Accelerated testing of noise performance of pavements

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ABSTRACT: Noise properties of road pavements change over time due to wear from traffic, impact of weather conditions, etc. With the introduction of noise reducing pavements in many countries, it has become increasingly important to understand how the noise properties of pavements change as they get older. The Danish Road Directorate and the University of California Pavement Research Centre have investigated the feasibility of using test results from Heavy Vehicle Simulator (HVS) test sections to predict the development of the noise properties of pavements. Pavement surface textures were measured at regular intervals with a three-dimensional scanner on a range of different HVS test sections on various projects. The Dutch Acoustical Optimization Tool (AOT), developed to predict the noise properties of road pavements based on texture data, and pavement type, was used for the analyses of the measured texture profiles.

1 INTRODUCTION

There are increasing demands for general improved environmental living conditions from modern society and communities living near roads are especially demanding reduced noise levels. Consequently there is increased pressure on road authorities to reduce noise levels. This has created a demand for durable and cost effective measures for noise abatement. The development of noise reducing road surfaces has in some countries proved to be an attractive solution that can be implemented by road authorities when constructing new roads or when maintaining, rehabilitating or widening existing pavements.

Noise emissions as well as noise reduction are often measured when a pavement is new. It is known from the literature (Lu, et al., 2009; Bendtsen, et al., 2009; Bendtsen, 2010) that noise emissions from pavements increase over time due to wear and environmental influence. However, reductions in noise levels have also been observed as pavements get older. When introducing quieter pavements, authorities need to know the expected average noise reduction over the lifetime of the new pavement type, which could be as long as ten to fifteen years. Long-term pavement performance studies measuring changes in noise levels over the life of the pavement, such as those being conducted by the Danish Road Directorate (DRD) in Denmark and University of California Pavement Research Center (UCPRC) in California, are important for research purposes, but of little immediate help to road authorities who need to make decisions on choice of pavement in a much shorter time frame.

In cooperation with the UCPRC, DRD recently performed a study of acoustical aging on asphalt pavements (Bendtsen, et al., 2009). This investigation concluded that there appears to be a linear relation between noise level and time/traffic. It also highlighted the need for measurements and analyses of the change in pavement texture over time to get a deeper insight and understanding of the ongoing noise level increases. In a follow-on study by the two institutions, a much faster method for predicting lifetime noise increases on pavements has been developed and tested. Some of the data used in the development of the prediction models was obtained from accelerated pavement tests (APT) at the UCPRC, where regular texture and other pavement surface property assessments could be taken on test pavements under controlled conditions.

2 EXPERIMENTAL LAYOUT

The UCPRC operates two Heavy Vehicle Simulators (HVS) to test the structural characteristics and durability of pavements. This equipment applies truck tire loads over a test pavement at a maximum speed of 8.5 km/h. An HVS Mk VI and close-up of the tires on the pavement are shown in Figures 1 and 2. Between 10,000 and 25,000 repetitions can be applied in a 24 hour period, depending on the trafficking configuration and time required to take measurements. Test duration depends on the purpose of the test, but are typically run until either an average maximum rut of 13 mm (high temperature rutting tests on asphalt) or a predetermined level of cracking is reached.
The primary purpose of the HVS tests discussed in this paper was the comparison of rutting performance of seven different gap-graded rubberized warm-mix asphalt mixes against two hot-mix asphalt controls of the same mix design. In order to accelerate the rutting accumulation, pavement temperatures were maintained at 50°C at 50 mm depth. The pavement surfaces were kept dry during testing. Changes in rutting were measured on a daily basis with a laser profilometer at 500 mm intervals along the middle 6 m of the 8 m test section (the 1 m acceleration and deceleration zones at each end of the test section are excluded). The total rut, calculated as the difference in elevations between the top of the heaved material on the side of the section and bottom of the deformed area in the wheelpath, is derived from the profile measurements. The testing was stopped once the average total rut exceeded 13 mm.

The tests were carried out using a dual truck tire configuration, standard tire pressures, unidirectional trafficking, and half-axle loading starting at the legal load (40 kN) and increasing to 60 kN after completion of 160,000 load repetitions. An environment chamber around the HVS is used to maintain pavement temperature. Heaters are placed next to the test section radiating heat onto the pavement. Thermostats in conjunction with thermocouples in the pavement are used to control the heaters and maintain the pavement temperature at 50°C ± 2°C at 50 mm depth.

