The Hamburg Rutting Test (HWTT) - Alternative Data Analysis Methods and HMA Screening Criteria

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Abstract: The Hamburg Wheel Tracking Test (HWTT) is a widely used routine laboratory test with a proven history of successfully identifying and screening hot-mix asphalt (HMA) mixes that are prone to rutting .The standard HMA pass-fail screening criterion under the current HWTT protocol is 12.5-mm rutting at 50 °C. However, with the recorded high summer temperatures of the recent years in Texas, several rutting failures have occurred with some HMA mixes that had passed the HWTT in the laboratory. These failures occurred mostly in high shear locations, in particular with slow moving (accelerating/decelerating) traffic at controlled highway intersections, stop-go sections, in areas of elevated temperatures, heavy/high traffic loading, and/or where lower performance grade (PG) of asphalt binders have been used. This laboratory hybrid study was thus initiated to explore new data analysis methods and parameters to supplement the traditional Texas HWTT pass-fail screening criteria (≤ 12.5 mm rut depth at 50 °C) for HMA mixes. Several HMA mixes commonly used in Texas were evaluated in the laboratory and new HWTT analysis parameters, such as the rutting area [Δ_A], the normalized rutting area [Rut_Δ], and the shape factor [SF] with the potential to capture the HMA rutting path-history, were formulated. In addition, a comparison between the newly formulated and traditional rutting parameters with field performance observations was conducted and yielded promising results in terms of superiority of the newly introduced HWTT parameters (Rut_Δ and SF) to predict the early-life rutting performance of HMA mixes.

Key Words: HMA, Rutting, High Shear Stress, High Temperature, HWTT, Rutting Area, Shape Factor.

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1. Introduction

Rutting is one of the major distresses occurring in hot-mix asphalt (HMA) pavements, typically manifesting itself as longitudinal depressions in the wheel paths [1, 2]. The HMA rutting is mainly caused through shear deformation in the upper HMA layers under repeated traffic loading [3, 4, 5, 6]. Currently, one of the routine laboratory tests used for screening HMA mixes and assessing their rutting susceptibility is the Hamburg Wheel Tracking Test (HWTT).

Traditionally run at a single test temperature of 50 °C (122°F) in the laboratory under Texas specification Tex-242-F, the HWTT has been proven as a reliable test method to identify and screen HMA mixes that are prone to rutting and/or susceptible to moisture damage (stripping) [7, 8, 9, 10]. However, with the record high summer temperatures of the recent years in Texas (i.e., over 122 °F), several rutting failures have occurred in the field with some HMA mixes that had passed the HWTT in the laboratory. These failures occurred mostly in high shear stress locations, in particular with slow moving (accelerating/decelerating) traffic at controlled highway (stop-go intersections, in areas of elevated temperatures, heavy/high traffic loading, and/or where lower performance grade (PG) asphalt-binder grades have been used for cost optimization purposes, etc.) [11, 12].

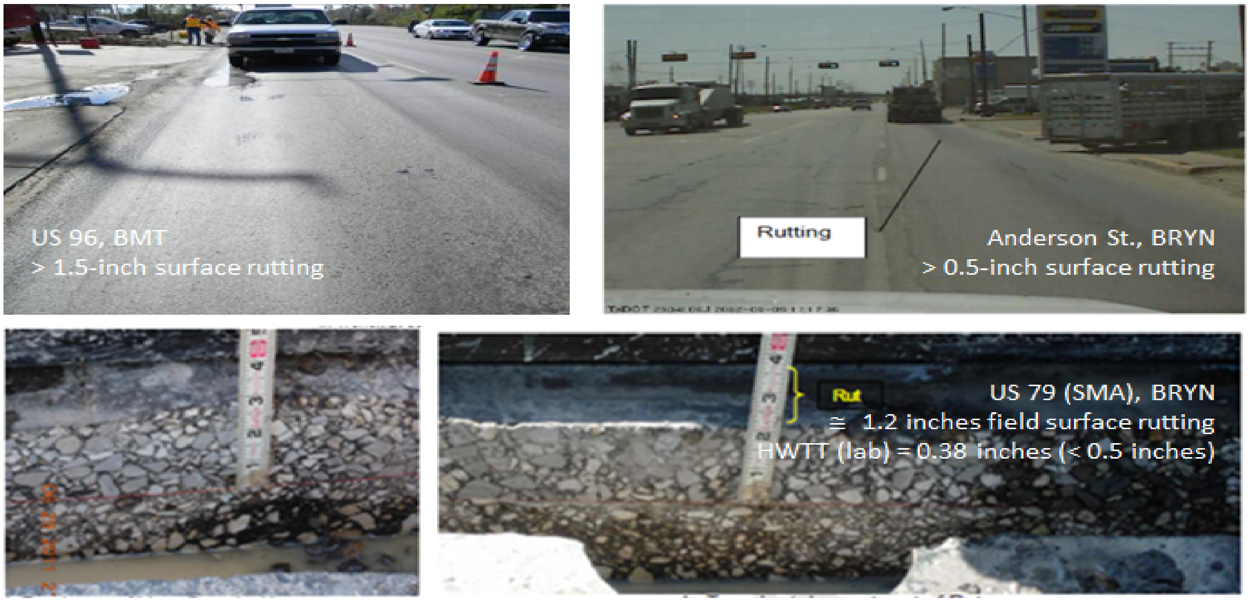

Fig. 1 Examples of premature and surface rutting on selected Texas highways.

