Novel Method for Moisture Susceptibility and Rutting Evaluation Using Hamburg Wheel Tracking Test

Fan Yin, Edith Arambula, Robert Lytton, Amy Epps Martin, and Lorena Garcia Cucalon

The Hamburg wheel tracking test (HWTT) has been widely used as a standard laboratory test to evaluate the moisture susceptibility and rutting resistance of asphalt mixtures. The stripping inflection point and the rut depth at a certain number of load cycles are two common parameters obtained from the test. Although these parameters have been widely adopted by several transportation agencies, the accuracy and variability in characterizing mixture properties of these parameters have been questioned. In this study, a novel method to analyze the HWTT results is introduced and three new parameters are proposed to measure the moisture susceptibility and rutting resistance of asphalt mixtures. The new parameters are compared against the current ones to assess their capability to discriminate between three types of asphalt mixtures with different performance results in the HWTT. Significant advantages in characterizing mixture resistance to stripping and rutting are demonstrated by the new parameters. In addition, the effect of antistripping additives and recycled materials on mixture performance in the HWTT is evaluated with mixtures from a field project in Texas. Test results for the new parameters show that the addition of antistripping additives improves the susceptibility of asphalt mixtures to moisture. Specifically, the use of lime is more beneficial for improving mixture performance than a liquid antistripping agent. Conversely, the addition of moisture-resistant materials provides mixtures with increased moisture susceptibility but improved rutting resistance.

The Hamburg wheel tracking test (HWTT) is a laboratory procedure that uses repetitive loading in the presence of water and measures the rut depth induced in an asphalt mixture with increasing load cycles. The test results are then processed to determine the asphalt mixture’s moisture susceptibility and rutting resistance. The Hamburg wheel tracking device was first developed by Esso A.G. in Hamburg, Germany, for testing a pair of slab specimens (1). However, with the wide implementation of the Superpave® gyratory compactor (SGC), several transportation agencies adopted a testing protocol using cylindrical specimens. Typically, two SGC cylindrical specimens with a diameter of 6.0 in. (150 mm) and a thickness of 2.4 in. (61 mm) are placed side by side, submerged in water at 122°F (50°C), and subjected to approximately 52 passes of a steel wheel per minute (AASHTO T324). Each set of specimens is loaded for a maximum of 20,000 load cycles or until the center of a specimen deforms by 0.5 in. (12.5 mm).

During testing, rut depths at different positions along the specimens are recorded with each load cycle. The average rut depth of the three center measurements is then plotted and presented as the output of the test. As shown in Figure 1, the resulting HWTT curves (i.e., rut depth at the center of the specimen versus load cycle) can be divided into the following three main phases: (a) postcompaction phase, (b) creep phase, and (c) stripping phase (2). The postcompaction phase consists of the consolidation of the specimen that occurs as the wheel load densifies the mixture and the air voids (AVs) decrease significantly. This phase usually occurs within the first 1,000 load cycles. The creep phase is the deformation that occurs primarily as a result of the viscous flow of the asphalt mixture and is represented by an approximately constant rate of increase in rut depth with load cycle. The stripping phase starts once the bond between the asphalt binder and the aggregate starts degrading, causing visible damage such as stripping or raveling with additional load cycles. The stripping inflection point (SIP) represents the number of load cycles on the HWTT curve at which a sudden increase in rut depth occurs, mainly as a result of the stripping of the asphalt binder from the aggregate (3). The SIP is graphically represented at the intersection of the fitted lines that characterize the creep phase and the stripping phase.

Currently, the SIP and rut depth at a certain number of load cycles are widely used as the two main HWTT parameters to evaluate the moisture susceptibility and rutting resistance of asphalt mixtures, respectively. Asphalt mixtures with higher SIP values and lower rut depths are considered to have good performance in the HWTT. In addition, the ratio of the slope of the creep phase to the stripping phase is used as a moisture susceptibility indicator (4).