It was not possible to perform actual noise measurements during testing due to the noise generated by the HVS. The sections are also too short for testing with other noise measuring equipment at the required speeds (Close Proximity [CPX] noise trailer at 50 or 80 km/h [ISO/CD 11819-2:2000] or Onboard Sound Intensity [OBSI] equipment at 80 or 100 km/h [Standard Method, 2010]). However, it is known from the literature (Sandberg and Ejsmont, 2002) that there is a close relationship between pavement texture and the tire rolling noise. Therefore, pavement texture was measured on each of the HVS test sections as an indicator for noise emission. These pavement textures were used as input to a model that predicts the noise emission from a pavement with a given surface texture (see description of the Acoustical Optimization Tool [AOT] below).

Pavement surface textures were measured with an Ames Engineering Laser Texture Scanner (Figure 3) for the duration of seven of the nine warm-mix asphalt tests in 2010 and 2011. The scanner is a stand-alone unit that is placed on the pavement surface. The device scans a surface directly under its base in multiple line scans with a scan line length of 100 mm and a maximum scan width of 75 mm. The number of lines scanned can be set by the user. Up to 1,200 lines with an average spacing between scan lines of as little as 0.064 mm can be scanned. It takes about nine seconds to complete one scan line. The greater the number of lines scanned, the longer it takes to complete one test. In this experiment a resolution of 100 scan lines was used.

Texture data were processed to create six 2,000 mm long strings of surface texture representing six lines of pavement texture in the direction of the wheelpath for input into the AOT model. This was achieved by randomly selecting 120 100 mm profile lines from a pool of scanned texture profiles and combining them into the six 2,000 mm long profile lines. Figure 4 shows a randomly selected example of 100 mm texture sections for one of the pavements after zero and 309,000 load repetitions.

3 WORKING HYPOTHESES AND NOISE GENERATING MECHANISMS

The working hypotheses for the experimental design of the project are:

- Pavement wear by the HVS creates pavement surface textures that are representative of pavements exposed to real traffic on roads.
Figure 4. Example of 100 mm texture sections for one of the test pavements when new (top) and worn down after 309,000 repetitions (bottom) of the test tires passing over.

– AOT can be used to predict noise levels representative of the trafficked pavements based on the texture measured on these pavements.

The generation of noise when the tires are rolling on a road surface is mainly caused by the following mechanisms (Sandberg and Ejsmont, 2002). Other mechanisms may have a minor role:

– Vibrations in the tires: Vibrations are generated by the contact between the surface of the pavement and the rubber blocks of the tread pattern on the tire. Tire vibrations generate noise in the frequency range from 500 to 1,500 Hz. The noise increases with increasing roughness of the road surface. An increase in the maximum aggregate size generally leads to an increase in noise. The mean profile depth (MPD) can be regarded as a very general indicator for pavement roughness.

– Air pumping effect: When the rubber blocks on the tread pattern of the tire contact the road surface, air is pressed out of the cavities between the rubber blocks. When the rubber blocks leave the road surface, air is drawn back into the cavities. This air pumping generates noise at high frequencies above 1,000 Hz. If the road surface is open or porous, the noise will be reduced.

– Horn effect: The curved tread pattern of the tires and the road surface act as an acoustical horn which amplifies the road noise generated around the contact point between the tire and the road surface. If the road surface is porous (and therefore sound absorbing) the amplification effect will be reduced.

– Absorption under propagation: The engine and road-tire noise propagate from the vehicles to the receivers. Under this propagation, the noise may be reflected from the road surface. If the road surface is porous, and therefore sound absorbing, the noise at some frequency bands will be reduced during propagation.

– Stiffness effect: The stiffness of the pavement is important for the determination of the noise generated by the contact between the surface of the pavement and the rubber blocks of the tread pattern on the tire. If the pavement has a low stiffness, the generated noise will be reduced.

