PERMANENT DEFORMATION AND TESTING RESULTS

Permanent strain values were determined using a Pneumatic Repeated Load System (PRLS) apparatus manufactured under the auspices of the Civil Engineering Department of the University of Baghdad [17] as depicted in Figure 3. Axial repeated and static load tests were performed. The cylindrical specimens, 101.6mm (4in) in diameter and 203.2mm (8in) in height, were subjected to conditioning in the PRLS test chamber at various testing temperatures (20°C, 40°C, and 60°C) for 2h. A linear variable differential transformer was used to monitor the deformation of the specimens under each load cycle. Compressive loading was applied at 138kPa in the form of a rectangular wave with a constant loading frequency of 60cycles/min and loading sequence including 0.1s load duration and 0.9s rest duration.

Fig. 3.   A photograph of the PRLS.

A. Permanent Deformation Characteristic Properties for Repeated Load Test

The values of the permanent strain were obtained at the following load repetitions: 1, 2, 10, 100, 500, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, and 10000. Permanent strain (ε_p) was calculated using (1):

$$\varepsilon_p = \frac{p_d \times 10^6}{h} \quad (1)$$

where ε_p is the axial permanent microstrain, p_d is the axial permanent deformation, and h is the specimen's height. The accumulative axial permanent strain versus the number of loading repetitions (N) is depicted in Figure 4.
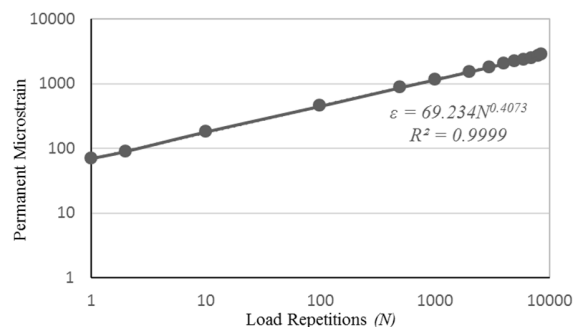

Fig. 4.   Cumulative permanent strain vs loading cycles from the repeated load test (log-log scale).

B. Permanent Deformation Characteristic Properties for Static (Creep) Load Test

Data for the following loadings were recorded at 1, 10, 30, 60, 100, 260, 360, 500, 1000, 2000, and 3000s. The values of the permanent strain were calculated at these loadings using the following expression:

$$\varepsilon_p = \frac{c_d \times 10^6}{h} \quad (2)$$

where c_d is the axial creep deformation. The cumulative axial permanent strain versus the number of loading times is depicted in Figure 5.
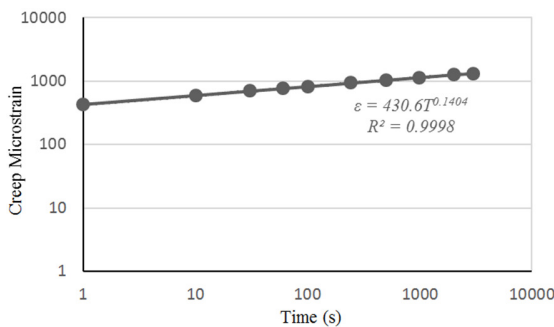

Fig. 5.   Cumulative permanent strain vs loading times from the creep load test (log-log scale).

C. Regression Analysis

Several formulas have been proposed to describe the relationship between ε_p and N. Authors in [18, 19] suggested a log-log relationship, as described in the following equation:

$$\varepsilon_p = aN^b \quad (3)$$

where N is the number of load repetitions, and a and b are positive regression constants, as depicted in Figure 4. The parameter a is the intercept with the permanent strain axis, and b is the slope of the linear portion of the logarithmic relationship. The double-logarithmic-scaled relationship between ε_p and N can be approximated using a linear function.