Previous studies have indicated that the HWTT is able to discriminate asphalt mixtures with different performance results in regard to moisture susceptibility and rutting resistance (5–7). However, laboratory experience with the test has proved that the current HWTT parameters are not always able to accurately evaluate these mixture properties. For instance, mixture resistance to rutting cannot be precisely characterized by rut depth at a certain number of load cycles because of the interacting effects on rut depth from both loading and stripping, especially for mixtures that are prone to stripping in the presence of water. In addition, fitting two straight lines
for the creep phase and the stripping phase is likely to introduce a significant bias to the evaluation of moisture susceptibility with the SIP because the postcompaction phase is assumed to be the first 1,000 cycles and a 1-mm rut depth is used to estimate the slope of the creep and stripping phases.

In this study, a novel methodology to analyze HWTT results is provided by curve fitting the entire output of rut depth versus load cycle. Three new parameters are proposed to evaluate mixture moisture susceptibility and rutting resistance separately and with significantly improved accuracy. A detailed discussion of the new analysis methodology is presented in the following section.

**DATA ANALYSIS METHODOLOGY**

The rut depth (RD) versus load cycle HWTT output data are first plotted to obtain a typical curve for the test as shown in Figure 2. Then, Equation 1 is used to model the results:

$$\text{RD}_{LC} = \rho \left( \ln \left( \frac{\text{LC}}{\text{LC}_{ult}} \right) \right)^{40}$$

where

- $\text{LC}$ = number of load cycles,
- $\text{RD}_{LC}$ = rut depth at certain number of load cycles (mm), and
- $\text{LC}_{ult}$, $\rho$, and $\beta$ = model coefficients.

The fitted curve is composed of one part with negative curvature followed by another part with positive curvature. In the part of the fitted curve with negative curvature, the mixture is expected to be stiffening by the action of the repeated wheel load, and the rut depth is increasing as a result of the viscoplastic deformation of the asphalt mixture. Thus, this part of the curve can be used to evaluate mixture resistance to rutting in the presence of water. In the part of the fitted curve with a positive curvature, the mixture is expected to be softening as a result of the stripping of the asphalt binder from the aggregate after water penetrates through the interface between the two components. The increasing rut depth in this part is more related to the stripping of the asphalt binder from the aggregate than the viscoplastic deformation of the mixture and, therefore, this part of the curve can be used to evaluate the mixture’s moisture susceptibility.

**Moisture Susceptibility Evaluation**

The critical point of the HWTT results is where the curvature of the rut depth versus load cycle curve changes from negative to positive (i.e., inflection point). As shown in Figure 2, this point is referred to as the stripping number (SN) in this study, and the number of load cycles at which the SN occurs ($\text{LC}_{SN}$) is proposed as a parameter to quantify moisture susceptibility.

To determine the $\text{LC}_{SN}$, the second derivative of Equation 1 is set to zero. The derivation is determined as shown in Equation 2:

$$\frac{\partial^2 \text{RD}}{\partial \text{LC}^2} = \frac{\rho}{\beta \cdot \text{LC}^*} \left( \frac{1}{\beta} + 1 \right) \left\{ \ln \left( \frac{\text{LC}_{ult}}{\text{LC}} \right) \right\}^{(\beta - 2)}$$

Setting Equation 2 to zero, the $\text{LC}_{SN}$ is found as expressed in Equation 3:

$$\text{LC}_{SN} = \text{LC}_{ult} \exp \left( -\frac{\beta + 1}{\beta} \right)$$

$\text{LC}_{SN}$ represents the maximum number of load cycles that the asphalt mixture can resist in the HWTT before the adhesive fracture between the asphalt binder and the aggregate occurs. Mixtures with higher $\text{LC}_{SN}$ values are expected to be less moisture susceptible as compared with those with lower $\text{LC}_{SN}$ values. Mixtures that do not show a stripping phase in the HWTT are considered to have a robust resistance to moisture damage, with $\text{LC}_{SN}$ values larger than the number of load cycles applied during the test (i.e., 20,000).

As previously mentioned, the rut depth accumulated before the SN is related primarily to the viscoplastic deformation of the asphalt mixture under loading. For the HWTT results, the viscoplastic strain in the specimen can be calculated as the ratio of the rut depth to the specimen thickness at any given number of load cycles up to $\text{LC}_{SN}$.

