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EVALUATION OF RUTTING POTENTIAL OF HOT MIX ASPHALT USING ASPHALT PAVEMENT ANALYZER
(Item: 2153 ORA: 125-6660)

Final Report (Draft)

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TABLE OF CONTENTS

Chapter Section Page

EXECUTIVE SUMMARY

Rutting of flexible pavement is a widespread problem nationally, including Oklahoma. Rutting is defined as the longitudinal depression along the wheel path due to progressive movement of materials under repeated traffic load. Recent studies have shown that rutting potential of hot mix asphalt (HMA) samples can be evaluated in the laboratory during the design phase of a project using an Asphalt Pavement Analyzer (APA). The rutting susceptibility is evaluated by subjecting HMA samples to moving wheel loads and measuring permanent deformation at selected points along the wheel path as a function of the number of loading cycle. A pressurized rubber hose is placed between the moving wheel and the HMA sample to approximately simulate traffic loading on a pavement in the field. Both rectangular beam and cylindrical samples can be used. A typical test usually involves 8,000 cycles of loading on three beam samples or six cylindrical samples or a combination. The Asphalt Vibratory Compactor (AVC) is used to prepare beam samples, while cylindrical samples are either prepared using a Superpave Gyratory Compactor or an Asphalt Vibratory Compactor. Temperature, magnitude and frequency of moving load, hose pressure and number of cycle can be varied between tests and within the same test, if so desired. Effect of moisture can also be considered by conducting a test under submerged condition.

The University of Oklahoma (OU) received funding for a project (Item 2153) to procure an Asphalt Pavement Analyzer and an Asphalt Vibratory Compactor for the Ray Broce Materials Laboratory at OU. This project, funded jointly by the Oklahoma Department of Transportation (ODOT), the Federal Highway Administration (FHWA) and the Oklahoma Asphalt Pavement Association (OAPA), has two major goals: (a) exploratory testing of selected mixes to gain confidence and experience in using APA for evaluation of rut potential; and (b) establishing "baseline data" for selected mixes having low and high rut susceptibility. The following tasks were identified to accomplish the project goals: (i) Procurement and installation of APA and AVC; (ii) Demonstration and training; (iii) Selection of mixes and collection of materials (ingredients); (iv) Preparation of sample; (v) Exploratory rut testing; (vi) Analysis of exploratory test data; (vii) Conducting tests for baseline data; (viii) Analysis of baseline data; (ix) Preparation of final report.

The APA and the AVC were purchased in August 1999. A new electrical panel was installed in the Broce lab to meet the power requirements. Also, compressed air supply in the lab was upgraded to provide compressed air to both pieces of equipment. The installation was completed in September 1999. The manufacturer, Pavement Technologies, Inc. of Georgia, conducted a weeklong demonstration and training in October 1999 that involved calibration of data acquisition system (DAS) for wheel load, horizontal and vertical displacements, DAS setting for beam and cylindrical samples, operation of temperature and preset counter controllers, rubber hose replacement, rut depth measurement (both manual and automated), sample preparation using AVC, safety training, and complete rut and fatigue testing. Three mixes, one for exploratory testing and two for baseline data, were selected in cooperation with ODOT. In addition, ten plant-produced mixes were selected for testing by both the ODOT Materials Division and the OU Team for comparison of results and to address the issue of reliability. Later, another limestone superpave mix was added for extensive testing in developing baseline data.

The mix design for exploratory testing of one of the mixes (3012-OAPA-99037) was selected from ODOT standards and specifications for type B-insoluble mix. About sixty-four samples were tested for rutting. About half of these samples were prepared using AVC, while Superpave Gyratory Compactor (SGC) was used for the remaining samples. Two different temperatures (60° and 64°C) and four different asphalt contents (4.5%, 5%, 5.5% and 6%) were used for this series of tests. In the initial stage, over 50 percent samples did not meet the target air void (7 ± 1%), particularly for samples prepared using AVC. Sample quality and air void compliance improved with time and experience of the research team. The rut values (8,000 cycles) varied between 2.0 mm and 6.4 mm and the average rut depth were found to be more sensitive to temperature than asphalt content. Although, one of the goals of exploratory testing was to address "reproducibility" of data, this goal could not be achieved partly because of the difficulties in achieving the target air void at the initial stage. Also, it became evident that rut potential evaluation using APA is not a trivial exercise because of the complexities and difficulties involved in preparing "identical" samples and testing, particularly rut measurement (location, averaging, level of accuracy, sensitivity, etc.). This task was completed in June 2000. Based on discussions at the Project Panel Meeting, the project was extended in August 2000 for a year to address the following items that were not addressed in the work plan of the original proposal (Item 2153). (1) Comparison of data for the ten plant- produced mixes with the ODOT data for the same mixes and packaging of the data; (2) a better control on achieving the air void requirement; (3) reproducibility of test data; (4) correlation between rutting and resilient modulus, (5) density gradient analysis. An extension for one year is sought to address these issues. Addressing these issues is considered important in enriching our knowledge and confidence in APA as a tool for performance-based testing of HMA. However, efforts during the past year have focused on the first three items, and equipment has been procured to pursue the remaining two items.

