STATE OF FLORIDA

INVESTIGATION OF THE SUITABILITY OF THE ASPHALT PAVEMENT ANALYZER FOR PREDICTING PAVEMENT RUTTING

Research Report
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STATE MATERIALS OFFICE

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EXECUTIVE SUMMARY

This report summarizes the findings of an investigation performed to evaluate a newly developed wheel tracking device, known as the Asphalt Pavement Analyzer (APA), for assessing the rutting potential of asphalt mixes. The evaluation process consisted of correlating the APA's predicted rutting with known field measurements. The correlation between beam and gyratory samples as well as the testing variability were also investigated. In addition, the APA test results were compared to those obtained using the Georgia Loaded Wheel Tester.

The findings of this investigation indicated that the APA may be an effective tool to rank asphalt mixtures in terms of their respective rut performance. However, the APA testing variability did not only significantly differ from test to test but also from testing location to testing location within each test. Differences in rut measurements of up to 4.7 and 6.3 mm were recorded for beam and gyratory samples, respectively. Therefore, using the APA in a clear pass/fail criteria for performance prediction purposes of asphalt mixtures may not be appropriate at the present time. It should be noted that these findings are based on data collected on three mixes. It is, thus, suggested that the APA testing variability (testing and testing locations) be further assessed for a wider range of mixtures. The intent of such an assessment should not only be to correlate the APA results to field data, but also to develop potential pass/fail limits and procedures.

INTRODUCTION

It is widely accepted that the conventional mix design procedures, Marshall and Hveem, are inadequate to address the present in-service performance problems. The development of the Superpave System under the Strategic Highway Research Program (SHRP) with its superior mix design methodology, and improved binder specifications represents an opportunity to screen out unsuitable mixes. However, because of a lack of a strength test under the Superpave system, there is not enough or full assurance that an asphalt mixture with properties satisfying the current Superpave design criteria will not deform as a result of the current trends toward heavier traffic loadings and higher tire pressures.

Permanent deformation or rutting is characterized by a longitudinal depression that forms in the wheel paths. It is an accumulation of small deformations caused by repeated heavy loads. Such deformations may be caused by too much repeated stress being applied to the subgrade or by an asphalt mixture that is too low in shear strength. In one case, the rutting is considered more of a structural problem. It is generally the result of an underdesigned pavement section or of a subgrade that has been weakened by the intrusion of moisture. In the other case, the rutting results from accumulated deformation in the asphalt layers rather than in the underlying subgrade. This latter type of rutting, which is of most concern here, is normally a mixture related problem. When an asphalt pavement layer has inadequate shear strength, a small, but permanent, shear deformation occurs each time a heavy truck applies a load. A rut will then appear with enough load applications. This distress type reduces pavement serviceability and poses a safety hazard.

Increasingly, transportation agencies are adding empirical performance-predicting tests to their mix design procedures. Such testing, if calibrated to field performance data, would potentially be a valuable tool in a clear accept/reject criteria of asphalt mixtures.

OBJECTIVES

The objective of the present study was to evaluate a newly developed wheel tracking device, known as Asphalt Pavement Analyzer (APA), for assessing the rutting potential of asphalt mixes. The evaluation process consisted of correlating the APA's predicted rutting with known field performance of asphalt concrete pavements in Florida. The correlation between beam and gyratory samples as well as the testing variability were included in this investigation. Furthermore, the APA test results were compared to those obtained in a previous study using the Georgia Loaded Wheel Tester. In addition, since the APA is prototypical, this project was also concerned with refining the device and assessing its testing characteristics.

LABORATORY WHEEL TRACKING DEVICES: OVERVIEW

Current Wheel Tracking Devices

In recent years, a number of laboratory wheel tracking devices have been developed and used to measure the behavior of asphalt mixtures under simulated field loading conditions. The basic principle of these devices is to simulate the stress conditions resulting from repeated, moving-wheel loads as they actually occur on in-service pavements. The common feature of these wheel tracking devices is the utilization of a moving wheel to apply the load on the compacted asphalt concrete samples.

In the following sections the Wheel Tracking Testers, also know as Loaded Wheel Testers (LWTs), presently in use are described. The description includes an overview of the development of each device and its physical and testing characteristics.

Georgia Loaded Wheel Tester

The Georgia Loaded Wheel Tester (GLWT) was developed at the Georgia Institute of Technology for the Georgia Department of Transportation in the mid-1980's *(1)*. It was designed with the objective of developing a simplified method to supplement the Marshall method for assessing the rutting characteristics of the asphalt mixes used in Georgia. A schematic drawing of one version of the device is shown in Figure 1.

The GLWT is capable of testing confined asphalt concrete beam specimens. It tests the specimens using a stiff pressurized hose mounted along the top of the specimens. The hose acts as a tire to transfer the load from the loaded wheel to the beam. One loading cycle consists of a back and forth pass of the loaded wheel. The entire LWT assembly is housed in a heated and insulated temperature chamber which serves to maintain the test temperature relatively constant. The rut depth is measured using a dial gauge and a reference template at set cycle intervals. The measurements are then compared to a pass/fail criteria.

Asphalt Pavement Analyzer

The Asphalt Pavement Analyzer (APA) is the new generation of the Georgia Loaded Wheel Tester *(2)*. The APA has additional features that include a water storage tank and is capable of testing both gyratory and beam specimens. Three beam or six gyratory samples can be tested simultaneously. Wheel loads are applied on test samples by means of three pneumatic cylinders, each equipped with an aluminum wheel. The magnitude of the load applied on each sample is regulated by air pressure supplied to each pneumatic cylinder. The load from each moving wheel is transferred to a test sample through a stiff pressurized rubber hose mounted along the top of the specimen. The pressure in the three hoses, acting as tires, is regulated by a common pressure regulator so that the pressure in the three hoses should always be the same. The equipment is designed to evaluate not only the rutting potential of an HMA mixture, but also its moisture susceptibility and fatigue cracking under service conditions. The APA rut testing characteristics are similar to those of the GLWT. For the moisture susceptibility testing, the specimens are first conditioned in accordance with AASHTO T-283. The specimens are then placed in the APA with the water tank raised for complete submersion. After a soaking period, the specimens are tested while submerged in water, using the same procedures as for the rutting evaluation. For the fatigue testing, only beams can be used. A # 40 gage transformer detecting wire is attached to the bottom of the beam specimen. The wires are then soldered to lead wires to form an electrical circuit. The testing is performed until breakage of the detecting wires. Such a breakage opens the electrical circuit causing the wheel tracking action to stop. The number of cycles required for the detecting wires to break is recorded and used for comparison with those of other mixtures. Figure 2 shows a schematic drawing of the device.

