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CONTENTS

Foreword 2

Introduction 3

Loaded Wheel Testers Used in the United States 3

Effect of Test Parameters and Mixture Properties on LWT Results 12

LWT Results Versus Field Performance 13

Summary 15

Acknowledgments 15

References 16

FOREWORD

Loaded wheel testers (LWT) are becoming increasingly popular with transportation agencies as they seek to identify hot mix asphalt mixtures that may be prone to rutting. This E-Circular provides the state of the practice on the use of LWTs within the United States as obtained from a review of literature. The intent is to provide background information on LWTs used in the United States and describe the key test parameters, limitations, material sensitivities, and boundary conditions utilized by various LWTs.

INTRODUCTION

Permanent deformation, or rutting, in hot mix asphalt (HMA) pavements has been and continues to be a major problem in the United States. Rutting is defined as the accumulation of small amounts of unrecoverable strain resulting from applied wheel loads to HMA pavement. This deformation is caused by consolidation or lateral movement, or both, of the HMA under traffic. Shear failure (lateral movement) in a HMA pavement generally occurs in the top 100 mm (4 in) of the HMA structure (*1*). Rutting not only decreases the useful life of a pavement but also creates a safety hazard for the traveling public. In recent years, the potential for rutting on the nation's highways has increased due to higher traffic volumes and the increased use of radial tires that typically exhibit higher inflation pressures.

A standardized laboratory equipment and test procedure that predicts field-rutting potential would be of great benefit to the HMA industry. Currently, the most common type of laboratory equipment of this nature is a loaded wheel tester (LWT).

In an effort to identify HMA mixtures that may be prone to rutting, many transportation agencies have begun using LWTs as supplements to their mix design procedure. The LWTs allow for an accelerated evaluation of rutting potential in the designed mixes. However, in order for these agencies to use LWTs with confidence, there needs to be an acceptable correlation between rutting in the laboratory and actual field rutting. Some agencies using LWTs have recognized this fact and have conducted research to determine the degree of correlation between field performance and results from laboratory LWTs.

LOADED WHEEL TESTERS USED IN THE UNITED STATES

Several LWTs currently are being used in the United States. They include the Georgia Loaded Wheel Tester (GLWT), Asphalt Pavement Analyzer (APA), Hamburg Wheel Tracking Device (HWTD), LCPC (French) Wheel Tracker, Purdue University Laboratory Wheel Tracking Device (PURWheel), and one-third scale Model Mobile Load Simulator (MMLS3). Following are descriptions for each of these LWTs.

Georgia Loaded Wheel Tester

The GLWT, shown in Figure 1, was developed during the mid- 1980s through a cooperative research study between the Georgia Department of Transportation and the Georgia Institute of Technology (*2*). Development of the GLWT consisted of modifying a wheel-tracking device originally designed by C.R. Benedict of Benedict Slurry Seals, Inc., to test slurry seals (*3*). The primary purpose for developing the GLWT was to perform efficient, effective, and routine laboratory rut proof testing and field production quality control of HMA (*4*).

The GLWT is capable of testing HMA beam or cylindrical specimens. Beam dimensions are generally 125 mm wide, 300 mm long, and 75 mm high (5 in x 12 in x 3 in). Compaction of beam specimens for testing in the GLWT has varied greatly according to the literature. The original work by Lai (*2*) utilized a "loaded foot" kneading compactor. Heated HMA was "spooned" into a mold as a loaded foot assembly compacted the mixture. A sliding rack, onto which the mold was placed, was employed as the kneading

compactor was stationary. West et al. (*5*) utilized a static compressive load to compact specimens. Heated HMA was placed into a mold and a compressive force of 267 kN (60,000 lbs) was loaded across the top of the sample and then released. This load sequence was performed a total of four times. In 1995, Lai and Shami (*6*) described a new method of compacting beam samples. This method utilized a rolling wheel to compact beam specimens.

Laboratory prepared cylindrical specimens are generally 150 mm in diameter and 75 mm high. Compaction methods for cylindrical specimens have included the "loaded foot" kneading compactor (*2*) and a Superpave gyratory compactor (*7*).

Both specimen types are most commonly compacted to either 4 or 7 percent air void content. However, some work has been accomplished in the GLWT at air void contents as low as 2 percent (*8*).

Testing of samples within the GLWT generally consists of applying a 445-N (100-lb) load onto a pneumatic linear hose pressurized to 690 kPa (100 psi). The load is applied through an aluminum wheel onto the linear hose, which resides on the sample. Test specimens are tracked back and forth under the applied stationary loading. Testing is typically accomplished for a total of 8,000 loading cycles (one cycle is defined as the backward and forward movement over samples by the wheel). However, some researchers have suggested fewer loading cycles may suffice (*5*).