Since improper HMA mix selection due to poor laboratory screening can undesirably lead to costly premature pavement failures, tying laboratory testing to field performance using actual laboratory and field data is critical to ensure optimal field performance and minimize maintenance/rehabilitation costs. Thus, the objective of this study was to explore new data analysis methods and parameters in order to make current HWTT protocol more simulative of field conditions of severe Texas summer and supplement the current Tex-242-F criteria for better assessment of rutting resistance of HMA mixes to meet screening purposes. In the subsequent sections, the Texas HWTT test protocol and Tex-242-F specification are described, followed by the laboratory experimental plan. Based on laboratory test results analyzed, the paper concludes with a synthesis and summary of the key findings and recommendations.

2. The HWTT test protocol and TEX-242-F specification

Current HWTT protocol of the Tex-242-F specification consists of the following test parameters: 72 kg (158 lb.) vertical load at a wheel speed of 52 passes per minute up to 20,000 passes at 50 ±1 °C (122°F) in a water bath [9]. This test method is routinely used to determine the HMA premature failure susceptibility caused by weak aggregate structure, inadequate asphalt-binder stiffness, or moisture damage (stripping). Figure 2 illustrates the HWTT equipment along with the sample loading configuration.

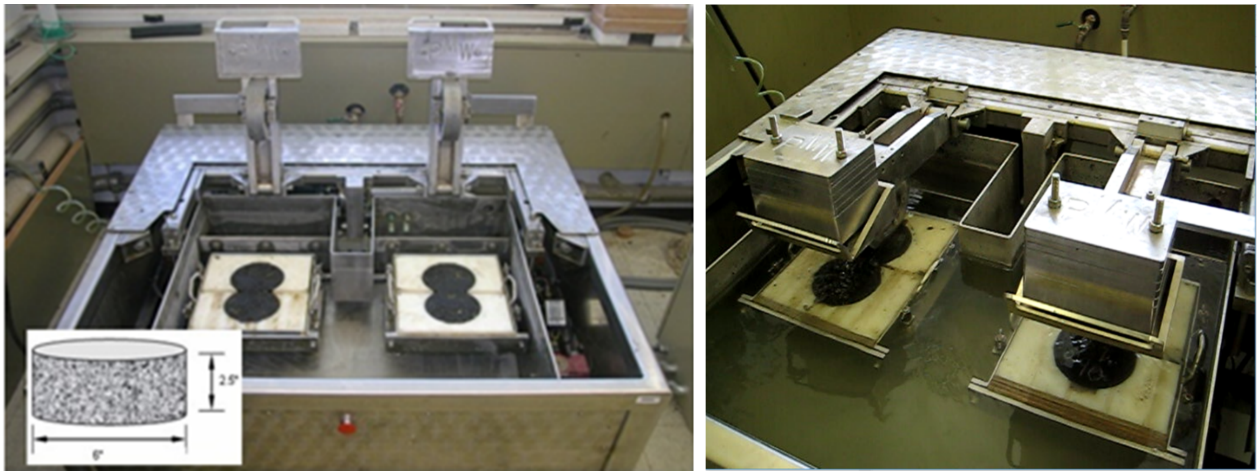

Fig. 2 The HWTT device.

The HMA pass-fail screening criteria are based on the measured rut depth (< 12.5 mm) and the number of HWTT load passes to failure (or test termination), whichever comes first. Additionally, the number of HWTT load passes to failure is based on the asphalt binder performance grade (PG) as follows: PG 64/58-XX = 10,000 load passes; PG 70-XX = 15,000 load passes; and PG 76-XX = 20,000 load passes [9, 12, 13]. As mentioned in the introduction, these failure criteria are not sufficient to assess HMA rutting resistance for mix screening purpose. Thus, as a supplement to these traditional criteria, new alternative data analysis methods and HMA screening parameters were derived in this study and are discussed in the subsequent sections.

3. Alternative HWTT data analysis and screening criteria

As previously stated, the current HMA pass-fail screening criteria of the HWTT, according to the Tex-248-F specification, is solely based on the magnitude of the measured rut depth (< 12.5 mm) and the number of load passes to failure (test termination), whichever comes first [9, 13]. However, these parameters do not capture the rutting path-history of the HMA and therefore, fails to effectively discriminate those HMA mixes that may be potentially susceptible to early-life rutting (shear failure) propensity. This limitation is illustrated in Figure 3, where the rutting response curves of three HMA mixes have been arbitrarily plotted as a function of the HWTT rut depth versus the number of load passes.