Evaluation of rut potentials for ten plant-produced mixes was completed in September 2000. These mixes were selected in cooperation with ODOT Materials Division. Seven of these mixes were type B-insoluble, and three recycled asphalt materials (RAP). For each mix six cylindrical (SGC) and two beam samples were prepared and tested, giving a total of 76 samples. A majority of these samples met the target air void (7 $\pm$ 1%). The measured rut depth values varied between 1 mm and 8 mm. The rut depths form beam samples were consistently higher than the corresponding cylindrical samples. Such variations are attributed to sample geometry and rut measurement details. ODOT Materials Division has conducted rut tests using APA on the same ten plant produced mixes. These data was collected from ODOT, and compared with the corresponding data obtained by the OU Team. There was not a significant difference in measured rut depths for the same mix, therefore, additional rut tests were not conducted An effort was made sort out bad data, if there is any. Ranking of these mixes according to their rut potential was completed in December 2000.

ODOT participated in the NCAT Test Track project and provided materials and mix designs for two test sections. In a meeting, the Oklahoma Asphalt Task Force suggested that the OU Broce Lab participate in rut testing of both mixes. We tested 12 samples (6 SGC cylindrical) x 2 mixes) for rutting. The rut depth from the track will be compared with the APA data when the field data becomes available.

Two gravel mixes (3011-OK99-63070 and 3011-OK99-63071) were selected, in cooperation with ODOT, for the development of "baseline data." For each of the two mixes, we tested 24 samples for rutting (1 gradation x 1–PG binder x 1–aging x 1-temperature x 4 asphalt contents x 6 samples (4 SGC cylindrical samples and 2 AVC beam samples). At that stage, it was possible to prepare HMA samples to target air voids fairly accurately. Several samples were tested under wet condition and with different loading conditions as well as hose pressure. The baseline data can be used for calibration of APA. As such, the baseline data are reproducible. Since it is very difficult to produce APA samples that are identical, addressing the issue of reproducibility is a difficult task. With significant experience over the past years in using APA and AVC for evaluation of rutting, a duplicate series of tests (24 samples) were conducted to address reproducibility.

Later, it was realized that the baseline data was lacking Superpave mixes, so a limestone mix designed in accordance with the superpave method was added with the test matrix. The limestone mix was designed using 13 different asphalt binders (unmodified and modified) that are currently used in Oklahoma. A total of 104 cylindrical SGC samples were prepared and tested for rutting, and the results statistically analyzed to enrich the baseline database. Twelve Superpave samples were prepared in OU laboratory. Half of these samples were tested for rutting at OU, while the remaining half will be tested at ODOT. Similarly, another 12 samples were prepared at ODOT using the same aggregate and binders used at OU. The rut test values thus obtained was compared to address the issue of repeatability and reproducibility.

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I. INTRODUCTION

1.1 General

Hot Mix Asphalt (HMA) combines bituminous binder and aggregate to give a pavement structure that is flexible over a wide range of climatic conditions. The fact that HMA can be produced from a wide variety of local aggregates and yet perform on a consistent basis makes it the pavement of choice throughout the United States and the rest of the world. Approximately 93% of all the road surfaces in the United States are paved with HMA. The vehicular miles traveled in America have increased approximately 75% in the past 20 years. The changing demographics in American society have also lead to many rural roads becoming high traffic roads as the population moves from urban to more rural areas. Many asphalt roads consist of layer after layer of nonstructural surface mix. These layers have been generated by making temporary repairs or placing thin overlay to improve the rideability of roads with little attention given to structural strength needed to support the traffic loads. With 176 million automobiles on the road today, there are as many cars in America as there are drivers. In the last decade, loads on the nation's highways have increased more than 60% (Brock et al., 1999). In addition to the increased loads, the increased distress due to use of radial tires and high tire pressures make it obvious to see why some asphalt roads are often rutting under these conditions.