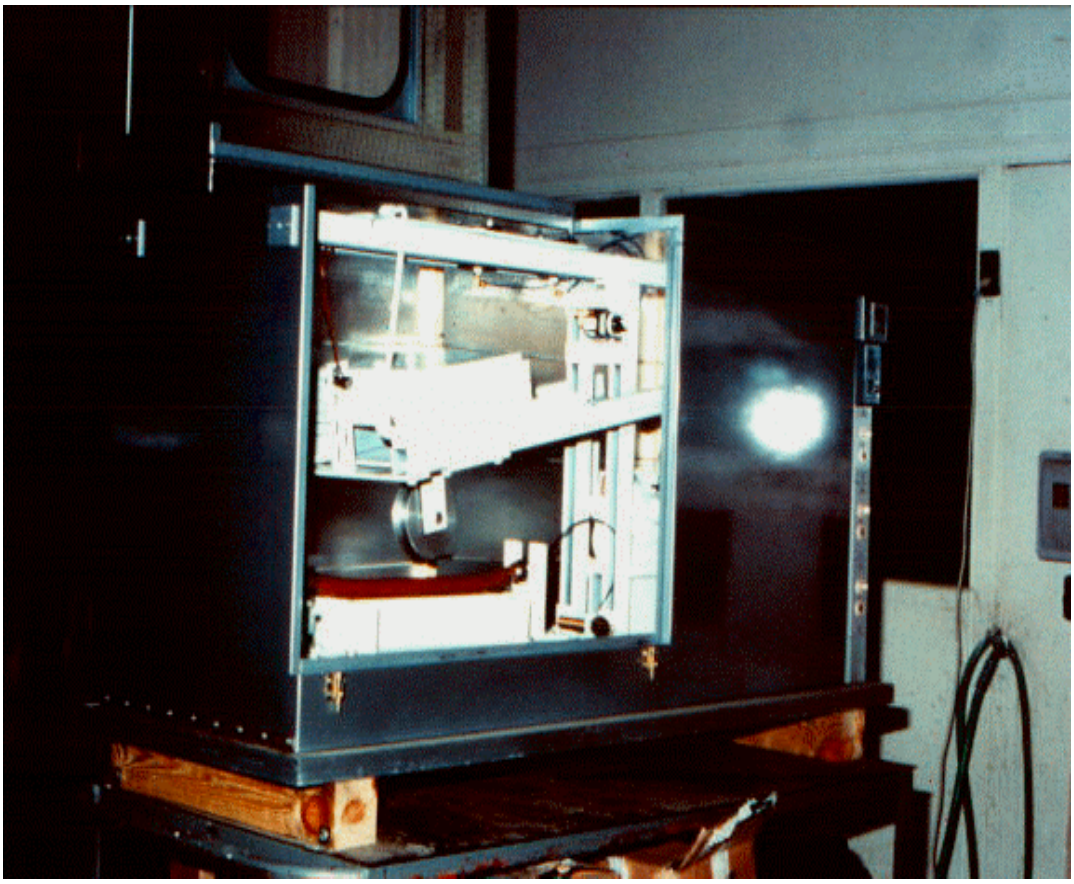

FIGURE 1 Georgia Loaded Wheel Tester.

Test temperatures for the GLWT have ranged from 35°C to 60°C (95°F to 140°F). Initial work by Lai (*2*) was conducted at 35°C (95°F). This temperature was selected because it was Georgia's mean summer air temperature (*3*). Test temperatures within the literature subsequently tended to increase to 40.6°C (105°F) (*3, 5, 9, 10, 11*), 46.1°C (115°F) (*11*), 50°C (122°F) (*3, 8*), and 60°C (140°F) (*8*).

At the conclusion of the 8,000 cycle loadings, permanent deformation (rutting) is measured. Rut depths are obtained by determining the average difference in specimen surface profile before and after testing. A template with seven slots that fits over the sample mold and a micrometer are typically used to measure rut depth (*2*).

Asphalt Pavement Analyzer

The APA, shown in Figure 2, is a modification of the GLWT and was first manufactured in 1996 by Pavement Technology, Inc. The APA has been used to evaluate the rutting, fatigue, and moisture resistance of HMA mixtures. Since the APA is the second generation of the GLWT, it follows the same rut testing procedure. A wheel is loaded onto a pressurized linear hose and tracked back and forth over a testing sample to induce rutting. Similar to the GLWT, most testing is carried out to 8,000 cycles. Unlike the GLWT, samples also can be tested while submerged in water.