As seen in Figure 3, three HMA mixes have the same rutting depths of 10 mm after 20,000 load passes, which means they have the same rutting propensity based on the current Tex-242-F criteria. However, it is clear that they show different path-history curves with different shapes of the rutting response curves. These path-histories and shapes of the rutting response curves are meaningful in terms of screening and quantifying the expected rutting performance of the HMA mixes. For instance, Mix-1 with a convex shaped rutting response curve suggests a higher propensity to early-life rutting (premature shear failure) than Mix-3 with a concave curve;, where the rutting response curve, as previously defined, is simply a plot of the HWTT rut depth versus the number of load passes. Similarly, the order of the propensity to early-life rutting and premature shear failures is as follows: Mix-1 > Mix-2 > Mix-3. Thus, it is obvious that this approach of path-history or shape of the rutting response curve will be effective to screen HMA mixes rather than the current Tex-242-F criteria that rely on only the magnitude of rutting depth and the number of HWTT load passes to failure.

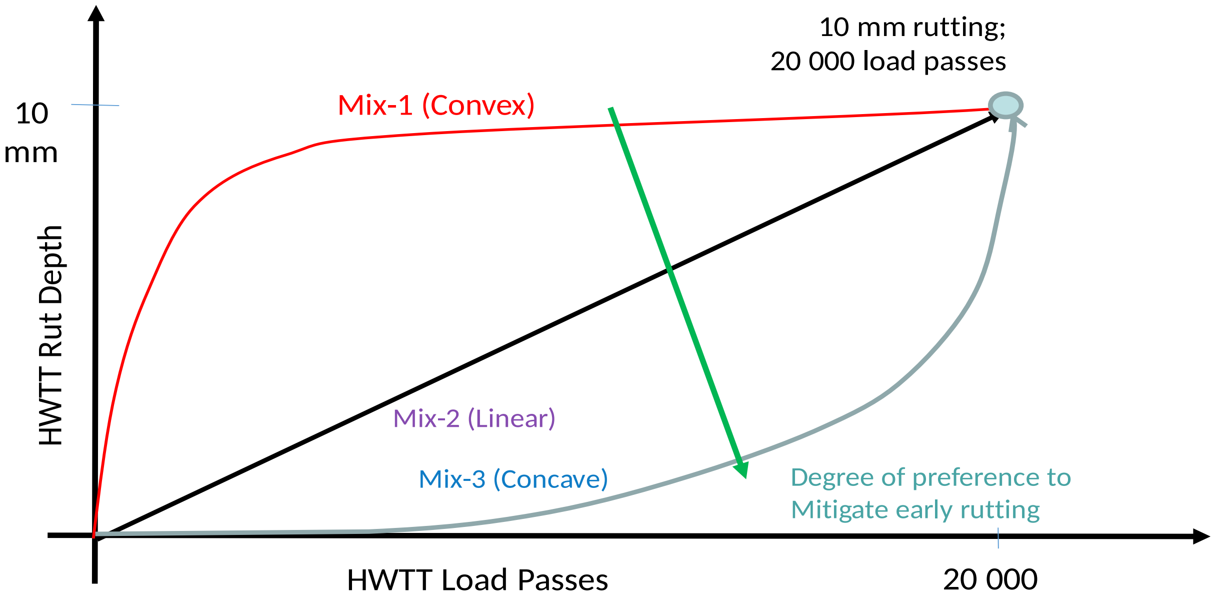

Fig. 3 Conceptual illustration of the HWTT rutting path-history.

Rutting is often more prevalent in the early life of HMA after construction. To mitigate the possibility of early-life rutting, Mix-3 with a concave-shaped rutting response curve will theoretically be preferred over the other mixes, especially for high shear-stress and temperature areas, urban stop-go environments, and highway intersections. The undesirable convex shaped rutting response curve of Mix 1 suggests that those mixes may be prone to early-life rutting, but stabilizes over time partly due to densification. In other words, Mix 1 would be undesirable where early-life rutting is to be mitigated, an aspect which the current Tex-242-F criteria would not readily capture. Besides, it should be noted that the linear-shaped rutting response curve illustrated for Mix-2 hardly ever occurs due to the non-linear viscoelastic nature of HMA [14].

Evidently, based on the path-history curve, there is a need to explore new data analysis methods and HWTT rutting parameters for screening HMA mixes as a supplement to the current Tex-242-F criteria. Three alternative HWTT data analysis parameters were then formulated and investigated in this study, namely, 1) Rutting area, 2) Normalized rutting area, and 3) Shape factor [14].