Porous pavements have connected cavities and are open over the entire thickness of the layer, while open-textured pavements are open only in the upper part of the pavement with cavities having a depth less than the maximum size of the aggregate used. The basic concept of using open-textured pavements for noise reduction is to create a pavement structure, with as cavities as large as possible near the surface of the pavement to reduce to some extent the noise generated from the air pumping effect, and at the same time ensuring a smooth surface so the noise generated by the vibrations of the tires does not increase. These noise reducing open-textured pavements can be thin, since the mechanisms determining the noise generation only depend on the surface structure of the pavement.

4 ACOUSTICAL OPTIMIZATION TOOL

The texture profiles collected for the APT experiments were used to perform noise simulations/predictions using the Dutch Noise Optimization Tool (AOT, 2009) developed for the Dutch national road administration (DVS) between 2006 and 2008. AOT is an acoustical optimization tool for low-noise road surfaces (Kuijpers, 2008; AOT User’s Manual, 2009). The AOT is based on models that describe the mechanisms generating tire road noise. Models included are a tire contact model, a tire interaction model, and a noise propagation model. The model framework was developed over a longer period and included theoretical development as well as empirical measurement results. A detailed presentation of the model framework is discussed in Kuijpers (2008).

AOT can simulate noise emissions caused by vehicles driving on a specific pavement surface at different speeds in the range from 50 to 120 km/h. There are four main input data describing the physical and acoustical properties of the pavement. These are presented below and related to the previously described noise generating mechanisms when a tire is rolling on a pavement (AOT User’s Manual, 2009):

– Surface texture, which is a measure of the roughness of the road. The road surface texture is influenced by the size, shape, and arrangement of the road surface constituents (such as aggregates, binder, and additives). The surface texture influences the noise generated from vibrations in the tire.

– Acoustical impedance, which is a measure describing the influence of the road surface in terms of...
reflection and absorption on the sound field that impinges on the surface. This term is related to the acoustic absorption of the road surface. Porous pavements have an absorbing effect on noise. The acoustical impedance of the road surface is used in the propagation part of the model. The acoustical impedance also influences the horn effect.

- Flow resistance, which is a measure of the resistance that the flow of air in the tire profile experiences in the rolling contact area. The flow resistance influences the noise generated from air pumping. The air flow resistance is the resistance that in the air that is expelled from the contact area between tire and road during the rolling process. If the airflow resistance is high, the air is effectively compressed in the contact area and might produce air pumping noise when the compressed air is released at the beginning or end of the contact patch. When the airflow resistance is low, for example on open-graded and porous pavements, then air is pressed down into the pavement structure with little resistance and the generation of air pumping noise is reduced.

- Mechanical impedance is a measure describing the influence of the road surface in terms of stiffness and damping on the vibrations of the tire. It has an influence on the noise generated from vibrations in the tire.

A series of measurement data from around forty Dutch test sections with many different kinds of noise reducing pavements are included in the AOT as default values, which can be selected by the user that has limited or no data. These test sections included amongst others single and double layer porous asphalt, thin overlays, poroelastic surfacings, dense-graded asphalt concrete, and standard stone-matrix asphalt (SMA) pavements. User can choose to use their own measured data for those parameters that they have available and then use AOT system data for the other parameters. In the study discussed in this paper, measured pavement texture data from the test sections were used in the analysis, together with AOT system data on acoustical impedance, flow resistance, and mechanical impedance. A standard SMA pavement with 11 mm maximum aggregate was selected as being closest to the tested asphalt pavements that had 12.5 mm aggregates.

Based on the selected input data, AOT predicts the noise for vehicles driving on the pavement described by the input data. The user can define the vehicle type used for the simulations (passenger cars or trucks) and can select results related to either the CPX measurement method (ISO/CD 11819-2:2000), or the SPB method (ISO 11819-1:1997), where the distance to the centerline of the road is 7.5 m and the receiver height is defined at 1.2 m, 3 m or 5 m.

The results are given as A-weighted noise levels \( L_A \) as well as the total noise in the third octave band spectra in the frequency range from 315 to 2,000 Hz. The spectral contributions from three individual noise generating mechanisms are also predicted. These are tire vibration generated noise (vibration), air pumping generated noise (airflow), and noise related to absorption (cavity).