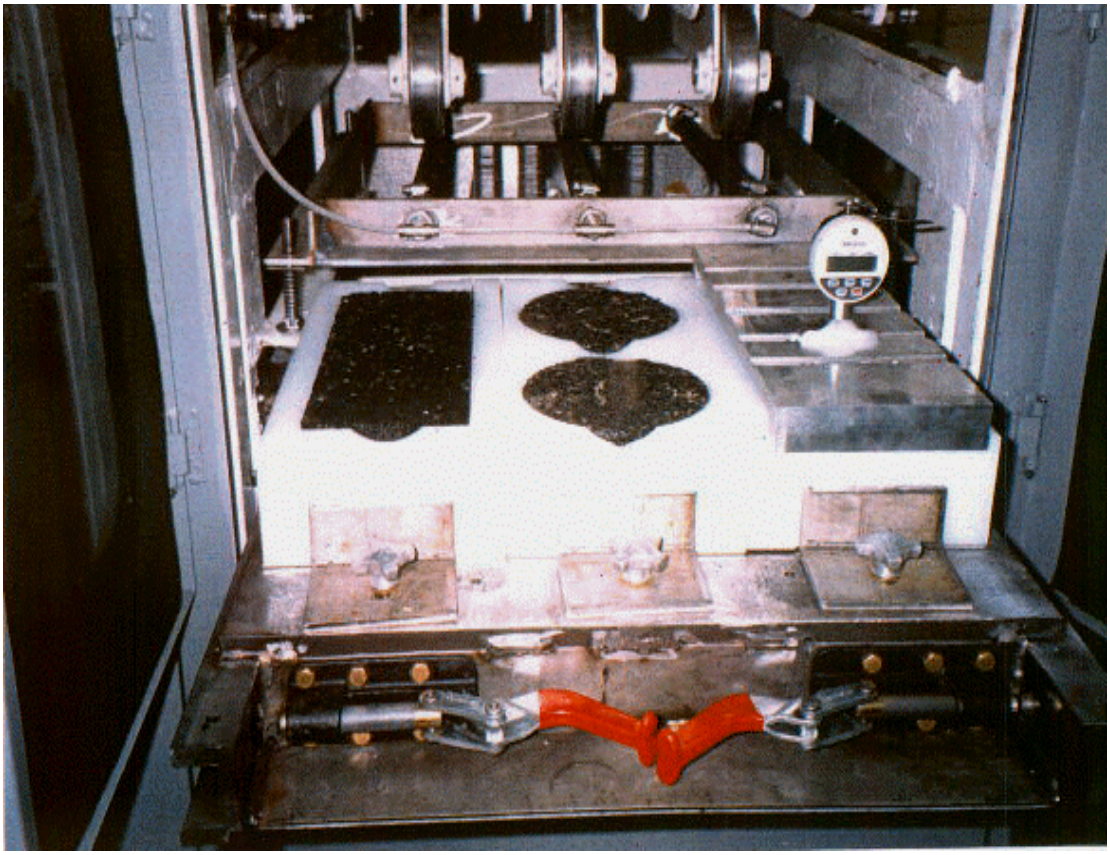

FIGURE 2 Asphalt Pavement Analyzer.

Testing specimens for the APA can be either beam or cylindrical. Currently, the most common method of compacting beam specimens is by the Asphalt Vibratory Compactor (*12*). However, some have used a linear kneading compactor for beams (*13*). The most common compactor for cylindrical specimens is the Superpave gyratory compactor (*14*). Beams are most often compacted to 7 percent air voids; cylindrical samples have been fabricated to both 4 and 7 percent air voids (*13*). Tests can also be performed on cores or slabs taken from an actual pavement.

Test temperatures for the APA have ranged from 40.6°C to 64°C (105°F to 147°F). The most recent work has been conducted at or slightly above expected high pavement temperatures (*14, 15*).

Wheel load and hose pressure have basically stayed the same as for the GLWT, 445 N and 690 kPa (100 lb and 100 psi), respectively. One recent research study (*15*) did use a wheel load of 533 N (120 lb) and hose pressure of 830 kPa (120 psi) with good success.

Hamburg Wheel-Tracking Device

The HWTD, shown in Figure 3, was developed by Helmut-Wind Incorporated of Hamburg, Germany (*16*). It is used as a specification requirement for some of the most traveled roadways in Germany to evaluate rutting and stripping. Tests within the HWTD

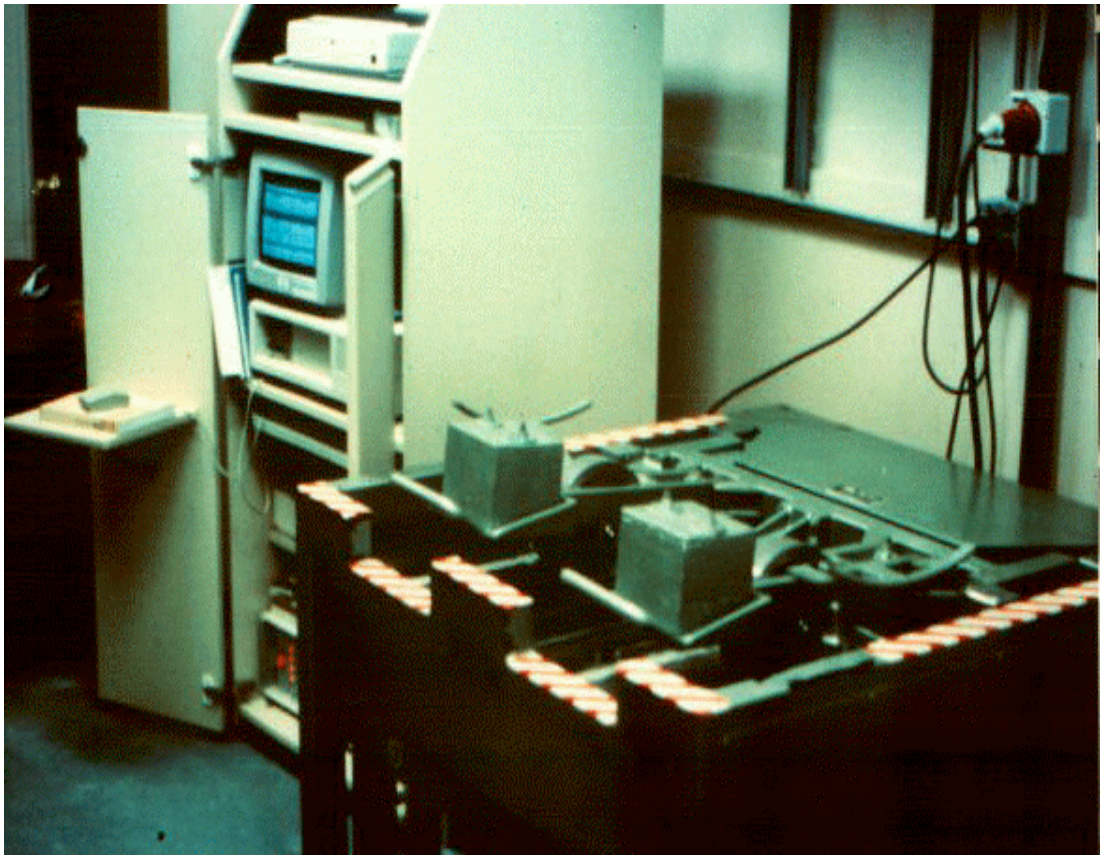

FIGURE 3 Hamburg Wheel Tracking Device.

are conducted on a slab that is 260 mm wide, 320 mm long, and typically 40 mm high (10.2 in x 12.6 in x 1.6 in). These slabs are normally compacted to 7±1 percent air voids using a linear kneading compactor.