IV. VESYS THEORY

Authors in [20] developed the VESYS software using multilayer visco-elastic theory to predict the RD in flexible pavement layers. The basic assumption of VESYS rutting models is that permanent strain is related to resilient strain as follows:

$$\varepsilon_p(N) = \varepsilon_r \mu N^{-\alpha} \quad (4)$$

where $\varepsilon_p(N)$ is the vertical permanent strain at the Nth load repetition, and μ and α are material properties that are functions of the stress state and temperature respectively. The material parameters are defined as $\alpha = 1 - b$ and $\mu = ab/\varepsilon_r$. These two parameters govern the permanent deformation behavior of the model. In particular, α is the rate of decrease or increase in permanent deformation as the number of load applications increases, and μ is the constant of proportionality between permanent and elastic strains ($\mu > 0$). Values greater than 1 indicate premature rutting. The most critical task in

using this model is the prediction of α and μ accurately for each pavement layer within the pavement system. The permanent deformation parameters could be predicted using laboratory or field data [21].

The comparative evaluation of the impact of repeated and creep stresses on permanent deformation parameters is listed in Table IV. Intercept a represents the deformation of the specimen after the first load repetition, whereas slope b refers to the rate of deformation throughout the fatigue life of asphalt concrete. Furthermore, this comparison also includes the average values of permanent strain and parameters α and β.

TABLE IV.   PERMANENT DEFORMATION PARAMETERS

	Temperature (°C)			Asphalt content (%)			Asphalt grade	
	20	40	60	4	4.6	5.2	40-50	60-70
Repeated Load Test (RLT)								
ε_p	266	5840	30000	9458	16160	16700	11160	17040
a	55	150	430	230	210	190	160	260
b	0.184	0.40	0.58	0.348	0.4	0.43	0.394	0.398
α	0.816	0.60	0.42	0.652	0.6	0.57	0.606	0.602
μ	0.105	0.270	0.50	0.340	0.285	0.250	0.23	0.36
Creep Load Test (CLT)								
ε_p	532	1730	9295	3850	3480	4219	3680	4020
a	210	555	1430	798	660	730	690	770
b	0.119	0.144	0.264	0.165	0.176	0.187	0.175	0.177
α	0.881	0.856	0.736	0.835	0.824	0.813	0.825	0.823
μ	0.120	0.145	0.260	0.165	0.175	0.189	0.176	0.178

V. DISCUSSION

The accumulated strain at the flow number increased for the Repeated Load Test (RLT) and exhibited the opposite behavior for the Static Load Test (SLT). The significant difference in the values of ε_p at the failure load for both tests is illustrated in Figure 6. Table V lists the ANOVA analysis that explains the impacts of the testing variables on the plastic strain. The Table lists the degrees of freedom (the number of variables used minus one), the F-test results, and the p-value (significance) for each test. The results particularly indicate that temperature plays a major role affecting plastic deformation (F value $\gg$ $F_{crit.}$). The variables (intercept and slope) used in this model when plotted on a log scale can be useful indicators of rutting resistance. The minimal values of each provide a good indicator of rutting resistance. Furthermore, the slope coefficient b is also used as a term of creep rate (fc) to an assessment of the asphalt performance in resistance to permanent deformation. The intercept values of RLT increased by 2.7 and 7.8 factors with an increase in temperature from 20°C to 40°C and 60°C respectively, whereas SLT increased by 2.6 and 6.8 respectively. The content and grade of the asphalt had only a minor impact. The slope or fc values for RLT increased by 2.17 and 3.15 with an increase in temperature from 20°C to 40°C and 60°C respectively, whereas that of SLT increased by 1.21 and 2.21 respectively. The content and grade of the asphalt did not affect the slope of the SLT. The sensitivity analysis of the VESYS 5W rutting model clearly indicated that α and μ had a considerable effect on the predicted RD. The values of both parameters were measured using RLT and SLT. Figures 7–9 illustrate the impact of temperature and mixture properties (asphalt content and grade)