Figure 5 is an example of the spectral output from an AOT simulation of a dense graded asphalt concrete (DGAC16) showing the total noise level as well as the contribution from the three noise generating mechanisms. The total noise level \( L_A \) is 96.6 dB (decibels) at a speed of 100 km/h for passenger cars. The frequency curve for the total noise level is shown with a black curve. In this example, the main contributor to the total noise level over 1,000 Hz is the airflow noise. At less than 1,000 Hz the noise from both vibrations and airflow have significance. The contribution from cavity or absorption is marginal as this pavement is dense with no high noise absorption.

Results related to the US OBSI method are not available as this is a European developed tool following ISO international standards. However, there is a close relation between the results measured by the CPX and the OBSI methods, depending on the reference tires used in the two methods. Consequently, the two methods will rank pavements in the same way in relation to noise. In principle, the noise levels and spectra that are predicted are the SPB and CPX levels for the tire group that was selected when the AOT was developed. They do not necessarily correspond to the standard indices for SPB and CPX (either survey or investigatory) methods. However, validation (Personal communication Kuijpers, 2009) has shown that, for example, the extended group of passenger car tires corresponds well with the “CPXcars” from the CPX standard. In this project CPX noise levels for passenger cars at a speed of 100 km/h was selected. The noise levels presented in this paper are A-weighted meaning that the noise at the different frequencies is weighted according to how the human ear perceives noise at these frequencies. The decibel unit “dB” is used and is the same as what is often denoted as “dB(A)” and “dBA”.

To date, practical experience with the use of the AOT tool is relatively limited. Kuijpers (2008) evaluated the uncertainty of the AOT model, and based on a comparison of results of SPB and CPX measurements on five different pavements in the Netherlands and AOT noise predictions using measured pavement
properties for these five pavements, it was concluded that in these cases the standard AOT modeling uncertainty was $\pm 0.5$ to 1.0 dB in the worst case. Noise emissions from road traffic are normally measured using the wayside SPB method or the Close-ProXimity (CPX) method. There is always uncertainty related to noise measurements. For measurements carried out according to the SPB standard, the uncertainty of the results for passenger cars is usually in the order of $\pm 0.3$ to 0.5 dB. For measurements carried out according to the CPX method the uncertainty is often stated to be in the order of $\pm 0.5$ to 0.7 dB. Based on this limited evaluation of AOT (Kuijpers, 2008) it would appear that the uncertainty of AOT predictions is higher than the uncertainty for actual SPB/CPX noise measurements.

5 TEST PAVEMENTS

The main objective of the HVS testing in this project was to compare the performance of different rubberized warm-mix asphalt technologies against a rubberized hot-mix asphalt control mix. The test pavements were all gap-graded aggregate with a maximum aggregate size of 12.5 mm and as-constructed air void contents ranging from 9 to 14% by volume. The five pavement sections discussed in this paper were 622HB, 623HA, 624HB, 625HA and 628HB.

Figure 4 shows a 100 mm section of the surface texture of an untested pavement and the same pavement after completion of HVS testing. Figure 6 shows the difference between the untrafficked and trafficked surface. From these two figures it can, as a first visual impression, be seen that the test pavement has a relatively rough surface texture before testing. After testing, the pavement surface appears to have a more convex surface structure where mortar and the smaller aggregates have been removed from the surface leaving the larger aggregates exposed. This can also be seen in Figure 7, which shows a horizontal view of the wheelpath after testing. In pavement acoustic analysis, the more convex a pavement surface is the more tire pavement noise is emitted.

6 RESULTS

As a very general indicator for the pavement surface structure, the mean profile depth (MPD) has been included in the data presented below. MPD generally does not correlate as well with noise as other pavement related factors like convex/concave texture, air void content, and aggregate size, etc., which also play an important role. Increasing MPD normally also leads to increases in tire/pavement noise. The measured MPD and the AOT predicted noise levels at different numbers of repetitions for the five sections tested are summarized in Table 1. Data from the SMA11 pavement used for the AOT predictions (SMA11-AOT) are also included. Between four and eight measurements were taken on each section depending on the number of repetitions to failure.

Bendtsen et al. (2009) concluded that a linear regression provides a good description of the relation
between noise level and the age of pavements, and that a logarithmic regression did not improve the result. Therefore linear regression has been used to analyze the relation between noise and the number of load repetitions with the HVS. Regression lines showing the results of the development of MPD and noise over the testing period are shown in Figures 8 and 9 for Sections 622HA and 625HA.