Testing in the HWTD is conducted under water at temperatures ranging from 25°C to 70°C (77°F to 158°F), with 50°C (122°F) being the most common temperature (*17*). Loading of samples in the HWTD is accomplished by applying a 705-N (158-lb) force onto a 47-mm-wide steel wheel. The steel wheel is then tracked back and forth over the slab sample. Test samples are loaded for 20,000 passes or until 20 mm of deformation occurs. The travel speed of the wheel is approximately 340 mm per second (*16*).

As shown in Figure 4, results obtained from the HWTD consist of rut depth, creep slope, stripping inflection point, and stripping slope. The creep slope is the inverse of the deformation rate within the linear region of the deformation curve after post compaction and prior to stripping (if stripping occurs). The stripping slope is the inverse of the deformation rate within the linear region of the deformation curve, after the onset of stripping. The stripping inflection point is the number of wheel passes corresponding to the intersection of the creep slope and the stripping slope. This value is used to estimate the relative resistance of the HMA sample to moisture-induced damage (*17*).

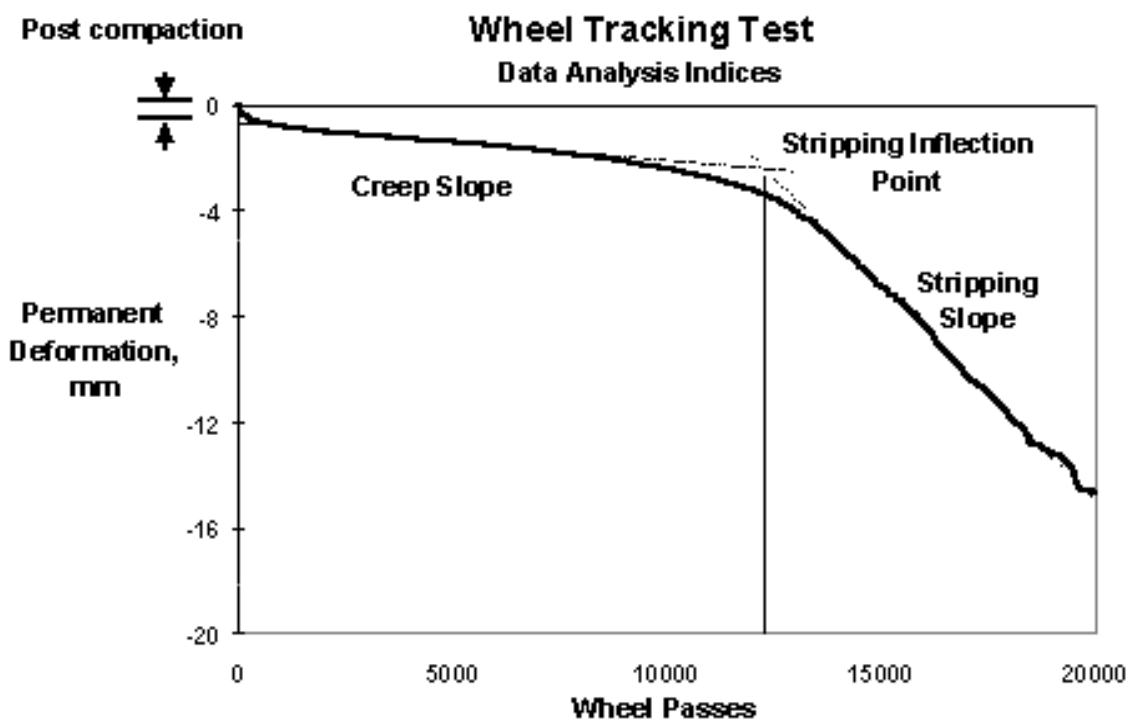

FIGURE 4 Typical Hamburg Wheel Tracker Test Results.

A slight modification of the HWTD was made by the Superfos Construction, U.S. (previously Couch, Inc.). This device, shown in Figure 5, was referred to as the Superfos Construction Rut Tester (SCRT). The SCRT used slab specimens with similar dimensions as the HWTD. The primary difference between the two was the loading mechanism. The