3.1 Rutting area

The rutting area (Δ_A) is defined as an integral area encompassed under the rutting response curve of the graphical plot of the rut depth versus the number of HWTT load passes. The unit of Δ_A is mm-number of passes or in.-cycle. As illustrated in Equation 1 and Figure 4, this rutting area (Δ_A) is mathematically calculated using the trapezoidal formula by dividing the area under the rutting response curve into ***n*** number of trapezoids [4]:

$$\Delta_A = \frac{N_d}{2n} = \left[f(x_o) + 2f(x_1) + 2f(x_2) + \ldots + 2f(x_{n-1}) + f(x_n)\right] \qquad \text{(Equation 1)}$$

Where, $f(x_o)$ and $f(x_n)$ are rut depth values at the left and right end of each trapezoid, respectively, and n is the number of trapezoids. N_d is the number of HWTT failure load cycles and represents the number of load passes to reach 12.5 mm rutting or 20,000 (test termination), whichever comes first [14]. Note that while the basic trapezoidal concept (Equation 1) was used for mathematically computing the integral area enclosed under the HWTT rutting response curve, other tools such as Matlab software can also be used to compute Δ_A in Figure 4 [4].

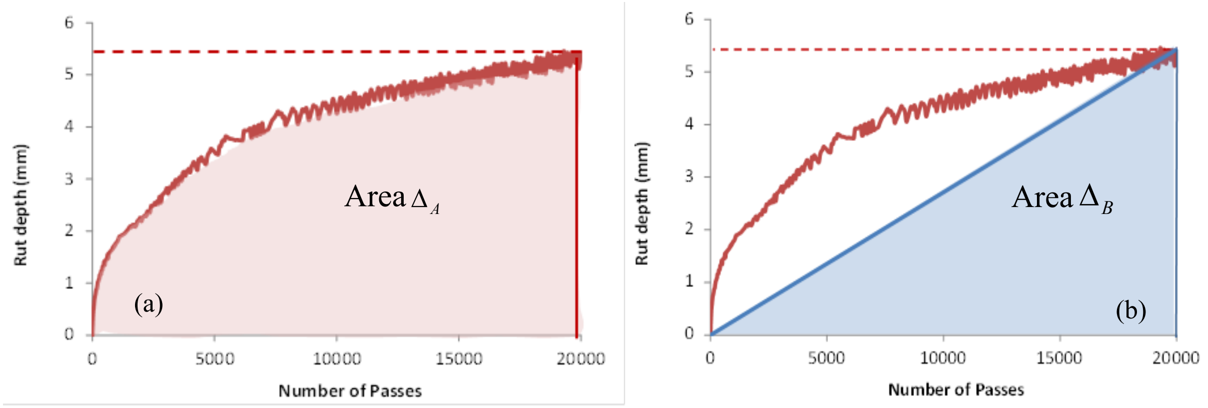

Fig. 4 Rutting response curve – plot of rut depth versus HWTT load passes.

3.2 Normalized rutting area

The normalized rutting area (Rut_Δ) is the area under the rutting response curve divided by the number of HWTT load passes to failure (test termination), i.e., N_d; see Figure 4a. That is removing the N_d factor from Equation 1 yields the normalized rutting area (Rut_Δ). This parameter was derived to capture and account for the rutting path-history of HMA when subjected to HWTT testing. Thus, as opposed to Δ_A, the results in this paper are presented and discussed in the context of Rut_Δ. The unit of Rut_Δ is mm-number of passes or in.-cycle. From Equation 1 and using Figure 4a, Rut_Δ can be computed as follows:

$$Rut_\Delta = \frac{Area\ under\ Rutting\ curve}{N_d} = \frac{\Delta_A}{N_d} = \frac{1}{2n}\left[f(x_o) + 2f(x_1) + 2f(x_2) + \ldots + 2f(x_{n-1}) + f(x_n)\right] \quad \text{(Equation 2)}$$

Mathematically, normalizing the rutting area (Rut_Δ) simply implies removing the N_d factor from the rutting area (Δ_A) in Equation 1 to Equation 2 – i.e., dividing Δ_A (Equation 1) by N_d to get Rut_Δ (Equation 2). Theoretically, higher Rut_Δ in magnitude indicates poor rutting resistance in the HMA mix. Thus, a smaller Rut_Δ in magnitude would theoretically be desired for rut-resistant mixes.

3.3 Shape factor

The Shape Factor (*SF*) is the ratio of the area under the HWTT rutting response curve to a hypothetical triangular area (Δ_B) shown in Figure 4b between the HWTT zero load passes and the failure or test termination point. This SF parameter was derived to capture and account for the shape of the HMA rutting response curve when subjected to HWTT testing. The parameter can be computed as expressed in Equation 3:

$$SF = \frac{Area\ under\ 'Rutting'\ curve}{Area\ under\ a\ triangular\ curve} = \frac{\Delta_A}{0.5 * N_d * Rut_{max}} = \frac{\Delta_A}{\Delta_B} \qquad \text{(Equation 3)}$$

Where $Rut_{\max}$ is the maximum rut depth measured at N_d, i.e., HMA rutting after 20,000 load passes or 12.5 mm whichever comes first; and Δ_B is the triangular area as illustrated in Figure 4b. Theoretically, a numerical value of 1.0 for *SF* suggests a linear rutting response curve (Mix-2 in Figure 3). A $SF > 1.00$ indicates a convex rutting response curve (e.g., Mix-1 in Figure 3), which is theoretically undesirable for high temperature and shear stress locations and urban stop-go sections in terms of the early-life rutting propensity of HMA mixes. On the contrary, A $SF < 1.00$ indicates a concave rutting response curve (e.g., Mix-3 in Figure 3), which would theoretically be more desirable [14].