on the RD of the AC layer. As mentioned above, temperature is considered to be the main factor that affects rutting in the AC layer. The results indicated that RD increased with an increase in temperature for both tests, as depicted in Figure 7. At 20°C, the RD increased slightly. However, at 40°C and 60°C, the RD value was larger for RLT than for SLT by a factor of 6.8 and 4.02 respectively. The asphalt content and grade had no effect on the RD for the creep test, as depicted in Figures 8 and 9. The higher value of α and lower value of μ coefficients indicate pavements with lower rutting. At a lower value of α, rutting will develop over the entire pavement life and the mainstream of the rutting will occur at the initial stage and taper off with the remaining life of the pavement when the AC layer is soft (higher initial strain) or the climatic region is hot (higher temperatures).
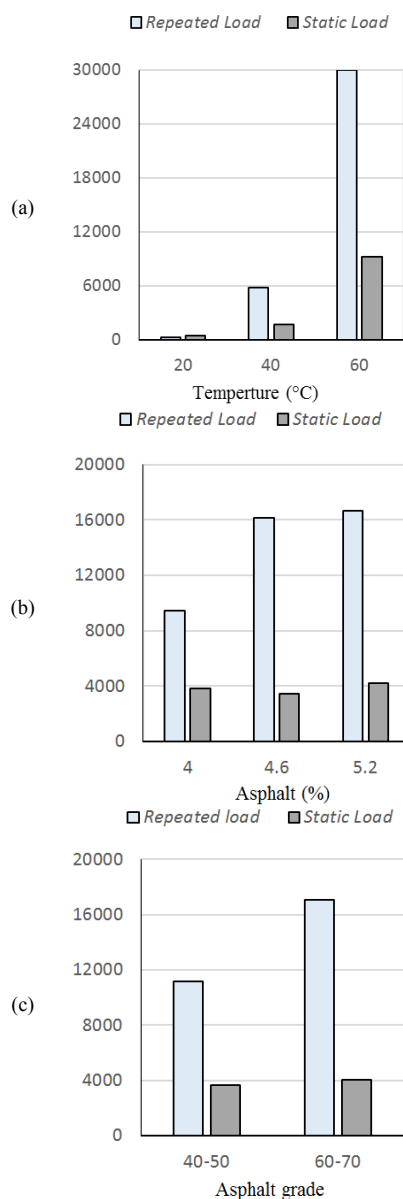
TABLE V.   IMPACT OF VARIABLES AND TEST METHODS ON PLASTIC STRAIN (WO-WAY ANOVA)

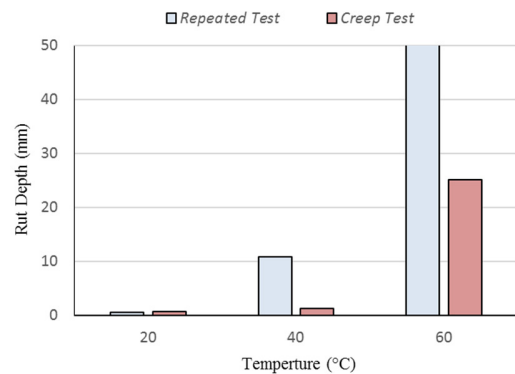| Source of Variation	df	F	P-value	F crit.
Repeated Load Test (RLT)				
Temperature (°C)	2.000	38.474	6.03E-06	3.885
Asphalt grade	1.000	2.666	0.128	4.747
Asphalt content (%)	2.000	1.381	0.310	3.326
Static Load Test (SLT)				
Temperature (°C)	2.000	291.438	6.74E-11	3.885
Asphalt grade	1.000	1.096	0.316	4.747
Asphalt content (%)	2.000	1.149	0.396	3.326

Fig. 7.   Temperature vs predicted rut depth on AC layer (VESYS 5W analysis).
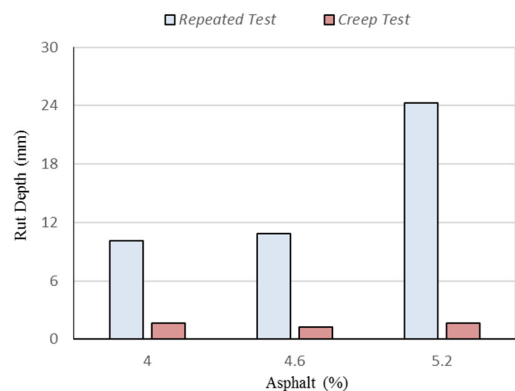

Fig. 8.   Asphalt content vs predicted rut depth on AC layer at 40°C (VESYS 5W analysis).