A typical viscoplastic strain versus load cycle HWTT curve including...
the postcompaction phase and part of the creep phase is presented in Figure 3a. The Tseng–Lytton model used to fit this part of the curve is shown in Equation 4 (8):

\[ \varepsilon^p = \varepsilon^{vp} \exp \left( -\frac{\alpha}{(\lambda T)^{\frac{1}{LC}}} \right) \]  

(4)

where

\( \varepsilon^{vp} \) = viscoplastic strain,
\( \varepsilon^{\infty vp} \) = saturated viscoplastic strain in the HWTT specimen,
\( \alpha \) and \( \lambda \) = model coefficients.

The total rut depth of the HWTT specimen in the stripping phase has two components: the contribution from stripping and from further viscoplastic deformation under loading. Once \( \varepsilon^{\infty vp}, \alpha, \) and \( \lambda \) are determined from a nonlinear regression analysis, the viscoplastic strain of the specimen can be projected into the stripping phase by using Equation 4, as shown by the extended fitted curve in Figure 3b. Therefore, the permanent strain induced by stripping \( (\varepsilon^s) \) can be calculated by the difference between the total permanent strain and the projected viscoplastic strain in the stripping phase. The total permanent strain \( (\varepsilon^p) \) of the HWTT specimen is determined with Equation 5:

\[ \varepsilon^p = \frac{RD_c}{T} \]  

(5)

where \( T \) is the thickness (in mm) of the HWTT specimen.

With Equation 4 subtracted from Equation 5, the stripping strain of the HWTT specimen is calculated as described in Equation 6:

\[ \varepsilon^s = \frac{RD_c}{T} - \varepsilon^{vp} \exp \left( -\frac{\alpha}{(\lambda T)^{\frac{1}{LC}}} \right) \]  

(6)

A typical stripping strain versus load cycle HWTT curve is presented in Figure 4. As shown, the stripping strain is zero at load cycles of up to LCSN, and afterward it increases rapidly. A step function as expressed in Equation 7 is then used to model the stripping strain of the specimen:

\[ \varepsilon^s = \begin{cases} \varepsilon^{s0} \{\exp[0(LC - LC_{SN})] - 1\} & \text{if } LC - LC_{SN} \geq 0 \\ 0 & \text{if } LC - LC_{SN} \leq 0 \end{cases} \]  

(7)

where \( \varepsilon^{s0} \) and \( \theta \) are model coefficients.

To quantify rut depth accumulation resulting from stripping, the parameter stripping life \( (LC_{ST}) \) is proposed. As shown in Figure 4, it represents the number of additional load cycles after LCSN needed for the rut depth accumulated by the predicted stripping strain to reach 0.5 in. (12.5 mm), which is the common HWTT failure criterion adopted by several agencies. The stripping strain corresponding to 0.5 in. (12.5 mm) rut depth is calculated with Equation 8:

\[ \varepsilon^{s0}_{12.5 \text{ mm}} = \frac{12.5}{T} \]  

(8)

With Equation 7 and Equation 8 equal, \( LC_{ST} \) is found as described in Equation 9:

\[ LC_{ST} = \frac{1}{\theta} \ln \left( \frac{12.5}{T} \varepsilon^{s0} + 1 \right) \]  

(9)
Mixtures with higher LCST values are expected to be less moisture susceptible after the SN as compared with those with lower LCST values. LCST cannot be determined for mixtures that do not exhibit a stripping phase during the test.

**Rutting Resistance Evaluation**

To quantify mixture resistance to rutting in the HWTT and compare different mixtures, the parameter viscoplastic strain increment (\(\Delta \varepsilon^p\)) is proposed. This parameter is calculated as the slope of the projected viscoplastic strain by the Tseng–Lytton model at a certain number of load cycles (i.e., 10,000 load cycles), as described in Equation 10:

\[
\Delta \varepsilon_{10,000}^p = \alpha \varepsilon^p \exp\left[ -\left( \frac{\alpha}{10,000} \right) \right] \left(10,000\right)^{(k+1)}
\]

The determination of this HWTT rutting resistance parameter isolates the viscoplastic strain during the creep phase and does not include contributions from the postcompaction phase as a result of different specimen AVs or after the SN as a result of the stripping of asphalt binder from the aggregates. Asphalt mixtures with higher \(\Delta \varepsilon_{10,000}^p\) values are expected to be more susceptible to rutting than those with lower \(\Delta \varepsilon_{10,000}^p\) values.