4. Experimental design plan – materials and HMA mixes

Five commonly used Texas mix types, namely: Type B, Type C, Type D, and CAM (Crack Attenuating Mixture) with 12 different mix-design characteristics, were evaluated and are listed in Table 1, which includes mix type, project site, asphalt binder PG grade and content (AC), aggregate type and addition of Reclaimed Asphalt Pavement (RAP). As documented elsewhere [14], these mixes were selected to geographically cover the main climatic zones of Texas, namely dry-warm (DW), wet-cold (WC), wet-warm (WW), and moderate (M) climatic regions except for dry-cold (DC).

Table 1 Materials and Mix-Design Characteristics.

Mix Type	District Source	Climatic	Highway	Asphalt Binder	Aggregate	Asphalt Binder Content (AC)
CG	Waco	M	IH 35	PG 64-22	Limestone + 30% RAP	4.6%
DG	Laredo	DW	Loop 480	PG 64-22	Crushed Gravel + 20% RAP	5.0%
DG	Laredo	DW	US 83	PG 64-28	Limestone + 17% RAP	4.6%
DG	Bryan	WW	SH 21	PG 64-22	Limestone + 17% RAP	4.8%
D*f*G	Paris	WC	US 277	PG 64-22	Limestone/Dolomite + 17% RAP	5.4%
DfG	Atlanta	WC	US 59	PG 64-22	Quartzite + 20% RAP	5.2%
D*f*G	FTW	WC	APT	PG 64-22	Bridgeport Rock	4.8%
FG	Paris	WC	US 271	PG 76-22	Sandstone	6.8%
CAM	Paris	WC	SH 121	PG 64-22	Igneous/Limestone	7.0%
DG	Corpus Christi	M	US 181	PG 64-22	Limestone/Dolomite + 20% RAP	5.1%
FG	Atlanta	WC	US 82	PG 70-22S	Sandstone	7.8%
DG	Tyler	WC	US 259	PG 70-22S	Sandstone + 1% Lime	4.3%

Legend: CAM = Crack Attenuating Mix (Texas fine-graded crack-resistant mix); CG = Coarse-graded (Texas Type B mix); DG = Dense-graded (Texas Type C mix); DfG = Dense to fine graded (Texas Type D mix); DW = Dry-Warm; FG = Fine-graded (Texas Type F mix); M = Moderate; RAP = Reclaimed Asphalt Pavement materials; WC = Wet-Cold

It should be mentioned that HMA samples for the mixes listed in Table 1 include both field-extracted cores from in-service highways and those molded from plant-mix or raw materials in the laboratory, respectively. With the exception of the field-extracted cores that were tested at the in-situ field density, all the lab-molded HMA specimens were molded to a target density of 93±1%, i.e., 7±1% air voids (AV), as specified by Texas Department of Transportation (TxDOT) standards [13]. Also, three replicates for each mix were tested.

5. Laboratory test results and analysis

This section presents the laboratory results and the corresponding analysis using the new parameters based on HWTT path-history curves. Along with the *SF* parameter, note that as opposed to the mathematical rutting area (Δ_A), the laboratory test results herein have been presented and discussed in terms of the normalized rutting area (Rut_{Δ}) that better accounted for the rutting path-history of HMA when subjected to HWTT testing than the Δ_A parameter [12, 14]. As can be seen in Figure 5, both the traditional

HWTT parameter (Rut_{max}) and newly introduced HWTT parameters (Rut_{Δ} and SF) for the HMA mixes (Table 1) evaluated are comparatively presented.