Fig. 9.   Asphalt grade vs predicted rut depth on AC layer at 40°C (VESYS 5W analysis).

Fig. 6.   Impact of testing temperature and asphalt mixture on the plastic strain.
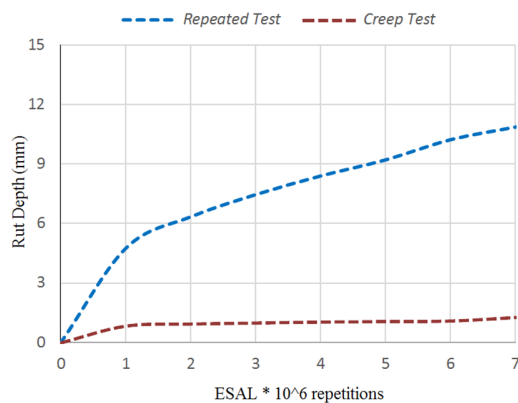
Fig. 10.   Impact of ESAL on the prediction of rut depth in AC layer at 40°C (VESYS 5W analysis).

To compare the trend of variation in RD with equivalent single-axle load (ESAL), Figure 10 depicts the application of various ESALs on the AC layer. The total RD for RLT is higher than that for SLT by a factor of 8.4. Therefore, it is significant that the RD at the first million repetitions is approximately the 44% of the total RD. Moreover, we can compare the predicted RD for the AC layer evaluated using RLT with the measured RD estimated using (5):

$$R_d = \varepsilon_p \times h \quad (5)$$

where R_d is the rutting depth (mm), ε_p is the permanent strain (mm/mm), and h is the total thickness (mm) of the asphalt concrete layer. ε_p is evaluated based on the model developed in [17] as follows:

$$LE_P = -34.463 + 0.983 \log N^{(0.00973T \, 0.00284S)} + 1.961 \log T + 1.812 \log S + 0.656 \log D - 37.277 \log B - 4.951 \log F - 1.455 \log A - 1.93 \log M \quad (6)$$

where LE_P is the log of accumulated permanent micro strain at the Nth load repetition, T is the test temperature (°C), S is the stress level (psi), D is the applied stress duration (s), B is the percentage absorbed asphalt (by weight of aggregates), A is the percentage of air voids, M is the percentage of voids in mineral aggregates, and F is the voids filled with asphalt. Similarly, using the trend of variation in RD with ESAL, as depicted in Figure 11, the values of RD for both the predicted and the measured data are closed. Therefore, the use of repeated load tests to predict RD is significantly accurate and reliable.
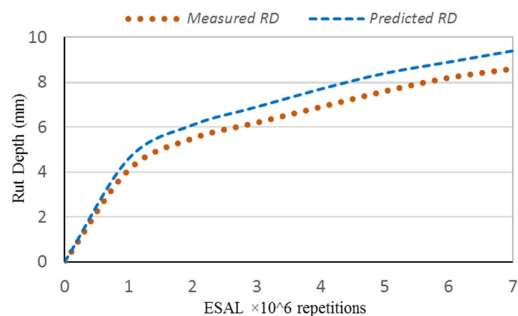

Fig. 11.   Comparison between the predicted and the measured rut depths for various ESAL repetitions.

In general, to evaluate the rutting resistance properly the parameters from unconfined RLTs in [9,14] can be used.

VI.   CONCLUSION

In this study, the power-law model was used to obtain parameters for simulating the permanent deformation of the asphalt layer under uniaxial repetitive and static compression loads. The results indicated that the accumulated plastic strain for the repeated load test was higher than that of the static load test for various mixture properties and climatic conditions (temperature). VESYS 5W was used to predict the rut depth at the asphalt concrete layer subjected to equivalent single-axle loads. The α and μ parameters exhibited a considerable impact on the predicted rut depths. Finally, the results of this study indicated a high difference between the above two tests. The predicted rut depth based on repeated load tests was in reasonable agreement with the actual rut depth.

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