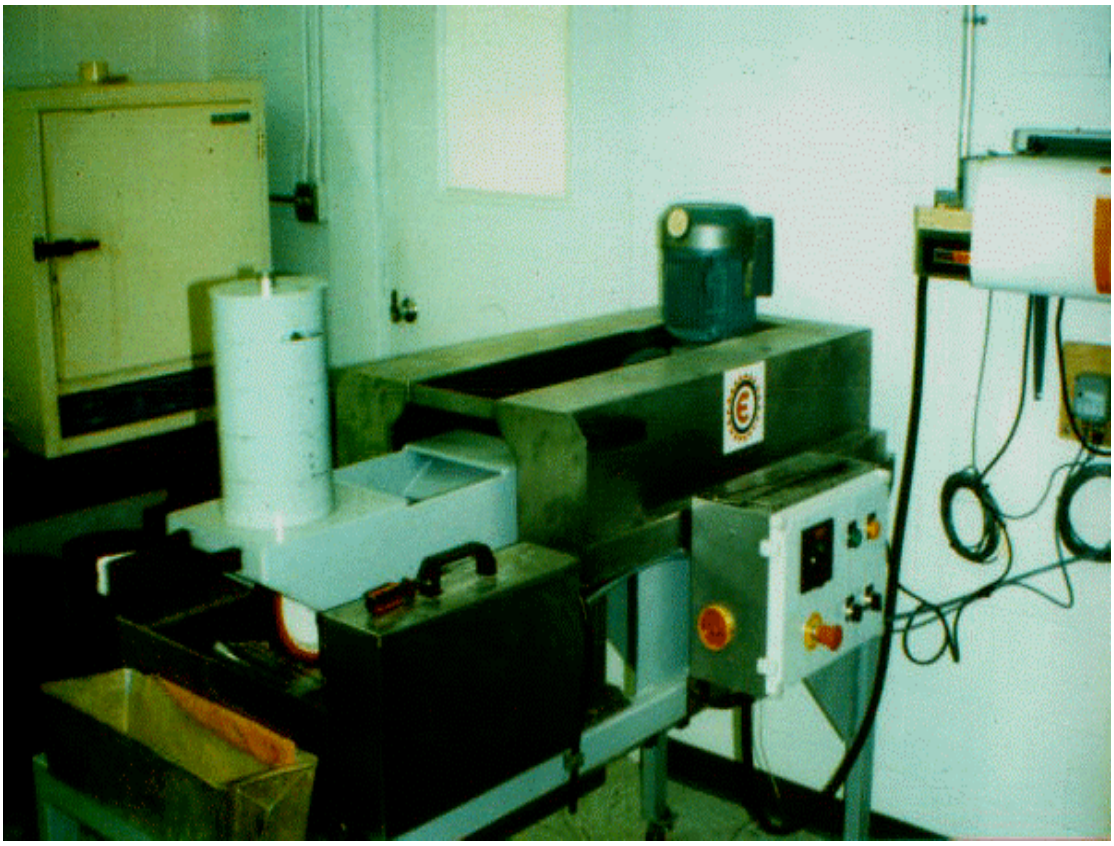

FIGURE 5 Superfos Construction Rut Tester.

SCRT applied an 82.6-kg (180-lb) vertical load onto a solid rubber wheel with a diameter of 194 mm and width of 46 mm. This loading configuration resulted in a contact pressure of approximately 940 kPa (140 psi) and contact area of 8.26 cm^2 (1.28 in^2) which was applied at a speed of approximately 556 mm per second (*18*).

Test temperatures ranging from 45°C to 60°C (113°F to 140°F) have been used with the SCRT. Recent research with the SCRT has used 60°C as the test temperature (*18, 19*). An air void content of 6 percent was generally used for dense-graded HMA samples (*18*).

Results from the SCRT are identical to those from the HWTD and include rut depth, creep slope, stripping slope, and stripping inflection point.

Another slight modification of the HWTD is the Evaluator of Rutting and Stripping (ERSA) equipment. This device was built by the Department of Civil Engineering at the University of Arkansas (*20*).

Testing of cylindrial or beam samples in the ERSA can be conducted in either wet or dry conditions. A 47-mm wide steel wheel is used to load specimens with 705 N (160 lb) for 20,000 cycles or a 20-mm rut depth, whichever occurs first.

LCPC (French) Wheel Tracker

The Laboratoire Central des Ponts et Chausées (LCPC) wheel tracker [also known as the French Rutting Tester(FRT)], shown in Figure 6, has been used in France for over 15 years

to successfully prevent rutting in HMA pavements (*21*). In recent years, the FRT has been used in the United States, most notably in the state of Colorado and FHWA's Turner Fairbank Highway Research Center.

The FRT is capable of simultaneously testing two HMA slabs. Slab dimensions are typically 180 mm wide, 50 mm long, and 20 to 100 mm thick (7.1 in x 19.7 in x 0.8 to 3.9 in) (*22*). Samples are generally compacted with a LCPC laboratory-tired compactor (*23*).

Loading of samples is accomplished by applying a 5000-N (1124-lb) load onto a *400 x 8 Treb Smooth* pneumatic tire inflated to 600 kPa (87 psi). During testing, the pneumatic tire passes over the center of the sample twice per second (*23*).

Within France, test temperatures for FRT testing are generally 60°C (140°F) for surface courses and 50°C (122°F) for base courses. However, it has been suggested that temperatures lower than 60°C (140°F) can be used for colder regions within the United States (*22*).

Rut depths within the FRT are defined by deformation expressed as a percentage of the original slab thickness. Deformation is defined as the average rut depth from a series of 15 measurements. These measurements consist of three measurements taken across the width of a specimen at five locations along the length of the slab. A "zero" rut depth is generally defined by loading a sample at ambient temperature for 1,000 cycles (*23*).

FIGURE 6 LCPC (French) Wheel Tracker.

Purdue University Laboratory Wheel Tracking Device

As the name states, the PURWheel, shown in Figure 7, was developed at Purdue University (*24*). PURWheel tests slab specimens that can either be cut from the roadway or compacted in the laboratory. Slab specimens are 290 mm wide by 310 mm long (11.4 in x 12.2 in) (*25*). Thicknesses of slab samples depend upon the type mixture being tested. For surface course mixes, a sample thickness of 38 mm (1.5 in) is used while binder and base course mixes are tested at thicknesses of 51 mm and 76 mm (2 in and 3 in), respectively (*25*).