Rutting is a widely encountered national problem now. Excessive rutting has been reported in Florida, Georgia, Illinois, Pennsylvania, Tennessee, and Virginia (Barkdale, 1993). Rutting is a prevailing concern in Oklahoma today. Roberts et al. (1996) defined rutting as the formation of twin longitudinal depressions under the wheel paths caused by the progressive movement of materials under repeated loads in the asphalt pavement layers or in underlying base through consolidation or plastic flow **(Figure 1.1).** Theses depressions or ruts are of concern for at least two reasons: (i) if the surface is impervious, rut tarps water and cause hydroplaning, which is a potential treat to passenger cars, (ii) as the rut deepens steering becomes increasingly difficult leading to added danger. Rutting can significantly reduce both structural and functional performance of an existing pavement. Sometimes the rutting magnitude may not be alarming for structural performance, but it is highly important from the safety point of view (Roberts et al. 1996). Accordingly, it is highly important to predict and categorize rutting in flexible pavement. Rutting can provide useful information in selecting rehabilitation methods if it is categorized (Gramling et al., 1991). In case of consolidation and shear manifest rutting, a heavier overlay can be used to improve serviceability. In case of rutting due to lateral distortion, rehabilitation strategies can involve milling or leveling with a new wearing course, or recycling of the surface course (Gramling et al. 1991).

Depending on the magnitude of the traffic load and the relative strength of the pavement layers, rutting can occur in the subgrade, base, or upper hot-mix asphalt layers. Studies conducted by National Center for Asphalt Technology (NCAT) have indicated that the rutting generally occurs in the top 75 to 100 mm (3 to 4 inch) of HMA pavement (Kandhal, et al., 1993; Brown et al., 1992). HMA is a composite material composed of a carefully graded aggregate embedded in a matrix of asphalt cement that fills part of the space between the aggregate particles and binds them together. The properties of the individual components and how they react with each other in the system affect its behavior. There are occasions when the asphalt binder and aggregate are adequate but the mix fails to exhibit desired performance because of poor compaction, use of incorrect binder content, poor adhesion or some other problems associated with the mixture. Also, mixture properties alone are not sufficient to ensure satisfactory performance. Rutting is resulted primarily from high-pressure truck tires and increased wheel loads. The stress pattern induced in a three-dimensional pavement structure due to traffic loading is complex. When the response also depends on the time or rate of loading and temperature, the characterization becomes even more difficult. Rutting prediction for given circumstances requires detailed knowledge of the elastic, viscous and plastic deformation characteristic of all the influential constituents of a pavement structure. However, it is possible to control rutting by selecting quality aggregates with proper gradation and asphalt binder with appropriate grade and amount, among others, so that adequate void exists in the mix to resist permanent deformation.

Traditionally, predicting field performance of HMA has been complicated. A safeguard is needed to protect against making substantial investments in asphalt pavement only to discover, after opening to traffic, that pavement will not meet expectations. Several types of laboratory equipment have been developed to measure rutting potential including French Rut Tester, Georgia Loaded Wheel Tester (LWT) and The Asphalt Pavement Analyzer (APA) (Collins, 1995). A detailed discussion about the strengths and weaknesses of some of these equipments is given in Chapter II: Literature

Review of this report. Recent studies have shown that rutting potential of HMA samples can be evaluated in the laboratory during the design phase of a project using an Asphalt Pavement Analyzer (APA). APA has the ability to rank mixture performance in the laboratory before costly surprises are encountered in the field. In this equipment, rutting susceptibility is evaluated by subjecting HMA samples to moving wheel loads and measuring permanent deformation at selected points along the wheel path as a function of the number of loading cycle. This study employed this equipment to perform a series of laboratory tests.

1.2 Hypotheses

Hypothesis 1:

Rutting is a mixture related problem. It results from accumulated deformation in the asphalt layers rather than in the underlying subgrade. It occurs each time a heavy truck applies a load on asphalt pavement layer of inadequate shear strength. A higher pavement temperature normally increases the rate of rutting. Recently developed APA can closely simulate and control the field conditions (truck load, tire pressure, temperature, wet and dry conditions) in laboratory. It is hypothesized that mixture's rutting potential can be evaluated based on APA test results.

Hypothesis 3:

Rutting is influenced by numerous parameters. It is difficult to separate the effect of individual parameter on rutting due to their interaction and combined effect. However, APA can be employed to investigate the influence of some of the main parameters on rutting potential of HMA mix. It is hypothesized that a statistical model can be developed to investigate rut-influencing parameters.