**Summary**

Thus in this study, two parameters (LC50 and LCST) are proposed to evaluate mixture susceptibility to moisture before and after the SN, respectively. LC50 is meant to complement \(\Delta \varepsilon_{10,000}^p\) to evaluate mixture resistance to rutting in the presence of water. Compared with the current HWTT parameters, the new parameters are calculated from the HWTT results by using nonlinear regression and avoiding subjective data interpretation when two straight lines are fitted to the creep phase and the stripping phase. More important, the new parameters allow mixture moisture susceptibility and rutting resistance in the HWTT to be evaluated separately.

**COMPARISON OF TEST PARAMETERS**

Actual HWTT results for three different field mixtures (i.e., mixtures A, B, and C) are analyzed in this section by using the new parameters. Comparisons of \(\Delta \varepsilon_{10,000}^p\) versus rut depth at a certain number of load cycles and LC50 and LCST versus SIP are performed to illustrate the capability of these parameters to characterize mixture rutting resistance and moisture susceptibility, respectively.

The HWTT results of rut depth versus load cycle for Mixture A and Mixture B are shown in Figure 5, together with rut depths at 5,000, 10,000, 15,000, and 20,000 load cycles. As illustrated, the rut depth of Mixture A was higher than that of Mixture B for the first 15,000 load cycles, while the opposite trend was shown with increasing load cycles. Therefore, an inconsistent conclusion in regard to evaluating rutting resistance of Mixture A versus Mixture B could be obtained on the basis of the number of load cycles selected for the rut depth evaluation. On the basis of the shape of the HWTT test result for Mixture B, the mixture likely experienced the postcompaction phase, creep phase, and stripping phase during the test. In other words, stripping occurred in the mixture before 20,000 load cycles was reached. Therefore, the accumulated rut depth of Mixture B after the SN resulted from both stripping and viscoplastic deformation. A significant difference in rut depth in the postcompaction phase between Mixture A and Mixture B is shown in Figure 5, which was likely attributed to the difference in mixture AV. Consequently, the characterization of mixture resistance to rutting in the HWTT based on rut depth at a certain number of load cycles does not necessarily adequately describe the behavior of the mixture.

To characterize mixture resistance to rutting better, the point at which stripping occurs should be first determined. In addition, the rut depth accumulated in the postcompaction phase should be discounted for an accurate rutting resistance analysis. LC50 values for Mixture A and Mixture B were calculated to be 20,000 and 4,667 load cycles, respectively. Therefore, no stripping was exhibited by Mixture A, while stripping occurred at 4,667 load cycles for Mixture B. Figure 6 presents the permanent strain and the viscoplastic strain versus load cycles for Mixture A and Mixture B. As illustrated, the fitted viscoplastic strain by the Tseng–Lytton model for Mixture A was

**FIGURE 5** HWTT results of rut depth at certain number of load cycles for Mixture A and Mixture B.

**FIGURE 6** HWTT results of \(\Delta \varepsilon_{10,000}^p\) for Mixture A and Mixture B.
The new moisture susceptibility parameter $LC_{SN}$ calculated for Mixture C with the two different ending points resulted in values of 4,032 and 4,051 for the long and short tests, respectively. The indication is that $LC_{SN}$ was much less dependent on the ending point of the test and that the calculation avoided the bias resulting from data interpolation when two straight lines are fitted for the creep phase and the stripping phase.