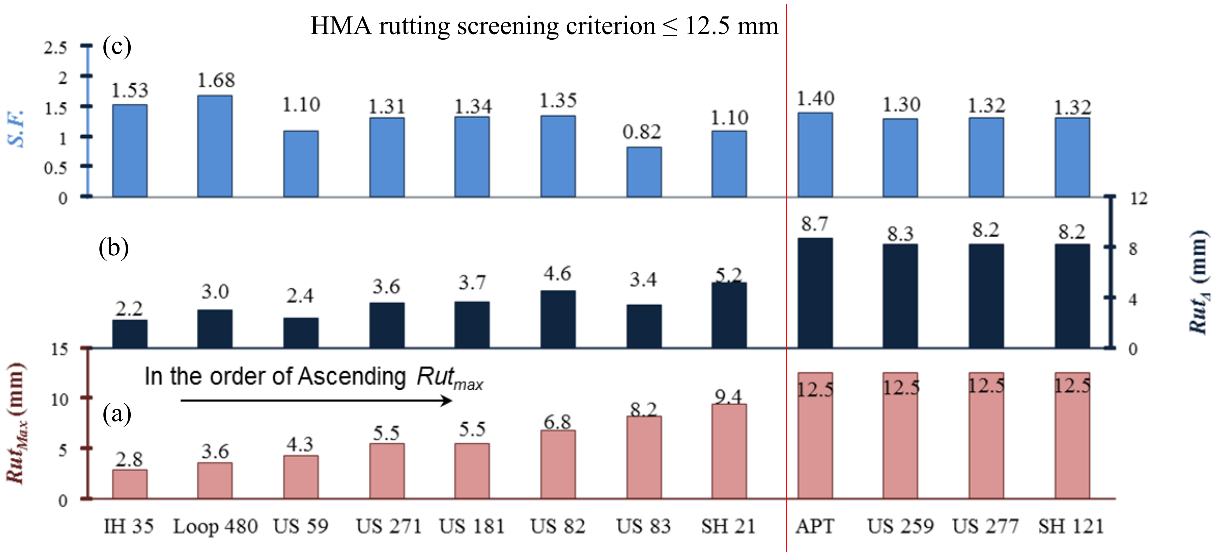

Fig. 5 Comparison of traditional and newly introduced HWTT parameters: (a) Rut_{max}, (b) Rut_{Δ}, and (c) *SF*.

In the Figure 5, the HM mixes (represented by respective in-service highways) are presented in the order of increasing Rut_{max} after 20,000 load passes, and new parameters of the normalized rutting area (Rut_{Δ}) and shape factor (SF) for each mix are presented. Although it is observed that the normalized rutting area (Rut_{Δ}) also closely follows this ranking of the mixes, there are some obvious outliers. For example, the US 83 (Type C) mix ranks worse than each of US 271 (Type F), US 181 (Type C), and US 82 (Type F) mixes based on the traditional HWTT result (Rut_{max}), whereas, due to a superior shape of the rutting curve, it ranks better than each of the three mixes (US 271, US 181, and US 82) in terms of the Rut_{Δ} parameter [14]. Also it is notable from Figure 5 that the SF parameter does not seem to have any correlation with the traditional HWTT parameter (Rut_{max}), implying that the shape of the curve does not depend on the final rut depth of the HMA. These observations are further confirmed by the correlation curves presented in Figure 6 [14].

As presented in Figure 6 (excluding some outliers such as US 83), the correlation curves between the traditional and newly introduced HWTT parameters both reconfirm the arguments drawn in the preceding paragraph. As illustrated in Figure 6a, the parameter Rut_{Δ} has a fairly linear correlation with HWTT rut depth (Rut_{max}). This linear-regression correlation at 92% coefficient of correlation may suggest that the Rut_{Δ} parameter, in addition to capturing the rutting path-history, also provides the same HMA rutting response data as the traditional parameter Rut_{max}. That is, similar to the Rut_{max} trend, the higher the Rut_{Δ} in magnitude, the greater the propensity of the HMA to rutting and vice versa.

On the other hand, the *SF* in Figure 6b shows no correlation whatsoever with the Rut_{max}, signifying that the shape of the curve does not depend on the final rut depth of the mix. In other words, the magnitude of the final rut depth of any given HMA mix is rutting-path independent. Thus, the following mix screening criteria are tentatively proposed for the newly introduced HWTT parameters as a safeguard against early-life mixture rutting: (a) $\mathrm{Rut}_{\Delta} \leq 8.0$ and (b) SF $\leq$ 1.25 [14].

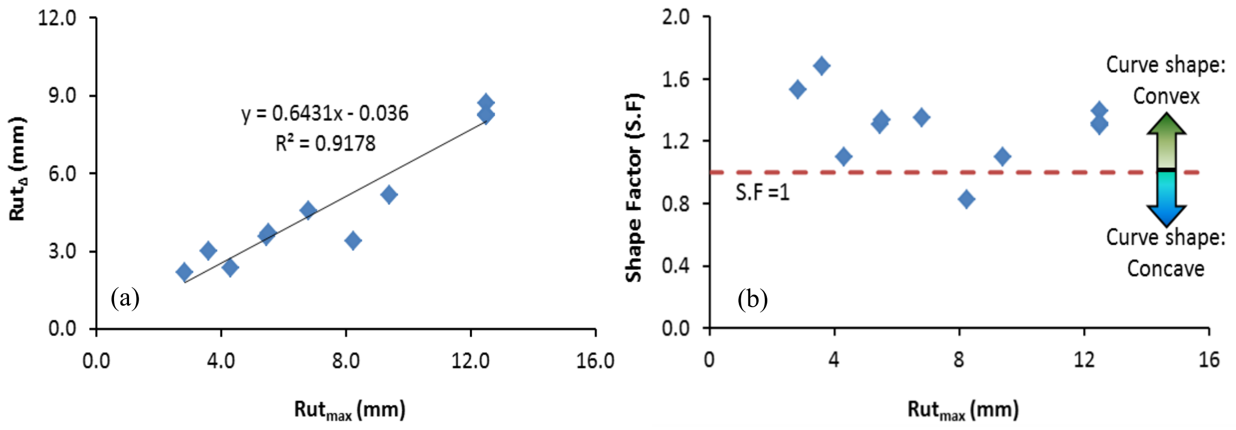

Fig. 6 Correlation of traditional versus newly formulated HWTT parameters: (a) Rut_{Δ} vs. Rut_{max}, and (b) *SF* vs. Rut_{max}..