Hypothesis 3:

Currently, there exists no model to incorporate many of the rut influencing parameters. A neuron-based model can be developed to predict rutting incorporating the parameters. However, the development of such model needs a number of data set for training and calibration of neural network model. It is hypothesized that rutting database (baseline data) can be developed based on the APA test results.

1.3 Objectives

The primary goals of this study are: to evaluate and analyze the rutting susceptibility of asphalt mixes based on the APA data, and to evaluate and analyze pertinent mix properties that lead to differential rutting potentials of HMA specimens. To accomplish these goals, the following objectives were defined as below:

- Review of pertinent rutting literature,
- Perform a series of APA rutting test as exploratory and rank the mixtures based on their rutting performance,
- Perform simple and multiple regression analyses to identify the significant rut influencing parameters. Develop a statistical method that uses the relationships between two or more quantitative variables to generate a model, which will

predict rutting from others. The objective is to develop relationships of asphalt, aggregate and mixture properties with rutting of HMA.

- The main objective of this study is to produce rut data to develop a rut database. Perform a series of tests to develop baseline data. The baseline data will be used for the calibration of APA and for verification of developed model.
- Perform test at OU and ODOT on same materials under similar testing conditions. Compare OU data with ODOT data to examine the variability issue of using APA.

1.4 Report Outline

This report is composed of eight chapters. Chapter I provide a brief statement of rutting problems, including specific goals and objectives of the present study. Chapter II provides a comprehensive review of literature focusing on the experimental and modeling aspects of rutting, particularly on evaluation of rutting potential using Asphalt Pavement Analyzer, mechanisms of rutting. The APA test data of exploratory and base mix of gravel type is discussed in chapter III. The APA data of plant-produced mixes along with a discussion of the results and rutting susceptibility of the mixes are discussed in Chapter IV. Also, the APA data are compared with the ODOT data, in Chapter IV whenever feasible. Chapter V discussed the binder's effect on the mixture performance of rutting. Chapter VI discussed the statistical evaluation of rut parameters. Chapter VII discussed the repeatability and reproducibility of APA rut testing. Finally, the contribution of this research and recommendation for potential future studies are presented in Chapter VIII.

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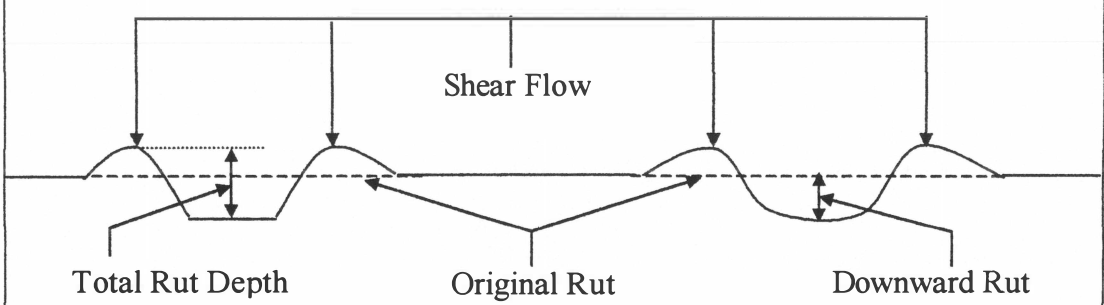

Figure 1.1 Typical Rutting Profile

II. LITERATURE REVIEW

2.1 Laboratory Rut Testing

During the past three decades, a wide variety of equipment and procedures have been developed and used to assess rutting characteristics of HMA mixes in the laboratory. These include: the traditional Marshall and Hveem tests, uniaxial and triaxial static and dynamic creep tests, and the Superpave direct shear test. Among these, Marshall and Hveem methods are widely used in the United States to establish optimum asphalt contents of HMA mixes based on the concept of stability (resistance to deformation). This stability, however, is neither based on fundamental engineering properties nor has been validated in the field to predict rutting in HMA pavements. The Marshall and Hveem test methods also do not indicate the potential for fatigue cracking in HMA pavements (Lai, 1996). Researchers have used various types of creep tests for laboratory evaluation of HMA permanent deformation (Collins et al., 1995). However, AASHTO or ASTM has neither adopted any creep test nor has validated any creep test in the field. Recently, an asphalt aggregate mix analysis system (AAMAS) was developed to evaluate HMA for permanent deformation and fatigue cracking. However, the AAMAS has also not been validated in the field.