Hamburg Wheel Tracker

The Hamburg Wheel Tracker (HWT) was developed by Helmut Wind, Inc., of Hamburg, Germany *(3)*. It is used as a specification requirement for German roadways. The device is also presently used in the United States as a research tool by some companies.

The HWT is capable of testing HMA beam and cylindrical samples only in water. The specimen is subjected to a 705 N vertical load applied through a solid rubber wheel. The loaded wheel has a diameter of 194 mm and a width of 47 mm. Specimens, compacted to an air void content of 7±1 percent, are normally subjected to a maximum of 20,000 loading passes at a rate of about 340 mm/s.

Couch Wheel Tracker

The Couch Wheel Tracker (CWT) is a modified version of the Hamburg Wheel Tracker. The CWT tests only HMA beam samples submerged in water. Test specimens are subjected to a 705 N vertical load applied through a solid rubber wheel. The loaded wheel has a diameter of 194 mm and a width of 47 mm. The samples are tested at an air void content of 6±0.5 percent for conventional (dense) HMA and 4.5±0.5 percent for stone matrix asphalt (SMA). The rut depths are determined by measuring the vertical position of the loading wheel at the midpoint of its travel span after 20,000 loading passes applied at a rate of about 550 mm/s. The measurements are continuously recorded on a chart during testing. Couch considers mixtures with rutting rates less than 1 mm/hr, when tested at 55 ^{o}C, as high performance mixtures.

LCPC Wheel Tracker

The Laboratoire Central des Ponts et Chaussées (LCPC) wheel tracker (FWT) has been successfully used in France for more than a decade to predict rutting in HMA pavements *(4)*. In recent years, some U.S. transportation agencies, such as the Colorado Department of Transportation and the FHWA's Turner Fairbank Highway Research Center, have used the FWT to evaluate the rutting and stripping potential of asphalt pavements *(4)*.

The FWT is capable of testing only beam samples in air. The beams are compacted to an air void content of 6±2 percent. The test consists of subjecting the samples to a load of about 5,000 N through a pneumatic tire inflated to 600 kPa. Initially, the test sample is loaded for a consolidation period of 1000 cycles at ambient temperature. The resulting deformation is used as a reference reading point. After a test temperature conditioning period, the specimen is tested for approximately 30,000 cycles at a rate of one cycle per second. Rut depth readings are taken after 100, 300, 1,000, 3,000, 10,000 and 30,000 cycles. The overall slab deformation depth is determined as the average of a series of 15 measurements (three measurements taken across the specimen width at each of five locations along the sample length). The passing criteria is an average deformation depth of less than 10 percent of the original sample thickness.

Correlation of Wheel Tracking Test Results with Field Performance

Several studies were performed, in the recent years, to determine a correlation between field performance and laboratory wheel tracking test results *(3,4,5)*. The University of Wyoming performed an evaluation of the feasibility of the Georgia Loaded Wheel Tester to predict rutting. Core samples were obtained from thirteen pavement sections throughout the state of Wyoming. The sections were selected as to consider both a wide range of temperature conditions and rutting performance. The core samples were tested using the GLWT at 41 and 46 degree Celsius. The test results were then compared to known field rutting performance of the corresponding pavement sections. This investigation concluded that the GLWT had a good testing repeatability and the laboratory test data, at 46 degree Celsius, correlated well with actual field measurements when elevation and pavement surfaces type were considered *(5)*.

The Colorado Department of Transportation compared the results obtained from the Hamburg Wheel Tester to known field performance data in terms of stripping *(3)*. A total of twenty pavement sections throughout the state of Colorado were considered. The field performance data rated seven of these sections as good, five as needing high maintenance, four as requiring complete rehabilitation, and the four remaining sections as completely disintegrated. Representative mixes were obtained and tested according to the HWT standard procedure at 45 and 50 degree Celsius. Testing parameters that included rut depth, creep slope, stripping slope, and the stripping inflection point were evaluated. The testing results indicated that the stripping slope and stripping inflection point distinguished between good and poor field stripping performances, but, the moisture conditioning system used by the Hamburg wheel tracker appeared to be extremely severe for rutting determination. Four of the seven sections rated as good had rut depth values higher than 4 mm after 20,000 passes. The study concluded that the HWT present specifications may be too stringent for Colorado conditions. Further evaluation was suggested to better correlate the Hamburg wheel tester results with actual field performance.

In another study, the Colorado Department of Transportation and the FHWA's Turner Fairbank Highway Research Center cooperated in a project to evaluate the French wheel tracker (FWT) in predicting rutting potential *(4)*. The study considered thirty-three pavement sections throughout Colorado which were rated as having performed either satisfactory or poorly in terms of rutting resistance. Three slab samples were obtained from each of the sections. The test results indicated that the French specifications are in general too severe for Colorado conditions. It was thought that a better correlation between field and lab data would have been obtained if the number of passes for low volume pavements and the test temperature for pavements in moderate to high elevations were decreased.

The Laboratoire Central des Ponts et Chaussées also investigated the correlation between the FWT test data and rutting measured on a circular test track at Nantes *(6)*. A total of four mixtures were evaluated using the loading device and were also placed on the test track. The study concluded that the FWT can be used to predict a good rutting performance of a mixture.

TESTING PROGRAM

Initial Preliminary Tests

Since the APA is prototypical, trial tests were conducted to assess its testing characteristics and potentially refine the equipment. These tests resulted in the modification/correction of several testing items that included: (1) repositioning and rewiring of thermocouples within the APA chamber for a more accurate temperature reading, (2) installing a new fan motor that does not shut down at temperatures less than 70 °C (160 °F) while the heat strips continue heating (which would, otherwise, damage the interior unit), (3) changing the heights of the molds for uniformity in testing, and (4) putting new circuit breakers in the APA compactor to withstand higher compacting pressures within the testing range. In addition, it was also observed that the supplied contact bar between the loading wheel and the load cell (which support the loading wheel during calibration) was not always effective in centering the loading wheel during the calibration process. A small eccentricity in the loading wheel position may induce a sort of cantilever effect, thus resulting in erroneous calibration load readings. Therefore, a saddle fitting the contour of the loading wheel was fabricated to help to self-center the wheel during calibration, and thus, reduce errors due to load eccentricity from the geometric center. Figure 3 shows both the supplied and the modified wheel support for load calibration.

Selection of Pavement Test Sections

Three sections from the Florida interstate pavement system were considered in this study. The sections were selected because of their different rutting performances. One section had very good performance under heavy traffic. The second section rutted severely and was removed after only four years of service. The last section exhibited light to moderate signs of rutting. These sections were constructed in the early 1980s using typical Florida S-I structural mixtures. General information regarding the mixtures is given in Table 1, noting that all these mixtures do not meet current FDOT specifications.