6. Preliminary correlations with field performance data

It is seen that the new parameters obtained from the HWTT rutting path-history curves are somewhat different from the traditional final rut depth. In order to implement these new parameters in practice, the correlation between new parameters and field performance should be investigated. Thus, this section is mainly to compare the new and traditional parameters with the field observations. For this purpose, five different in-service highway test sections, randomly selected from Table 1 because of their field data availability, were utilized to compare and validate the laboratory test results with field performance observations. As shown in Table 2, the in-service highway sections have varying traffic, climatic, and pavement structural conditions, but bearing the same HMA mixes that were tested in the laboratory as previously listed in Table 1.

Table 2 Description of the Selected In-Service Highway Test Sections.

Highway	PVMNT Type	Mix Type	Date of Construction	Climatic Region	Max PVMNT Temperature	AADTT*
US 59	Overlay-HMA-LTB	D*f*G	Apr 2011	Wet-Cold	135.5°F	1502
Loop 480	New Construction	DG	June 2012	Dry-Warm	145.5°F	60
SH 121	Overlay-HMA-CTB	CAM	Oct 2011	Wet-Cold	137.5°F	468
SH 21	Overlay-HMA-FB	DG	July 2012	Wet-Warm	127.5°F	560
IH 35 Frontage	New Construction	CG	Oct 2011	Moderate	131.3°F	53

LTB = Lime Treated Base; CTB = Cement Treated Base; AADTT = Average Annual Daily Truck Traffic

Figure 7 presents the HWTT rutting response curves of the five HMA mixes along with their respective field rutting performances, which were measured from the five in-service highway test sections listed in Table 2 [14]. It is observed that the shape of the HWTT rutting curves can be effectively implemented as a critical tool to predict the field rutting performance of a mix, particularly with respect to early-life rutting. For example, the US 59 and the IH 35 HWTT and field rutting history curves up to 7 months follow a similar pattern [14]. In order to compare the HWTT laboratory results with field performance of the mixes, it is vital that only the field rutting contribution of the relevant HMA layer should be taken into account. Since a full-scale forensic evaluation was beyond the scope of this study, the contributions of the respective layers were estimated through mechanistic-empirical (M-E) modeling (using the MEPDG software) of the in-service highway pavement structures [14]. Each highway section was modeled using the M-E PDG design software to calculate the percentage contribution of each layer towards the total surface rut depth. These estimated percentages were then used to estimate the rutting contribution of the relevant top HMA layers shown in Figure 7 from the total surface rut depth measured from field surveys of the in-service highway test sections. Table 3 presents HWTT rutting parameters calculated for these HMA mixes along with their respective field rutting performances.

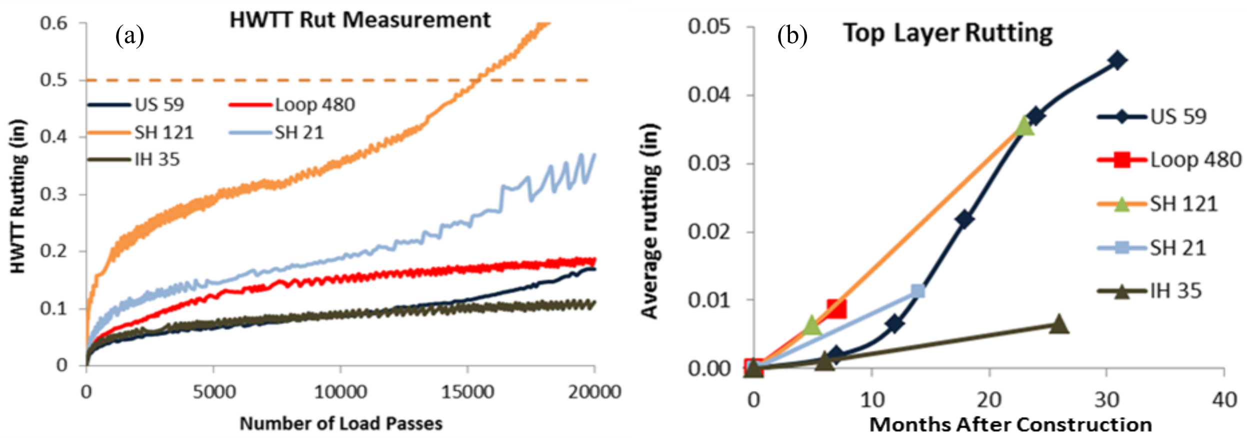

Fig.7 Comparison of HWTT output rutting curves with field rutting: (a) HWTT rutting response curves, and (b) field rutting performance curves.