The Strategic Highway Research Program (SHRP), which was conducted between October 1987 and March 1993, developed the Superior Performing Asphalt Pavements (Superpave) mixture design and analysis system. The adoption of Superpave methods by governmental agencies in the wake of the Strategic Highway Research Program (SHRP) has attracted worldwide attention, as pavement professionals seek to advance mix design methodologies to keep pace with across the board increases in traffic volumes and axle loads. Internationally, many developing countries will likely follow the American lead as they seek to implement more cost-effective methods to build and maintain necessary transportation infrastructures at lower life cycle costs. While the hot-mix asphalt (HMA) industry has invested its resources in improving designs, traditional test methods intended to quantify performance in mixes with dense aggregate structures (e.g. Marshall stability testing) are no longer be applicable for new mixes with stone-on-stone gradations. Thus, materials engineers have struggled with exactly how to evaluate performance in the practical manner to which they have become accustomed. As full Superpave implementation nears, the industry has been naturally drawn towards relatively new types of empirical tests to fill the consequential performance evaluation void. A standardized laboratory equipment and test procedure that predicts field-rutting potential would be of great benefit to the HMA industry. As mix design evolved from conventional Marshall design to the superpave design and beyond, it becomes increasingly important to identify practical laboratory test methods to predict the performance of HMA pavements. Performance testing has been deemed necessary for a broad acceptance of the Superpave mix design system. Researchers have sought for a simple and yet reliable testing procedure to assess rutting potential of HMA for more than a decade. Currently, the most common type of laboratory equipment of this nature is a loaded wheel tester (LWT). 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) (Colley et. al., 2001).

2.2 APA Rut Testing

The most recent and significant changes in equipment and procedure occurred when the PTI started a commercial development of the APA. APA is the modified version of the Georgia LWT. AVC has also been developed by PTI to allow either beam or cylindrical samples with consistent bulk density values that closely simulate the compaction of asphalt mixes in the field. The PTI, Inc. also formed an APA users group to share ideas and collectively worked toward refining the rut test procedure and other (fatigue) test procedure using the APA. During 1998 and 1999, the APA User Group performed a ruggedness study to identify APA testing factors that have the greatest influence on the outcome of tests (West, 1999). Currently, a "Method of test for Determining Rutting Susceptibility Using the Asphalt Pavement Analyzer" is at the development stage (proposed to be included as an ASTM procedure).

In a recent study by Jackson and Ownby (1998), it was noted that the APA is capable of providing valuable data on permanent deformation and it can be used in conjunction with the Superpave design. Most recently, Kandhal and Mallick (1999) have shown that APA is sensitive to aggregates, gradations and binder types and, therefore, has the potential to predict relative rutting of hot mix asphalt mixtures. Mixes from poor, fair and good performing pavements were tested with the APA to develop rut depth criteria for evaluation of mixes. They have found that in case of granite and limestone mixes, the gradation below the restricted zone generally showed the highest amount of rutting whereas, the gradation through the restricted zone showed lowest rut depth. However, in case of gravel mixes, the gradation below the restricted zone showed the least amount of rutting whereas, the gradation above the restricted zone showed the maximum amount rutting. The APA was also found to be sensitive to the PG grade asphalt binder based on statistical significance of differences in rut depths. The rut depths of mixes with PG 58-22 asphalt binder (tested at 58°C) were higher than the depths of those mixes with PG 64-22 asphalt binder (tested at 64°C). In case of granite and limestone wearing course mixes, the rut depth increased with an increase in asphalt film thickness. However, an opposite effect was observed in case of gravel wearing course mixes, and binder course mixes containing granite and limestone. Based on very limited data, they suggested that the APA rut depth after 8000 passes should be less than 4.5 – 5.0 mm to minimize rutting in the field. However, more laboratory and field-test sections need to be evaluated to establish reliable criteria.