Traffic and rutting performance data as collected for the three projects is summarized in Table 2. The rut depths reported for these sites were measured using a 2-m straightedge. It should be noted that the only rutting type considered in this study is that resulting from plastic flow.

Preparation of Test Samples

Core samples were obtained from the three sections to determine the in-place aggregate gradations and asphalt contents. Since the in-place gradation may have varied from that shown in the mix design, all test specimens were prepared to closely match the gradations and asphalt contents, shown in Table 3, as determined from the roadway cores. In addition, the aggregates were obtained from their original sources. However, the original asphalt cements were not available, so a standard grade AC-20 meeting the original asphalt specification requirements was used for all three mixtures. It was felt that preparing the asphalt mixtures using the original raw materials, blended based on the gradations and asphalt contents as determined from roadway cores would reflect changes that could have occurred during plant mix production and/or placement and, consequently, the error would be minimal when comparing laboratory and field test data. The respective results of Marshall test and voids analyses performed on the original and reproduced designs are illustrated in Table 4.

The aggregate and asphalt materials were heated to 150 ºC (300 ºF), blended, then returned to the oven prior to compaction. All samples were compacted to a target air void content of 7 percent to simulate the typical initial density achieved in the field. Actual air void contents of test samples are given in Tables 5 and 6 for beam and gyratory samples, respectively.

For the APA testing, nine beam samples per mix (a total of 27 beams) were compacted using the Asphalt Vibratory Compactor (AVC). The AVC compacts the mixtures using a combination of a static compaction force along with vibration. The desired density of a given HMA mixture is obtained by adjusting the compaction force and vibration time of the AVC. This type of compaction method is supposed to simulate the field vibratory compaction. Additionally, 18 gyratory specimens per mixture were prepared using the Superpave Gyratory Compactor.

The GLWT testing data were obtained from a previous study *(7)*. At that time, the beam samples were compacted using a static compaction procedure. Nine beam samples per mix (a total of 27 beams) were prepared.

In all cases, the compacted samples were removed from the molds and allowed to cure at room temperature for seven days. During the curing period, bulk density, and air void content were determined for each test sample. Prior to actual testing, the test specimens were conditioned in the tester device chamber at the test temperature for 24 hours. Testing in both the APA and GLWT was performed at 41 ºC (105 ºF) with the sample sides in full confinement. The wheel load and the hose pressure were respectively set at 540 N (122 lbs.) and 690 kPa (100 psi). Rut measurements were collected at 0, 1000, 4000, and 8000 loading cycles.

DATA ANALYSIS

The APA rut depth measurements as collected during the course of this investigation are summarized in Tables 7 and 8. The data was first analyzed to consider the APA testing repeatability as well as the correlation between beam and gyratory samples. The effectiveness for assessing the rut potential of asphalt mixes using the APA was then evaluated. The evaluation process consisted of correlating the APA rut measurements with known field rut data of asphalt concrete mixtures used in Florida. Finally, the APA test results were compared to those obtained using the Georgia Loaded Wheel Tester (GLWT).

APA Testing Repeatability

As mentioned above, the APA was designed to evaluate three beam or six gyratory samples simultaneously. The magnitude of the load applied on each sample is regulated by air pressure so that the pressure in the three pneumatic cylinders should always be the same. Because of such a testing set-up, it was decided first to assess the testing repeatability between the three possible loading positions within each test and between the three tests (thus, within each loading position). The results of this assessment are summarized in Tables 9 and 10, for beam and gyratory samples, respectively. These tables show considerable variability between the three testing locations and between the tests, both for gyratory (front and back positions within each location) and beam samples. This variability seems to be mix dependent and increases with the increase of the number of loading cycles and rut depth. To illustrate the relatively lower testing repeatability observed during this study, differences in rut measurement of up to 4.7 and 6.3 mm were, respectively, recorded for beam and gyratory samples (considering both testing and testing location).

To further analyze the APA rut data, paired-difference experiments were conducted. The purpose of this analysis was to determine the significance level of the observed differences among the respective average measurements of the three tests as well as among the three testing locations within each test. The hypothesis concerning the equality between the corresponding average results of any two of the three tests or between any two of the three testing locations within each test was tested using the Student t-test. The paired-difference analysis results are summarized in Table 11 for both beam and gyratory samples. The critical value of t based upon $n - 1 = 8$ (n is the number of paired differences, which is 9) degrees of freedom and a level of significance $\alpha = 0.05$ is $t_\alpha = 2.365$. This latter value is compared with the tabulated t values (Table 11) to determine wether to accept the null hypothesis of no difference between the respective rut measurements. This comparison indicates that, within the test range, the relative differences between the average data of Tests 2 and 3 (beam samples), and between Test 1 and 3 (gyratory samples) are statistically significant. The paired-difference analysis also showed that the testing location affected the results of Test 1 (center vs. right) and Test 3 (left vs. center and left vs. right) for beam samples and all the test results for gyratory samples (apart from left vs. right position of Test 3). All these findings seem to indicate that the APA testing variability may differ from test to test and, within each test, from location to location. It may be hypothesized that the present APA testing set up is not completely effective in keeping the air pressure within the three pneumatic cylinders uniform throughout the loading duration. Thus, this testing variability could have been induced by possible pressure fluctuations within the cylinders during testing. It would have been of interest if it were possible to electronically monitor and record in real time the magnitude of the testing loads throughout the loading duration. The calibration of the three loading wheels was checked before and after each test. Such a check did not show any significant deviations from the set loading level.

Beam vs. Gyratory Samples

The average beam and gyratory rut depth measurements at different loading cycles are plotted in Figure 4. The latter shows that the rut levels of gyratory samples were relatively higher that those of beam samples for Mixes B and D. Conversely, the beam samples rutted more that the gyratory samples for Mix C. This comparison is also illustrated in Figure 5, which shows a linear relationship between the beam and gyratory rut measurements (R-square value of 0.97). All the measurements fall near a straight line with small dispersion about the line. In addition, the regression line intersects the equality line at approximately a rut depth of 10 mm. Such an observation would indicate that, for comparable air void contents and loading conditions, the gyratory samples rut relatively deeper than beam samples when the ruts are less that 10 mm. Above the 10 mm mark, the beam would deform more regardless of the mixture type. It is important for the purpose of this study to note that the actual air void levels of all gyratory and beam test samples (see Tables 5 and 6) did not significantly vary from the target air void of 7 percent.

The significance level of the differences mentioned above was evaluated using the paired-difference analysis. The t values for the respective nine paired-differences (9 paired-differences per mix type) for Mixes B, C, and D were determined to be 9.695, 2.574, and 5.710. Again, the critical value of t based upon n-1= 8 (n: number of paired differences, which is 9) degrees of freedom and a level of significance $\alpha = 0.05$ is $t_\alpha = 2.365$. Since all the calculated t values exceed the latter, the null hypothesis of no difference between the respective beam and gyratory average rut measurements is rejected. Therefore, it could be concluded that, within the test range, the beam and gyratory samples did not result in statistically similar results, regardless of the mix type. Thus, it may not be appropriate to use the same pass/fail test criteria for both beam and gyratory specimens.