The other moisture susceptibility parameter $LC_{ST}$ for Mixture C was calculated to be 15,690 and 15,860, for the long and short tests, respectively. In addition to the parameter of $LC_{SN}$ for characterizing mixture moisture susceptibility before the SN, $LC_{ST}$ was able to illustrate mixture performance in the HWTT after the SN. To summarize, the new parameters $LC_{SN}$ and $LC_{ST}$ were able to better characterize the moisture susceptibility of a mixture in the HWTT as compared with the current SIP parameter.

**EXPERIMENTAL DESIGN AND TEST RESULTS**

Previous studies evaluating the moisture susceptibility of asphalt mixtures indicated that mixture moisture susceptibility and rutting resistance can be improved through the addition of antistripping additives and recycled materials [i.e., reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS)] (10–13).

In this part of the study, several laboratory mixed and laboratory compacted specimens, including a hot-mix asphalt (HMA) and a warm-mix asphalt (WMA) mixture (Evotherm), were prepared by using the SGC as designed. A companion set of specimens was also prepared with 1% lime by weight of mix and 0.5% liquid antistripping agent (LAS) by weight of binder. The as-designed mixtures replicated mixtures used in a field project in Texas. In addition, an HMA and a WMA mixture (Evotherm) with 15% RAP and 3% RAS were fabricated. The asphalt binder used in the asphalt mixtures without recycled materials was a performance graded (PG) 70-22, while that used in mixtures with recycled materials was a PG 64-22. All laboratory mixed and laboratory compacted specimens had an AV range of 6.5% to 7.5%. The effect of the two antistripping additives and recycled materials [i.e., reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS)] (10–13).
LAS. However, mixture resistance to stripping as indicated by LCSN and LCST was reduced with the addition of recycled materials, which could speed up the water penetration through the interface between the aggregate and the overaged binder in the recycled mixture.

As illustrated in Figure 8 and Figure 9, for both HMA and WMA mixtures, the incorporation of either antistripping agent significantly improved mixture moisture susceptibility, as indicated by higher LCSN and LCST values, and this improvement was more pronounced for HMA than for WMA. In addition, the effect of both antistripping agents on LCSN and LCST was equivalent for HMA, while for WMA the effect of adding lime was more pronounced than that from adding LAS. However, mixture resistance to stripping as indicated by LCSN and LCST for both HMA and WMA was reduced with the addition of RAP and RAS. This behavior could be attributed to poor bonding between the aggregate and the overaged binder in the recycled materials, which could speed up the water penetration through the interface between the two components, subsequently causing early adhesive fracture and stripping in the mixture.

Figure 10 shows that the HMA with lime had lower Δε_{10,000} values and thus better rutting resistance than the as-designed mixture, while no improvement was observed after adding LAS. In addition, equivalent rutting resistance was shown by the WMA mixture with lime and LAS as compared with the as-designed WMA mixture, indicating that lime and LAS were not able to improve the WMA rutting resistance in the HWTT. The comparison in Δε_{10,000}^vp for the HMA with RAP and RAS versus the as-designed HMA shows that the incorporation of recycled materials yielded a stiffer mixture with better resistance to rutting in the HWTT. In the case of WMA with RAP and RAS, the calculated LCSN value was lower than 1,000 load cycles, as shown in Figure 8, which revealed that stripping occurred early during the test (i.e., in the postcompaction phase). Therefore, no creep phase was observed for the mixture, and consequently, the contribution from RAP and RAS to the rutting resistance for WMA could not be determined.

In general, the addition of either of the two antistripping additives was able to improve the HMA and WMA mixture moisture susceptibility. However, no improvement in rutting resistance was observed by adding either of the two antistripping additives, except for HMA with lime, which exhibited better rutting resistance versus the as-designed HMA mixture. In addition, better or equivalent performance was shown by HMA and WMA mixtures with lime versus those with LAS. The addition of recycled materials in HMA improved mixture stiffness and consequently resistance to rutting in the HWTT. However, the effect on mixture susceptibility to moisture was adverse for HMA and WMA mixtures.