Figure 8 shows the development of the results for the 622HA pavement over a period of 190,000 repetitions. Increases in both MPD and noise are evident as the HVS testing continues. MPD increased around 0.1 mm and noise increased 0.5 dB during the testing.

Figure 9 shows similar results for the 625HA pavement over a range of 300,000 load repetitions. MPD increased around 0.07 mm, but for this pavement a decrease in noise of 0.8 dB was noted during HVS testing. The spread of the measured MPD levels on this section was high (R² is 0.10). This is reflected in the regression line for the AOT predicted noise, where R² is 0.27 and the standard deviation is 0.6 dB (Table 2).

In Figure 10, regression lines for the development of MPD (measured) during HVS testing on the five pavements are shown. The initial MPD of 1.01 mm for the SMA11 pavement, used as the standard pavement in the AOT predictions, is also shown. The SMA11 had a higher MPD than the five pavements (0.83 to 0.99 mm) before the start of HVS testing. MPD increased during testing on all pavements. This should be reflected by an increase in noise; however, as shown in Figure 11, the noise increased on Sections 622HA, 624HB and 628HB, but decreased on the other two pavements (623HA and 625HA). All in all, the range of variation and development of noise for the five pavements during the testing was less than 1 dB. The initial noise levels for the five test pavements were 0.2 to 1.0 dB higher than the SMA11 pavement.

Table 2. Slopes for regression analyses of noise per 100,000 repetitions and per year (assuming 30,000 repetitions correspond to one year).

<table>
<thead>
<tr>
<th>Test section</th>
<th>No. of measurements</th>
<th>Slope (dB/10⁵ Reps)</th>
<th>Std. Dev. (dB)</th>
<th>Δ Noise/ year (dB/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>622HA</td>
<td>4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>623HA</td>
<td>5</td>
<td>−0.1</td>
<td>0.3</td>
<td>0.0</td>
</tr>
<tr>
<td>624HB</td>
<td>8</td>
<td>0.03</td>
<td>0.3</td>
<td>0.0</td>
</tr>
<tr>
<td>625HA</td>
<td>6</td>
<td>−0.3</td>
<td>0.6</td>
<td>−0.1</td>
</tr>
<tr>
<td>628HB</td>
<td>5</td>
<td>0.2</td>
<td>0.7</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Std. Dev. = standard deviation
whereas for the 625HA and 628HA pavements, the standard deviation was 0.6 and 0.7 dB. The increase in noise per 100,000 load repetitions is also shown. In order to be able to express the development of noise as a change of decibels per year, it is necessary to define the lifetime of the tested pavements. For this study, it was generally assumed that the lifetime was ten years and equivalent to 300,000 HVS load repetitions. Using these parameters, the noise increase per year was calculated and is presented in Table 2. The results are presented with one decimal and vary from -0.1 dB/year to +0.1 dB/year with an average yearly increase on all five pavements of zero dB/year.

The spectral development of the noise can be seen in the figures below. Two examples are provided. Section 622HA had the highest increase of 0.30 dB/10^5 repetitions (Figure 12) and Section 625HA had the highest decrease of -0.30 dB/10^5 repetitions (Figure 13). The spectra are not broken down into the different components as in Figure 5; instead the total spectra are shown in the frequency range 315 to 2,000 Hz, as predicted by the AOT.

Figure 12 shows that the spectral change for the 622HA pavement occurs in the low frequency range below 1,000 Hz where a slight increase in noise can be seen with increasing load repetitions. This indicates that the pavement surface texture becomes rougher, which would increase the vibration generated noise. There was no change in noise levels over 1,000 Hz during the testing, indicating that the noise generated by air pumping did not change.

In Figure 13, the spectral change with a general noise decrease on the 625HA pavement can be seen. From zero to 121,000 repetitions, an increase of noise was predicted in the low frequency range below 1,000 Hz indicating that the pavement surface texture became rougher and increased the vibration generated noise, similar to the 622HA pavement. However, near the end of testing (i.e., after 260,000 repetitions) a remarkable decrease in the low frequencies of up to 4 dB can be seen. This indicates that the surface texture became smoother, which would decrease the generation of tire vibration noise. There was also no change in noise levels over 1,000 Hz indicating that the noise generated by air pumping did not change during the testing.