Comparison of APA Test Results with Field Measurements

The field performance of each of the three mixes considered in this study is illustrated in Figure 6. A comparison of the plot in the latter figure to that of Figure 4 shows that the APA ranked the mixes according to their field performance ranking. This ranking is the same using either beam or gyratory specimens. In addition, the comparison of field rut measurements to the average APA values seems to suggest that average values within the ranges of 7 to 8 mm and of 8 to 9 mm may be used as a limiting criteria at 8000 cycles for beam and gyratory samples, respectively. However, it should be noted that these suggested ranges are based on data collected on three mixes using an average of 9 measurements (3 tests and 3 samples per tests). Thus, simply adopting them for performance testing purposes may not be advisable at the present time. It is suggested that the APA testing variability (testing and testing locations) be further assessed for a wider range of mixtures. The intent of such an assessment should not only be to correlate the APA results to field data, but also to develop potential pass/fail limits and procedures.

APA vs. GLWT Test Results

The respective APA and GLWT average rut measurements at different loading cycles are shown in Figure 7 for all three mixes. It indicates that the GLWT results are relatively lower than those obtained using the APA, particularly for Mix B. However, this observation could be skewed by the differences in air void contents of test samples summarized in Table 12, although a previous study did not find any evidence of the effect of air void content variability, within the test range, on the GWLT test results*(7)*. Still, it was decided for the purpose of this comparison to consider the rut depth per unit of air void of the corresponding test sample (rut measurements were divided by air void content of each respective test sample). The comparison of these "normalized" rut measurements (rut depth per unit of air void content) is illustrated in Figure 8. The latter shows that there is a good correlation between the APA and GLWT data (R-square of 0.97) regardless of the type of mix and that the APA deformation depth is approximately twice that of the GLWT at any loading cycle number.

CONCLUSIONS

The Asphalt Pavement Analyzer (APA) was evaluated for assessing the rut potential of asphalt mixes. The evaluation consisted of correlating the APA's predicted rutting with known field measurements. The correlation between beam and gyratory samples as well as the testing variability were also investigated. In addition, the APA test results were compared to those obtained using the Georgia Loaded Wheel Tester. Based on the findings of this investigation, the following conclusions can be drawn:

- The APA testing variability may differ from test to test and, within each test, from location to location, both for gyratory and beam samples.
- A good correlation was obtained between the respective average measurements on gyratory and beam samples. However, the magnitude levels of these respective measurements were statistically different, regardless of the mix type. A linear regression analysis indicated that, under similar testing conditions, gyratory samples may rut relatively deeper than beam samples when the ruts are less that 10 mm. Above the 10 mm mark, the beams may deform more. Therefore, it may not be appropriate to use the same pass/fail test criteria for both beam and gyratory specimens.
- APA ranked the mixes considered in this study according to their field performance ranking.

This ranking is the same using either beam or gyratory specimens.

! Average values within the ranges of 7 to 8 mm and of 8 to 9 mm may be used as a performance limiting criteria at 8000 cycles for beam and gyratory samples, respectively. The average values were determined using the results of 3 tests and 3 samples per test.

! Under similar testing conditions, a good correlation between the APA and GLWT test results was obtained, independently of the mix type and loading cycle number. However, the magnitude of the respective rut depths were not comparable. The APA deformations were approximately twice as large as those of the GLWT.

RECOMMENDATIONS

The findings of this investigation indicated that the APA may be an effective tool to rank asphalt mixtures in terms of their respective rutting performance. However, the APA testing variability not only significantly differed from test to test but also from testing location to testing location within each test. Differences in rut measurements of up to 4.7 and 6.3 mm were recorded for beam and gyratory samples, respectively . Therefore, using the APA in a clear pass/fail criteria for asphalt mixtures may not be appropriate at the present time. Again, it should be noted that these findings are based on data collected on three mixes using one APA device. It is, therefore, suggested that the APA testing variability (testing and testing locations) be further assessed for a wider range of mixtures. The intent of such an assessment should not only be to correlate the APA results to field data, but also to develop potential pass/fail limits and procedures.

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REFERENCES

1. Lai, J. S. *Development of a Simplified Test Method to Predict Rutting Characteristics of Asphalt Mix*. Georgia DOT Project 8503, Final Report, Georgia Department of Transportation, Forest Park, GA, 1986.

2. Collins, R., S. Shami, and J. S. Lai. Use of Georgia Loaded Wheel Tester to Evaluate Rutting of Asphalt Samples Prepared by Superpave Gyratory. In *Transportation Research Record 1545*, TRB, National Research Council, Washington, D.C., 1996.

3. Aschenbrener, T. Evaluation of Hamburg Wheel-Tracking Device to Predict Moisture Damage in Hot-Mix Asphalt. In *Transportation Research Record 1492*, TRB, National Research Council, Washington, D.C., 1995.

4. Aschenbrener, T. Comparison of Results Obtained from the LCPC Rutting Tester with Pavements of Known Field Performance. In *Transportation Research Record 1454*, TRB, National Research Council, Washington, D.C., 1994.

5. Miller, T., K. Ksaibati, and M. Farrar. Utilizing Georgia Loaded Wheel Tester to Predict Rutting. In *Transportation Research Record 1473*, TRB, National Research Council, Washington, D.C., 1995.

6. Corté, J. F., Y. Brosseaud, J. P. Simoncelli, and G. Caroff. Investigation of Rutting of Asphalt Surface Layers: Influence of Binder and Axle Loading Configuration. In *Transportation Research Record 1436*, TRB, National Research Council, Washington, D.C., 1994.

7. West, R. C., G. C. Page, and K. H. Murphy. *Evaluation of the Loaded Wheel Tester*. Research Report FL/DOT/91-391, Florida Department of Transportation, Gainesville, December 1991.