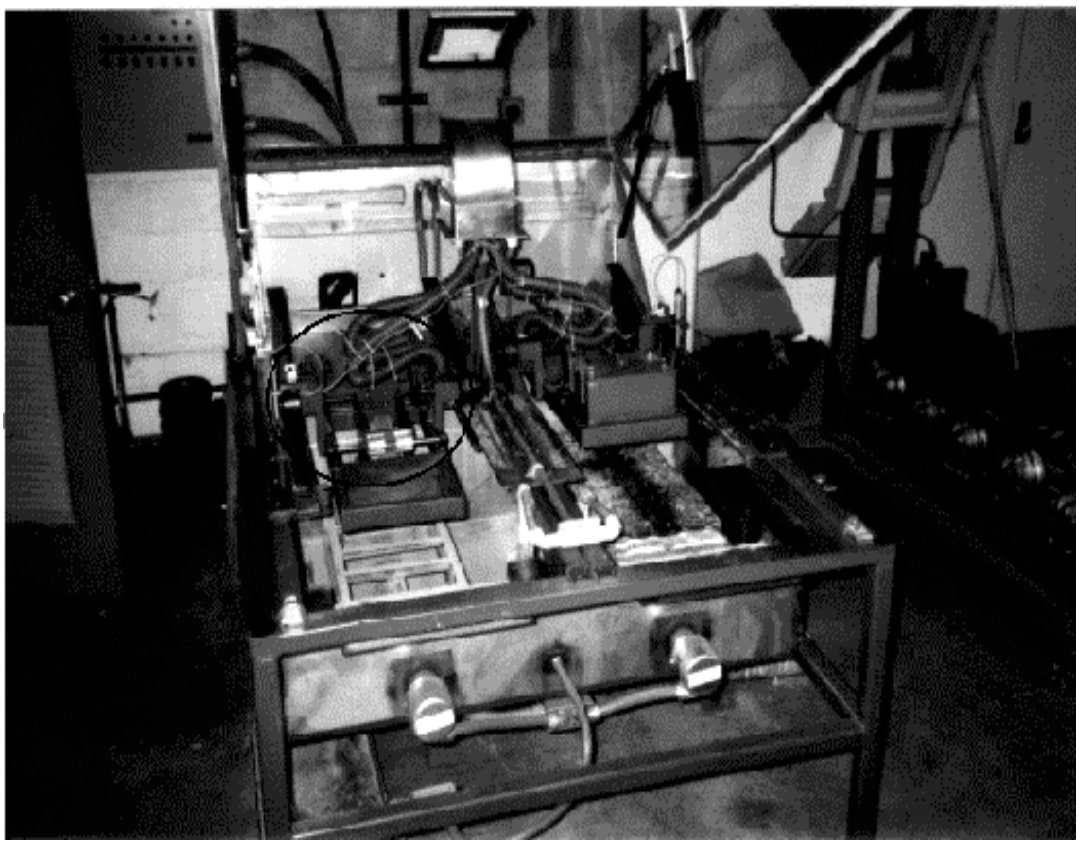

FIGURE 7 Purdue University Laboratory Wheel Tracking Device.

Laboratory samples are compacted using a linear compactor also developed by Purdue University (*25*). This compactor was based upon a similar compactor owned by Koch Materials in preparing samples for the HWTD (*26*). The primary difference being that the Purdue version can compact larger specimens. Samples are compacted to an air void content range of 6 to 8 percent.

PURWheel was designed to evaluate rutting potential and/or moisture sensitivity (*25*). Test samples can be tested in either dry or wet conditions. Moisture sensitivity is defined as the ratio of the number of cycles to 12.7 mm of rutting in a wet condition to the

number of cycles to 12.7 mm of rutting in the dry condition. The 12.7-mm rut depth is used to differentiate between good and bad performing mixes with respect to rutting (*25*).

Loading of test samples in PURWheel is conducted utilizing a pneumatic tire. A gross contact pressure of 620 kPa (90 psi) is applied to the sample. This is accomplished by applying a 175-kg (385-lb) load onto the wheel that is pressurized to 793 kPa (115 psi). A loading rate of 332 mm/sec is applied. Testing is conducted to 20,000 wheel passes or until 20 mm of rutting is developed (*24*).

PURWheel is very similar to the HWTD. However, one interesting feature about PURWheel is that it can incorporate wheel wander into testing (*25*). This feature is unique among the LWTs common in the United States.

Model Mobile Load Simulator (MMLS3)

The one-third scale MMLS3 was developed recently in South Africa for testing HMA in either the laboratory or field. This prototype device, shown in Figure 8, is similar to the full-scale Texas Mobile Load Simulator (TxMLS) but scaled in size and load. The scaled load of 2.1-kN (472-lb) is approximately one-ninth (the scaling factor squared) of the load on a single tire of an equivalent single axle load carried on dual tires (*27*).