The AOT can separate the total noise spectra into the spectra related to vibration and air flow, respectively (see Figure 5). Examples of this for Section 622HA are provided in Figures 14 and 15. The main changes in
The spectra during the HVS testing were for the vibration noise (Figure 14), which increased slightly. There were no real changes in the spectra for air flow noise (Figure 15), which emphasizes the conclusions drawn above concerning the 622HA pavement.

The increase in noise during the HVS testing was converted to noise increase per year by assuming that 300,000 repetitions in the HVS testing corresponds to ten years of trafficking on a similar in-service pavement. Predictions for analysis periods of five and fifteen years were also considered. Results of this analysis are provided in Table 3.

### Table 3. Prediction of the yearly increase of noise depending on different assumptions of the pavement lifetime.

<table>
<thead>
<tr>
<th>Pavement life</th>
<th>Test section</th>
<th>5 years</th>
<th>10 years</th>
<th>15 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 years</td>
<td>10 years</td>
<td>15 years</td>
<td></td>
</tr>
<tr>
<td>622HA</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>623HA</td>
<td>-0.1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>624HB</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>625HA</td>
<td>-0.2</td>
<td>-0.1</td>
<td>-0.1</td>
<td></td>
</tr>
<tr>
<td>628HB</td>
<td>0.1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

The visual impression looking at photographs of new pavements and the same pavements after HVS trafficking is that the pavement surface becomes rougher and acquires a more convex texture. This would be expected to result in a significant increase in the tire pavement noise generated. However, MPD measurements show only small increases in the pavements’ general roughness, while noise predictions only show marginal increases for some of the pavement sections tested.

The predicted noise levels were 0.2 to 1.2 dB higher than the noise level predicted by AOT for the SMA11 pavement used as reference for the predictions. This was attributed in part to the tested pavements having a larger aggregate size (12.5 mm) than the SMA11 pavement (11 mm), and partly due to the channelized trafficking and relatively short nature of the test on pavements, which had not been exposed to extended environmental aging.

Assuming that 300,000 load repetitions is equivalent to ten years of in-service trafficking (very conservative), two of the pavements tested had a 0.1 dB/year increase in noise, two pavements had no increase, and one had a decrease of −0.1 dB/year. The average increase for all five pavements was 0.0 dB/year for passenger cars. These results are in the lower end of what has been observed in other investigations. In the European SILENCE project, DRD collected data from long-time noise measurements on pavements in Europe (Kragh, 2008). There was a large spread in the data, but the average results for passenger cars dense-graded asphalt concrete highways was an increase of 0.1 dB/year and 0.4 dB/year on porous pavements. The results of the study discussed in this paper are close to the results of this compilation of European results. In another project using Danish and Californian long-term noise measurement data (Bendtsen, 2009), the results for passenger cars on dense-graded asphalt concrete highways was an average increase of 0.4 dB/year. Research to obtain a better understanding of acoustic aging phenomena for asphalt pavements is still ongoing.

This study found a reasonable consistency in the development of the measured pavement textures expressed as MPD during the testing. The study also found a reasonable consistency in the noise levels predicted by the AOT using only texture measurements, in that the standard deviation of the results in relation to the regression line were generally low (0.3 to 0.7 dB). Based on these observations, it can be concluded that the selected method and the two hypotheses tested appear to produce reasonable results given the uncertainty related to the AOT and similar models.

There was, however, a spread in the individual results around the regression line, which is expected when using a limited number of data points (in this case, 3 to 8 texture measurements) to describe the full life cycle of a pavement. In these instances, the result
defined as the slope of the regression line can become very dependent on one “outlying” measurement point. The method could be improved by measuring texture at more frequent intervals (e.g., every 25,000 load repetitions), by testing on a wider range of pavements that are trafficked with wheel wander instead of channelized mode (as used in these tests), and testing on experiments of longer duration (e.g., fatigue cracking tests). This will result in the slope of the regression line being less dependent on individual measurement points. For practical reasons, it was not possible to obtain these types of measurements in the warm-mix asphalt rutting study.

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REFERENCES