Table 1 General Information on Field Mixtures

Mix Designation	Mix B	Mix C	Mix D
FDOT Mix Design No.	QA 79-794	QA 80-829	QA 80-1039
Project Number	36210-3419	32100-3442	18130-3422
Location	Marion County	Columbia County	Sumter County
Aggregate Type	Florida Limestone	Alabama Limestone	Florida Limestone
Asphalt Content, %	6.5	5.5	6.5
Rutting Performance	Good	Very Poor	Moderate

Table 2 Traffic and Field Rut Depth Data

Year	AADT[1]			ESAL[2], thousands			Rut Depth, mm		
	Mix B	Mix C	Mix D	Mix B	Mix C	Mix D	Mix B	Mix C	Mix D
1981	*	24,590	*	*	1,069	*	*	3.2	*
1982	31,327	24,887	16,927	1,320	1,082	701	0.0	6.4	0.0
1983	33,389	25,957	18,216	1,382	1,128	754	1.6	9.5	2.1
1984	37,571	27,376	19,118	1,604	1,190	793	1.6	14.3	2.1
1985	41,752	28,795	20,020	1,728	1,251	829	1.6	15.9	2.1
1986	43,376	**	21,592	1,991	**	877	3.2	**	6.4
1987	45,000	**	23,165	1,745	**	941	6.4	**	6.4
1988	46,623	**	24,737	1,900	**	1,049	6.4	**	6.4
1989	48,247	**	26,310	1,858	**	1,087	6.4	**	6.4
1990	49,871	**	27,882	2,064	**	1,154	6.4	**	6.4
1991	43,310	**	29,103	1,793	**	1,205	6.4	**	6.4
1992	48,500	**	29,924	2,007	**	1,239	6.4	**	7.9
1993	54,000	**	30,595	2,235	**	1,266	6.4	**	7.9
1994	54,000	**	29,821	2,235	**	1,234	6.4	**	7.9

[1] Annual Average Daily Traffic.
[2] Equivalent Single Axle Loads.
* Under construction.
** Removed and replaced.

Table 3 Aggregate Gradations

Sieve Size, mm	19.0	12.5	9.5	4.75	2.00	0.425	0.180	0.075
				Mix B Gradation, % Passing				
Design	100	99	90	63	47	35	13	4
Recovered	100	99	92	65	47	36	14	5.7
Reproduced	100	99	91	64	49	32	13	5.3
				Mix C Gradation, % Passing				
Design	100	98	84	57	44	36	17	3
Recovered	100	98	90	61	44	35	18	4.6
Reproduced	100	99	90	63	45	39	20	3.9
				Mix D Gradation, % Passing				
Design	100	99	88	62	47	32	9	2.6
Recovered	100	97	89	62	49	35	11	4
Reproduced	100	99	90	64	49	30	11	4.2

Table 4 Marshall and Voids Properties of Test Mixtures

	Mix B		Mix C		Mix D	
	Designed	Reproduced	Designed	Reproduced	Designed	Reproduced
Stability, N	8941	9119	5071	3826	6762	9875
Flow, 0.25 mm	10	8.8	10	9.2	9	9.2
V.M.A., %	14.5	15.3	15.3	15.7	15.9	13.7
Air Voids, %	3	4.3	3.6	2.8	4.2	3.3

Table 5 Air Void Contents of Beam Specimens, %

Mix Type	Test 1			Test 2			Test 3		
	Left	Center	Right	Left	Center	Right	Left	Center	Right
Mix B	7.2	6.9	7.0	6.8	7.1	6.9	6.8	6.8	7.0
Mix C	7.0	6.9	7.1	7.0	6.6	6.7	6.7	6.9	7.1
Mix D	7.1	7.2	7.1	7.1	6.9	7.3	7.2	7.2	6.9

Table 6 Air Void Contents of Gyratory Specimens, %

Mix Type	Sample Location within APA Testing Set-Up					
	Left		Center		Right	
	Front	Back	Front	Back	Front	Back
	Test 1					
Mix B	7.1	7.2	7.1	6.9	7.2	6.9
Mix C	7.1	7.1	7.2	6.9	6.9	7.2
Mix D	6.9	7.0	6.8	6.9	6.9	7.2
	Test 2					
Mix B	7.1	7.1	7.4	7.4	7.3	7.1
Mix C	7.1	7.2	7.1	7.1	6.9	7.1
Mix D	7.1	7.2	6.9	7.0	7.3	7.0
	Test 3					
Mix B	7.2	7.4	7.4	7.2	7.1	7.0
Mix C	7.1	7.2	7.0	7.2	6.9	7.1
Mix D	7.1	7.2	7.3	7.1	7.0	7.0

Table 7 APA Rut Depth Measurements, mm - Beam Samples

Mix Type	Test 1 Left	Test 1 Center	Test 1 Right	Test 1 Avg.	Test 2 Left	Test 2 Center	Test 2 Right	Test 2 Avg.	Test 3 Left	Test 3 Center	Test 3 Right	Test 3 Avg.
	Sample Location Within APA Testing Set-Up											
1000 Cycles												
Mix B	2.4	2.7	2.7	2.6	3.2	3.2	3.1	3.1	3.7	3.9	3.2	3.6
Mix C	8.3	7.0	8.4	7.9	7.6	8.1	7.8	7.9	8.9	8.8	8.0	8.6
Mix D	4.2	4.1	5.3	4.5	4.0	4.6	3.6	4.1	4.5	4.2	4.7	4.5
4000 Cycles												
Mix B	4.9	5.3	5.7	5.3	5.2	5.3	5.5	5.4	5.8	5.9	5.1	5.6
Mix C	14.2	11.6	14.1	13.3	12.6	13.6	14.1	13.4	15.0	14.1	12.9	14.0
Mix D	7.0	6.1	8.2	7.1	7.2	6.9	6.1	6.7	7.2	6.3	7.0	6.8
8000 Cycles												
Mix B	6.3	9.0	7.7	7.7	6.3	6.4	6.9	6.5	7.2	7.1	6.7	7.0
Mix C	19.4	15.4	18.5	17.8	16.7	18.1	19.9	18.2	20.1	18.3	16.9	18.4
Mix D	9.1	7.5	10.1	8.9	9.7	8.6	7.7	8.7	9.4	7.8	8.5	8.6