### CONCLUSIONS AND RECOMMENDATIONS

The HWTT has been widely used as a standard laboratory test to evaluate the moisture susceptibility and rutting resistance of asphalt mixtures. Two parameters are commonly used to describe mixture performance, the SIP and the rut depth at a certain number of load cycles. Although widely adopted by several transportation agencies, these parameters do not always provide accurate conclusions based on the behavior of the mixtures during testing. In this study, a novel method was introduced to analyze HWTT results, and three new parameters were proposed to quantify mixture susceptibility to moisture and rutting resistance. The current and new parameters were compared for three field mixtures with different performance results in the HWTT to evaluate their capability to adequately characterize mixture performance. In addition, several HMA and WMA mixtures from a field project in Texas were used to evaluate the effect of antistripping additives and recycled materials by using the proposed HWTT parameters. The following conclusions based on this study are made:

1. LCSN, LCST, and Δε_{10,000}^vp are proposed as performance parameters in this study based on curve fitting of the entire rut depth versus load cycle HWTT results. Compared with the current parameters, the calculation of the new parameters avoids the bias introduced from the subjective data interpolation when two straight lines are fitted for the creep phase and the stripping phase, and the interference on mixture performance evaluation of the ending point of the test. In addition, the mixture property characterization based on the new parameters is not biased from the arbitrary assumption of the duration of the postcompaction phase (i.e., 1,000 load cycles) and the difference in mixture performance resulting from specimen AV.

2. The number of load cycles at which the mixture transitions from the creep phase to the stripping phase, LCSN, is proposed in this study as an indicator of moisture susceptibility before the SN. It represents the maximum number of load cycles that the asphalt mixture can resist in the HWTT before water penetrates through the interface of the asphalt binder and the aggregate, causing adhesive fracture between the two components. Another moisture susceptibility parameter,
LC$_{SN}$ and LC$_{ST}$ values are expected to be less moisture susceptible mixtures with different moisture susceptibility. Mixtures with higher LC$_{SN}$ and LC$_{ST}$ values are expected to be less moisture susceptible as compared with those with lower LC$_{SN}$ and LC$_{ST}$ values.

3. Rut depth accumulated in the HWTT specimen before the SN is related primarily to the viscoelastic deformation of the mixture with increasing load cycles. The proposed mixture rutting resistance parameter $\Delta\varepsilon_{2000}^{vp}$ is able to discriminate asphalt mixtures with different rutting resistance in the presence of water in the HWTT. Mixtures with lower $\Delta\varepsilon_{2000}^{vp}$ values are expected to have better resistance to rutting as compared with those with higher $\Delta\varepsilon_{2000}^{vp}$ values.

4. The inclusion of antistripping agents was able to improve mixture moisture susceptibility, while the improvement in rutting resistance was insignificant. For the majority of cases in this study, the use of lime as an antistripping agent was more beneficial than LAS for improving mixture performance in the HWTT. In addition, the benefits of adding antistripping agents were more pronounced for HMA versus WMA.

5. The inclusion of recycled materials was able to increase mixture stiffness and improve rutting resistance. However, mixture moisture susceptibility was increased, which might be attributed to poor bonding between the aggregate and the overaged binder in the recycled materials.

The following recommendations based on this study are made:

1. Future research into the correlation between the proposed HWTT parameters with actual field pavement performance is necessary.
2. A bias and precision statement for the proposed parameters is needed to discriminate asphalt mixtures with different rutting and moisture susceptibility characteristics.
3. Early stripping (i.e., LC$_{SN}$ less than 2,000 load cycles) has frequently been observed in the HWTT for several asphalt mixtures, especially those with relatively lower PG grade binders. These mixtures (such as the WMA with RAP and RAS in this study) have a limited duration of the creep phase before the SN. Therefore, determination of the viscoplastic deformation and the rutting resistance parameter $\Delta\varepsilon_{1000}^{vp}$ is usually unfeasible. To evaluate the rutting resistance of the asphalt mixtures that exhibit early stripping, the HWTT could be performed at a lower temperature.
4. Further characterization of mixture moisture susceptibility after the SN could include fracture mechanics analysis of crack propagation under wheel loading and water softening in the HWTT. The evolution of damage density and the use of the J-integral formulation of Paris’ law in the stripping phase are recommended.

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