Table 3 Comparison of HWTT lab results with field rutting performance.

	HWTT (Tex-242-F)				Field Rutting (Inches)		Top HMA Layer Rutting (Inches)	
Highway	Rut_{max} (Inches)	Δ_A (in-cycle)	Rut_Δ (inches)	*SF*	7 months after construction	August 2014	7 months after construction	August 2014
US 59	0.170	1865	0.090	1.099	0.006	0.130	0.002	0.045
Loop 480	0.190	2700	0.130	1.433	0.063	0.063	0.009	0.009
SH 121	0.500	4928	0.320	1.316	0.026	0.063	0.012	0.036
SH 21	0.370	4050	0.200	1.096	0.030	0.060	0.002	0.011
IH 35	0.110	1708	0.090	1.496	0.020	0.040	0.001	0.007

Based on the comparison between the HWTT results and the field rutting performance presented in Table 3, it is observed that the traditional HWTT rut depth may not be sufficient to accurately predict the field rutting performance of a mix. For example, the US 59 Type D and the Loop 480 Type C mixes have almost similar HWTT rut depths (Rut_{max} = 0.17 inch and 0.19 inch, respectively), while the early-life field rutting performance of these two HMA mixes are widely different [14]. However, considering the HWTT rutting path-history of the HMA mixes can lead to a better prediction of their field rutting performance. Though not very pronounced, as seen in Figure 7, the Loop 480 Type C mix has a somewhat undesirable convex-like shape for the HWTT rutting response curve, indicating that the mix will be more prone to early-life rutting as compared to the US 59-Type D mix, which exhibits a concave-like shape for the HWTT rutting response curve.

When comparing the laboratory HWTT results of the HMA mixes with their respective field performances, it needs to be considered that the five in-service highway test sections selected for this study vary widely in terms of the traffic, climatic, and pavement structural conditions, as listed previously in Table 2, which they are subjected to. Also, since all five test sections are at different stages of their service lives, the field rutting performances at 7 months after construction of each test section were considered for baseline comparison of all the test sections.

To obtain a truly objective correlation between laboratory and field rutting performance, it is imperative that these conditions are kept uniform among the test sections to be compared. Thus, continued field monitoring of these test sections is warranted to enable adequate and conclusive comparisons with the laboratory test data in the future.

7. Summary and recommendations

In this study, the HWTT data analysis and HMA mix screening procedure were reviewed in an attempt to generate new HWTT data analysis methods and HMA pass-fail screening parameters that can better predict the HMA field performance, particular early-life rutting. Based on the evaluation of different HMA mixes, the key findings and recommendations drawn from this study are summarized as follows:

- The current HWTT protocol specifies rutting performance of any HMA mix at the end of the test only, without considering the rutting path-history. Thus, the current HWTT protocol fails to explain HMA mixes having similar laboratory rutting performances but widely varied field rutting performance, especially in terms of early-life rutting.

- To address this issue and capture the HMA rutting path-history, three new HWTT data analysis parameters were introduced, namely the rutting area (Δ_A), the normalized rutting area (Rut_Δ), and the shape factor (SF). Among these parameters, the Rut_Δ and the SF showed promising potential to capture the HWTT rutting response and path-history.
- Analysis of the HWTT data of several commonly used Texas mixes conceptually confirmed the superiority of the Rut_Δ and the SF parameters in capturing the effects of the HWTT rutting path-history as well as the total rut depth.
- Based on the comparative evaluation and discussion, , it is proposed herein that the Rut_Δ and SF parameters should be considered in the HWTT protocol and Tex-242-F test procedure as a supplement to the traditional HWTT parameters (i.e., the magnitude of the measured rut depth [≤ 12.5 mm] and the number of load passes to failure [test termination]), with the following tentative HMA mix pass-fail screening criteria: (a) $\text{Rut}_\Delta \leq 8.0$ and (b) SF ≤ 1.25. These parameters are particularly critical for assessing the HMA's potential and susceptibility to early-life rutting.

Overall, the newly derived HWTT data analysis parameters (Δ_A, Rut_Δ, and SF) yielded promising results in terms of predicting the early-life rutting performance of the HMA mixes. Only preliminary correlations with limited field data were conducted in this study. However, more lab testing and correlations with field performance data are strongly recommended to supplement and validate the findings reported in this paper. As such, a comprehensive field verification study is still warranted to aid in validating the concepts and refining the proposed HMA pass-fail screening criteria based the Rut_Δ and SF parameters. Additionally, there is also an inherent need to comparatively evaluate these newly formulated HWTT parameters against other traditional tests such as the dynamic modulus, flow number, repeated load permanent deformation, etc., in future studies.

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