Table 8 APA Rut Depth Measurements, mm - Gyratory Samples

Test Number	Mix Type	Location Within APA Testing Set-Up						Average		
		Left		Center		Right				
		Front	Back	Front	Back	Front	Back	Front	Back	Both
Test 1	1000 Cycles									
	Mix B	4.6	4.6	3.6	3.8	5.4	4.8	4.5	4.4	4.5
	Mix C	5.7	6.7	5.8	5.7	6.7	7.0	6.1	6.5	6.3
	Mix D	5.2	5.0	4.5	4.5	4.8	5.1	4.9	4.8	4.9
	4000 Cycles									
	Mix B	6.7	7.2	5.8	6.1	8.0	7.4	6.8	6.9	6.9
	Mix C	10.6	12.3	10.6	9.6	12.0	12.4	11.1	11.4	11.2
	Mix D	8.1	7.5	6.5	7.3	7.8	8.2	7.5	7.7	7.6
	8000 Cycles									
	Mix B	8.3	8.8	7.2	7.7	9.7	8.9	8.4	8.5	8.4
	Mix C	15.0	15.9	14.8	12.9	16.7	16.5	15.5	15.1	15.3
	Mix D	9.8	9.2	8.0	9.2	9.9	10.6	9.2	9.7	9.5
Test 2	1000 Cycles									
	Mix B	4.1	4.2	3.5	4.0	3.2	3.8	3.6	4.0	3.8
	Mix C	6.2	5.7	6.1	5.8	6.6	5.4	6.3	5.6	6.0
	Mix D	6.1	6.7	4.9	5.5	6.3	6.3	5.7	6.2	5.9
	4000 Cycles									
	Mix B	6.7	6.9	5.5	6.9	6.7	6.4	6.3	6.7	6.5
	Mix C	11.4	10.2	10.4	9.7	11.4	10.0	11.0	10.0	10.5
	Mix D	8.7	9.3	7.0	7.7	9.0	8.4	8.2	8.4	8.3
	8000 Cycles									
	Mix B	8.1	8.4	6.8	7.9	8.3	7.7	7.7	8.0	7.9
	Mix C	15.6	13.9	14.2	13.4	16.0	13.8	15.3	13.7	14.5
	Mix D	10.1	10.8	8.3	8.8	10.3	9.7	9.6	9.8	9.7
Test 3	1000 Cycles									
	Mix B	4.5	5.4	4.4	4.4	5.1	5.8	4.7	5.2	4.9
	Mix C	9.4	9.4	9.6	8.8	10.4	9.9	9.8	9.4	9.6
	Mix D	5.2	5.8	4.5	5.4	4.7	5.4	4.8	5.5	5.2
	4000 Cycles									
	Mix B	6.8	7.7	6.7	6.4	8.0	8.2	7.2	7.4	7.3
	Mix C	15.1	14.5	15.5	13.9	15.8	15.0	15.5	14.5	15.0
	Mix D	8.3	8.6	6.8	8.2	7.5	8.6	7.5	8.5	8.0
	8000 Cycles									
	Mix B	8.1	9.2	8.0	7.7	9.4	9.6	8.5	8.8	8.6
	Mix C	18.3	17.2	19.1	16.9	19.0	18.9	18.8	17.7	18.2
	Mix D	9.9	10.7	8.2	9.8	9.2	10.8	9.1	10.4	9.8

Table 9 Variability of APA Rut Depth Measurements - Beam Samples

Mix Type	Range of Differences in Rut Measurements, mm						
	Between Locations			Between Tests			Tests & Locations
	Test 1	Test 2	Test 1	Left	Center	Right	
	1000 Cycles						
Mix B	0.3	0.1	0.7	1.3	1.2	0.5	1.5
Mix C	1.4	0.5	0.9	1.3	1.8	0.6	1.9
Mix D	1.2	1.0	0.4	0.5	0.5	1.6	1.6
	4000 Cycles						
Mix B	0.9	0.4	0.8	1	0.6	0.7	1.0
Mix C	2.6	1.5	2.1	2.4	2.5	1.2	3.4
Mix D	2.1	1.0	0.9	0.3	0.8	2.1	2.1
	8000 Cycles						
Mix B	2.7	0.6	0.5	0.9	2.6	0.9	2.7
Mix C	4.0	3.3	3.3	3.5	2.9	3.1	4.7
Mix D	2.7	1.9	1.7	0.5	1.2	2.4	2.7

Table 10 Variability of APA Rut Depth Measurements - Gyratory Samples

Mix Type	Range of Differences in Rut Measurements, mm																	
	Between Testing Locations									Between Tests						Between Tests & Locations		
	Test 1			Test 2			Test 3			Left		Center		Right				
	Front	Back	Both	Front	Back	Both	Front	Back	Both	Front	Back	Front	Back	Front	Back	Front	Back	Both
1000 Cycles																		
Mix B	1.8	0.9	1.8	0.9	0.4	1.0	0.8	1.5	1.5	0.5	1.2	0.9	0.5	2.1	2.0	2.1	2.0	2.6
Mix C	0.9	1.3	1.3	0.4	0.5	1.2	1.0	1.1	1.6	3.7	3.7	3.8	3.1	3.9	4.5	4.7	4.5	5.1
Mix D	0.8	0.6	0.8	1.4	1.3	1.8	0.7	0.4	1.3	0.8	1.7	0.4	1.0	1.5	1.2	1.8	2.2	2.2
4000 Cycles																		
Mix B	2.3	1.3	2.3	1.2	0.5	1.3	1.3	1.8	1.8	0.1	0.9	1.2	0.7	1.3	1.8	2.5	2.1	2.6
Mix C	1.4	2.8	2.8	1.1	0.5	1.7	0.6	1.1	1.9	4.5	4.2	5.2	4.3	4.3	5.1	5.4	5.4	6.2
Mix D	1.6	0.9	1.7	2.0	1.6	2.3	1.4	0.4	1.8	0.6	1.8	0.5	0.9	1.5	0.4	2.5	1.9	2.8
8000 Cycles																		
Mix B	2.5	1.3	2.5	1.5	0.7	1.6	1.4	1.8	1.8	0.2	0.8	1.2	0.3	1.5	1.8	2.9	1.9	2.9
Mix C	1.9	3.6	3.9	1.9	0.5	2.7	0.9	1.9	2.2	3.3	3.3	5.0	4.0	2.9	5.1	5.0	6.0	6.3
Mix D	2.0	1.5	2.7	2.0	2.0	2.5	1.7	1.0	2.6	0.3	1.6	0.4	1.0	1.2	1.0	2.4	2.0	2.8

Table 11 Results of Paired-Difference Experiments

Source			Beam Samples		Gyratory Samples	
			Variance	t-statistic	Variance	t-statistic
Testing	Test 1 & Test 2		0.259	0.644	0.470	0.648
	Test 1 & Test 3		0.324	1.145	2.230	2.721
	Test 2 & Test 3		0.063	3.902	3.738	2.331
Location	Test 1	Left &Center	3.721	1.227	0.117	8.615
		Center & Right	2.035	2.804	0.439	7.190
		Left & Right	0.340	0.172	0.146	4.772
	Test 2	Left &Center	0.538	1.045	0.359	4.678
		Center & Right	0.791	0.037	0.377	3.539
		Left & Right	2.228	0.491	0.057	2.643
	Test 3	Left &Center	0.543	2.444	0.225	3.422
		Center & Right	0.659	1.396	0.227	5.900
		Left & Right	1.092	2.807	0.365	1.958

Table 12 Average Air Void Contents of Beam Test Samples

	Mix B	Mix C	Mix D
		APA	
Average, %	6.9	6.9	7.1
Standard Deviation, %	0.13	0.16	0.13
		GLWT	
Average, %	7.5	5.2	6.9
Standard Deviation, %	0.57	0.36	1.54