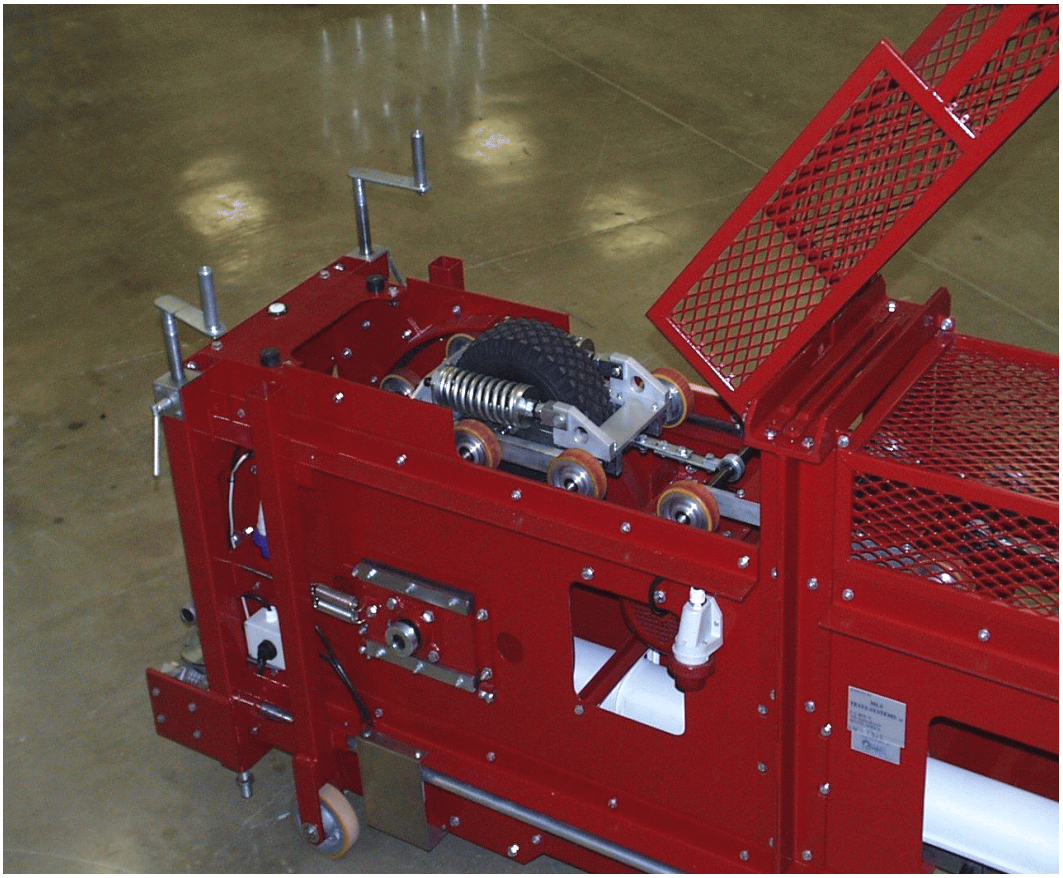

FIGURE 8 Model Mobile Load Simulator.

The MMLS3 can be used for testing samples in dry or wet conditions. An environmental chamber surrounding the machine is recommended to control temperature. Temperatures of 50°C and 60°C have been used for dry tests, and wet tests have been conducted at 30°C. MMLS3 samples are 1.2 m (47 in) in length and 240 mm (9.5 in) in width, with the device applying approximately 7200 single-wheel loads per hour by means of a 300-mm (12-in) diameter, 80-mm (3-in) wide tire at inflation pressures up to 800 kPa (116 psi) with a typical value of 690 kPa (100 psi). Wander can be incorporated up to the full sample width of 240 mm.

Performance monitoring during MMLS3 testing includes measuring rut depth from transverse profiles and determining Seismic Analysis of Surface Waves moduli to evaluate rutting potential and damage due to cracking or moisture, respectively. Rut depth criteria for acceptable performance are currently being developed (*28*).

Currently there is no standard for laboratory specimen fabrication, although research is being proposed to the Texas Department of Transportation.

EFFECT OF TEST PARAMETERS AND MIXTURE PROPERTIES ON LWT RESULTS

As shown in the previous descriptions on LWTs, all have similar operating principles. Essentially, a load is tracked back and forth over a HMA test sample. Therefore, the effect of various test parameters and material constituents should be similar for each. Following are descriptions of how different test parameters and constituents can affect LWT results.

Within the operating specifications for each of the LWTs, two test parameters are always specified: air voids and test temperature. This is primarily due to the fact that these two parameters have the most effect on test results; especially rut depths (*29*). As air voids increase, rut depths also increase. This has been shown by several research studies (*8, 29*). Likewise, as test temperature increases, rut depths also increase (*8, 30, 31, 32*). Unfortunately, nothing could be found in the literature about the effect of air voids and test temperature on moisture susceptibility results.

Air void contents for each of the LWTs are generally specified based upon two concepts (*12*). First, some believe that specimen air void contents should be approximately 7 percent, since this air void content represents typical as-constructed density. Others believe that test specimens should be compacted to 4 percent air voids, as actual shear failure of mixes usually takes place below approximately 3 percent.

Another test parameter that can significantly affect test results is the type and compaction method of test samples (*29*). The two predominant “types” of test specimens are cylinders and beams/slabs. For rutting and moisture susceptibility, the literature indicates that the two sample types do provide different rut depths and stripping inflection points; however, both types generally rank mixes similarly (*20, 33, 34*). The primary reason these two types of specimens do not produce the same rut depths is that they are generally compacted by different methods. For instance, cylindrical specimens are typically compacted using the Superpave gyratory compactor while beam samples are generally compacted with a vibratory or kneading compactor. The method of compaction influences the density (air void) gradients and aggregate orientation within samples (*35, 36*).

For moisture susceptibility, research has shown that different sample types also yield different stripping inflection points, even on samples compacted similarly (*20*). Several researchers have even sawn cylindrical samples so that they "butt" up against each other and compared to beam specimens (*20, 32*). This sample configuration has also shown differences in stripping inflection points between beams and cylinders. However, similar to rutting, the cylindrical and beams specimens tend to rank mixes similarly with respect to moisture damage.

Another test parameter that significantly affects test results is the magnitude of loading. A wide range of loadings are used in the different devices. Although a recent study indicated that small changes in the magnitude of loading may not affect LWT rut results (*29*), previous research has shown that significant differences in loadings can affect test results (*2*).

Depending upon whether rutting or moisture testing is to be conducted, sample conditioning prior to LWT testing is different. For rutting, it has been shown that six hours at the test temperature is sufficient (*29*). If samples are not preheated sufficiently, low rut depths can be expected. Conditioning of samples for moisture testing purposes generally takes place under water (*12*). No specific time interval has been recommended. Some users have utilized freeze-thaw cycles to condition specimens prior to moisture testing in LWTs (*31*). During actual mixing and compacting of test samples, it has been suggested that samples be short-term aged using the Superpave protocols (*14, 32*). This short-term aging procedure is believed to age the mixture similar to aging that occurs through field production and placement.

Several research studies have shown that LWTs can differentiate between asphalt binder types (*7, 8, 14, 32*). Researchers have compared identical aggregates and gradations but using different binder grades in LWTs. When tested at similar temperatures, mixes containing stiffer grades of asphalt binder will provide lower rut depths. Rutting tends to follow the $G^*/\sin\delta$ of the binder when tested using the Dynamic Shear Rheometer (*14, 32*).