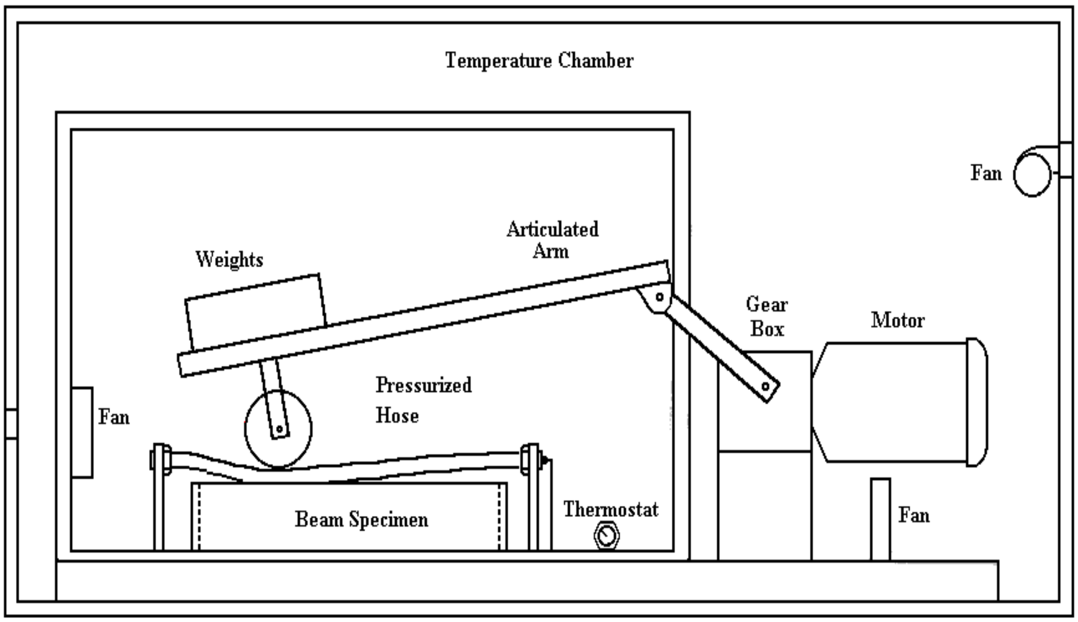

Figure 1 Schematic Drawing of one Version of the Georgia Loaded Wheel Tester (not to scale)

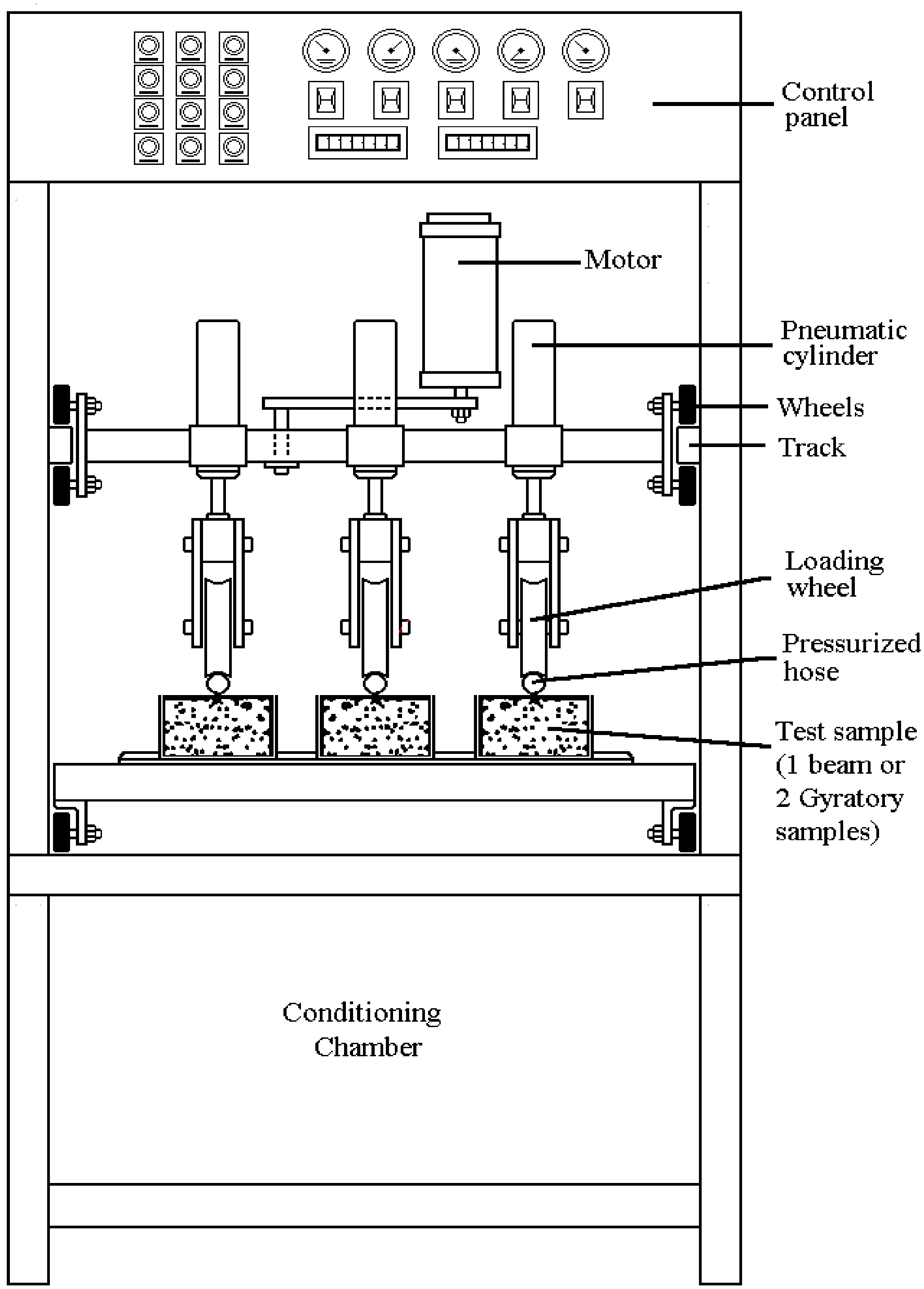

Figure 2 Schematic Drawing of the Asphalt Pavement Analyzer (not to scale)

(a) Supplied loaded wheel support bar with calibration cell

(b) Modified loaded wheel support bar with calibration cell

Figure 3 Respective photographs of supplied and modified loaded wheel calibration support bars