Another mixture characteristic that affects LWT results is nominal maximum aggregate size (*2*). For a given aggregate and binder type, mixes with larger nominal maximum aggregate size gradations tend to provide lower rut depths.

LWT RESULTS VERSUS FIELD PERFORMANCE

Numerous studies have been conducted to compare results of LWT testing to actual field performance. Most of these studies have been to relate LWT rut depths to actual field rutting.

In the development of the GLWT, the researchers used four mixes of known field rut performance from Georgia (*2*). Three of the four mixes had shown a tendency to rut in the field. Results of this work showed that the GLWT was capable of ranking mixtures similar to actual field performance. A similar study conducted in Florida (*5*) used three mixes of known field performance. One of these mixes had very good rutting performance, one was poor, and the third had a moderate field history. Again, results from the GLWT were able to rank the mixtures similar to the actual field rutting performance.

The University of Wyoming and Wyoming Department of Transportation participated in a study (*11*) to evaluate the ability of the GLWT to predict rutting. For this

study, 150-mm cores were obtained from 13 pavements that provided a range of rutting performance. Results showed that the GLWT correlated well with actual field rutting when project elevation and pavement surface type were considered. The effect of elevation on rut depths was most likely due to different climates at respective elevation intervals.

After the APA came on the market, the Florida Department of Transportation conducted a study (*34*) similar to the GLWT study described previously (*5*). Again, three mixes of known field performance were tested in the APA. Within this study, however, beams and cylinders were both tested. Results showed that both sample types ranked the mixes similar to the field performance data. Therefore, the authors concluded that the APA had the capability to rank mixes according to their rutting potential.

The Colorado Department of Transportation and the FHWA's Turner Fairbank Highway Research Center participated in a research study to evaluate the FRT and actual field performance (*22*). A total of 33 pavements from throughout Colorado that showed a range of rutting performance were used. The research indicated that the French rutting specification (rut depth of less than 10 percent of slab thickness after 30,000 passes) was too severe for many of the pavements in Colorado. By reducing the number of passes for low-volume roads and decreasing the test temperature for pavements located in moderate to high elevations (i.e., colder climates), the correlation between the FRT results and actual field rutting was greatly increased.

Another research study by the LCPC compared rut depths from the FRT and field rutting (*37*). Four mixtures were tested in the FRT and placed on a full-scale circular test track in Nantes, France. Results showed that the FRT can be used as a method of determining whether a mixture will have good rutting performance.

The FHWA conducted a field pavement study at Turner-Fairbank Highway Research Center (*38*) using an accelerated loading facility (ALF). HMA mixtures were produced and placed over an aggregate base on a linear test section. Three LWTs were used to test mixes placed on the ALF in order to compare LWT results with rutting accumulated under the ALF. The three LWTs were the FRT, GLWT, and HWTD. Based upon this study, the results from the LWTs did not always rank the mixtures similar to the ALF.

A joint study by the FHWA and Virginia Transportation Research Council (*15*) evaluated the ability of three LWTs to predict rutting performance on mixtures placed at the full-scale pavement study WesTrack. The three LWTs were the APA, FRT, and HWTD. For this research, 10 test sections from WesTrack were used. The relationship between LWT and field rutting for all three LWTs was strong. The HWTD had the highest correlation (R^2=0.91), followed by the APA (R^2=0.90) and FRT (R^2=0.83).

The only study found in the literature dealing with moisture susceptibility was conducted by the Colorado Department of Transportation (*16*). This study compared results from the HWTD with known field performance in terms of stripping. Twenty pavements from throughout the state of Colorado were evaluated. Test results from the HWTD indicated that the stripping inflection point and stripping slope generally distinguished between good and poor performance.

Three studies by the Texas Department of Transportation (*28, 39, 40*) utilized the prototype MMLS3 to determine the relative performance of two rehabilitation processes and establish the predictive capability of this laboratory-scale device. For the first two studies, the MMLS3 tested eight full-scale pavement sections in the field adjacent to sections trafficked with the TxMLS. Field testing combined with additional laboratory

testing indicated that one of the rehabilitation processes was more susceptible to moisture damage and less resistant to permanent deformation compared to the second process. This second process was less resistant to fatigue cracking. In addition, a comparison of pavement response under full-scale (TxMLS) and scaled (MMLS3) accelerated loading showed good correlation when actual loading and environmental conditions were considered.

An ongoing third study aims to tie MMLS3 results with actual measured performance of four sections at WesTrack (*28*). A high testing temperature (60°C) was selected based on the critical temperature for permanent deformation during a 5-day trafficking period during which failure occurred for three of the four sections (*41, 42*). Limited laboratory testing using the HWTD and the APA is also included in this study, but only the rankings from HWTD results show good correlation with actual performance. Results indicate that the MMLS3 is capable of correctly ranking performance of the four WesTrack sections.

SUMMARY

Based upon review of the laboratory wheel tracking devices and the related literature detailing the laboratory and field research projects, the following observations are provided.

- Both cylindrical and beam specimens, depending upon the type of wheel tracking device, can be used to rank mixtures with respect to rutting.
- Results obtained from the wheel tracking devices seem to correlate reasonably well to actual field performance when the in-service loading and environmental conditions of that location are considered.
- The wheel tracking devices seem to reasonably differentiate between performance grades of binders.
- Wheel tracking devices, when properly correlated to a specific site's traffic and environmental conditions, have the potential to allow the user agency the option of a pass/fail or "go/no go" criteria. The ability of the wheel tracking devices to adequately predict the magnitude of the rutting for a particular pavement has not been determined at this time.
- A device with the capability of conducting wheel-tracking tests in both air and in a submerged state will offer the user agency the most options of evaluating their materials.

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