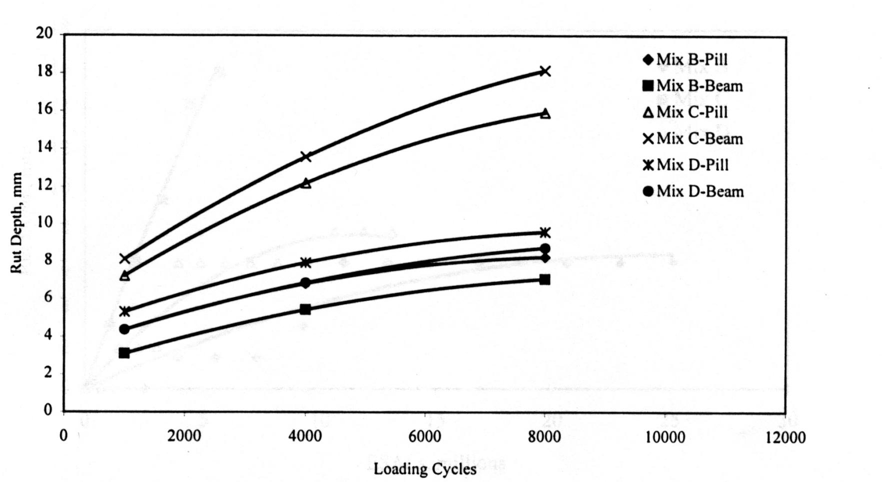

Figure 4 Average rut depth measurements at different loading cycles

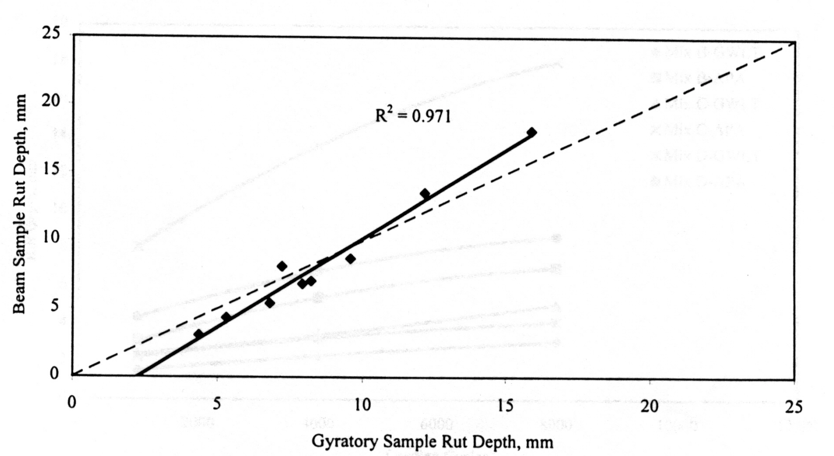

Figure 5 Illustrative comparison of beam and gyratory average rut measurements

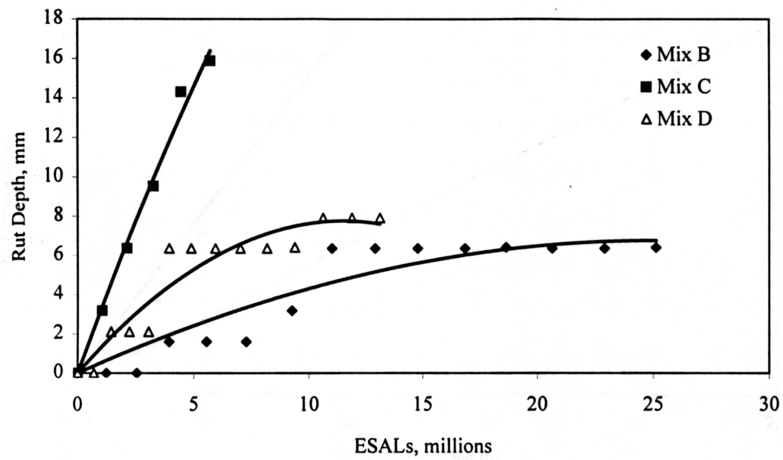

Figure 6 Field rut measurements

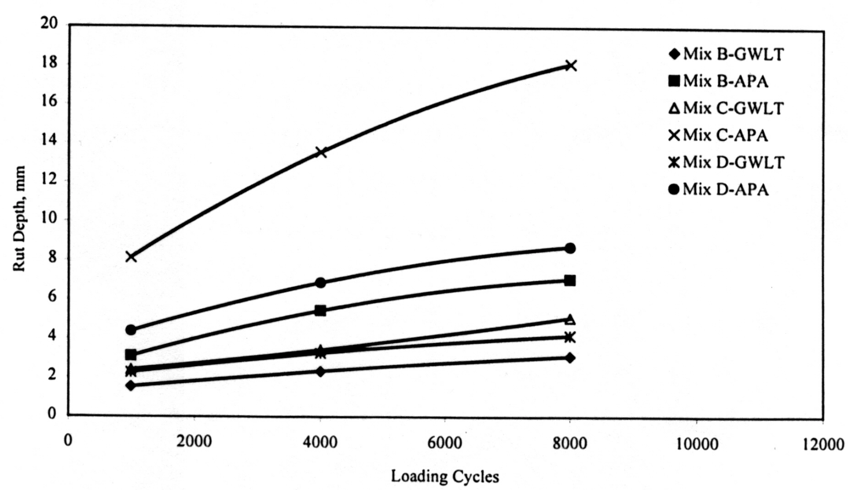

Figure 7 Respective APA and GLWT average rut measurements

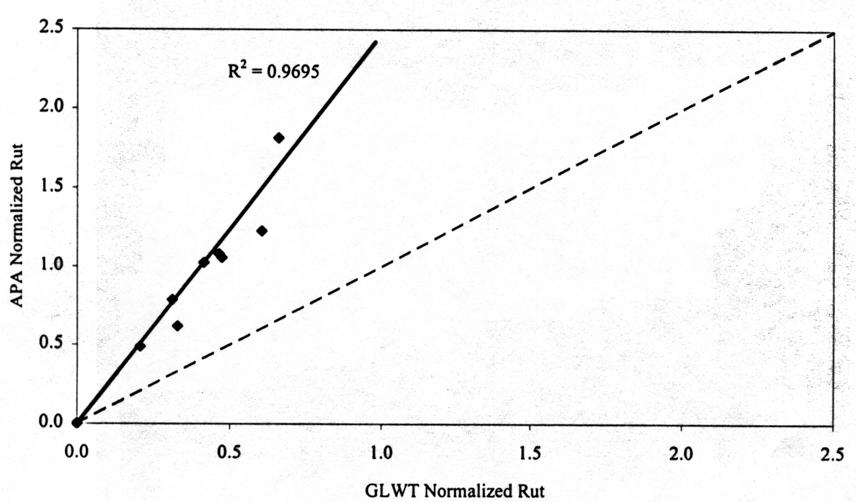

Figure 8 Illustrative comparison of APA and GLWT normalized average rut measurements