2.2.1 Asphalt Pavement Analyzer

Asphalt Pavement Analyzer is a widely used laboratory equipment designed to determine the rutting susceptibility of HMA mixes by applying repetitive linear loads to compacted test specimens through pressurized hoses, **Figure 2.1.** The APA specifications are as follows **(Table 2.1)**: Dimensions of the device are 35 in (89 cm) x 70in (178 cm) x 80 in (203 cm), with weight of 3,000 lbs (1,361 kg), and the water tank capacity is eight cubic feet (0.226 m^3). The APA consists of the following basic components:

a. Wheel Tracking/Loading System (WTS), which consists of drive, loading, and valve assemblies and three special rubber hoses. The WTS applies wheel loading on repetitive linear wheel tracking actions that control magnitude and contact pressure on beam and cylindrical samples for rut testing.

b. Sampling Holding Assembly (SHA), consisting of sample tray and molds, holds the asphalt concrete samples directly underneath the rubber hoses to allow the samples to be subjected to the wheel tracking actions during rut testing. The sliding tray design allows the samples to be pulled out from inside the machine, making it easier to perform rut depth measurements and for installation of the sample.

c. Temperature Control System (TCS): the temperature of the APA chamber can be controlled and maintained accurately. The test and conditioning chamber temperatures are set at any point between 86°F and 140°F (30°C and 60°C) within ± 34°F (1°C).

d. Water Submersion System (WSS) consists of water tank, water tray and pneumatic cylinder. The WSS allows the water to cover the test sample during the submerged-in-water test and automatically drains the water upon completing the test before the sample tray is pulled out.

e. Operating Controls: all the controls for operating the machine are mounted on the control panel located in the front of the machine. The function of each feature on the control panel is self-explanatory.

f. Sample Temperature Conditioning Shelf is located inside the lower front doors. It can hold extra beams or cylindrical samples to allow heat soaking.

2.2.2 APA Results Versus Field Performance

APA is the modified version of GLWT. The researchers showed that the GLWT was capable of ranking mixtures similar to actual field performance (Lai, 1986). A similar study conducted in Florida (West et. al., 1991) 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 (Miller et. al., 1995) 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. After the APA came on the market, the Florida Department of Transportation conducted a study (Choubane et al., 1998) similar to the GLWT study described previously (West et. al., 1991). 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.

A joint study by the FHWA and Virginia Transportation Research Council (Williams et al., 1999) 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). Based upon review of the laboratory wheel tracking devices and the related literature detailing the laboratory and field research projects Cooley et al concluded that results obtained from the APA seem to correlate reasonably well to actual field performance when the in-service loading and environmental conditions of that location are considered (Cooley et. al., 2001).

2.3 Compaction of Rut Specimen

The compaction method used to prepare rut specimens is a significant component in any mix design and analysis methods. The compaction methods evaluated by various researchers include: the rotating bases Marshall compactor, the Superpave Gyratory Compactor (SGC), and the Asphalt Vibratory Compactor (AVC). It is a standard practice in most agencies in the United States to design HMA by the Marshal mix design method in general accordance with ASTM D 1559-89 and the Asphalt Institute Manual Series Number 2. The Marshall compaction method was developed with close correspondence between the density achieved in the laboratory and density observed on the roadway after exposure to traffic (Roberts, et al., 1996). It has been argued that the impact compaction used in Marshall design does not adequately simulate the compaction during construction (Von Quintus, et. al., 1991). The gyratory compaction was identified to be the most suitable method for a Superpave mix design project. The SGC can orient the aggregate particles in a way that is similar to that observed in the field and has the capability to accommodate larger aggregates (up to 50 mm) in the mix (Roberts, et. al., 1996). However, SGC has a tendency to compact mixes in excess of what can be achieved with conventional paving equipment in the field. Recently, PTI developed a vibratory compactor, which can more closely simulate actual roadway compaction in the laboratory.

2.3.1 Superpave Gyratory Compactor

The Superpave Gyratory Compactor (SGC) is a mechanical device that can be perceived as a modified version of the Texas Gyratory Compactor. The Superpave design procedure, at least Level 1 procedure, is rapidly becoming the standard HMA mix design method in the United States. However, there are some concerns from the asphalt industry in implementing the Superpave Levels 2 and 3 procedures because of the complexities of the apparatus needed and time required to perform these procedures. On the other hand, the Superpave Level 1 method alone is not sufficient for assessing permanent deformation of asphalt mixes (Lai, 1996). It employs the compaction principles of the French Gyratory Compactor. It is a device that was well suited to mixing facility quality control and quality assurance. The compaction angle of the SGC is 1.25 degrees, and the applied vertical load to the specimen is 87 psi (600 kPa). The loading ram diameter nominally matches the inside diameter (6 in or 150 mm) of the mold. This device can make from 30 to 40 gyrations per minute. A photographic view of the SGC is shown in **Figure 2.2.** The SGC consists of the following components:

a. Compactor Assembly, which is a rigid steel cubic construction.

b. Testing Mold Chamber, where the mold is placed with a safety door on the rotating set.

c. Specimens Extractor is equipped with an air cylinder to extract compacted specimen.

d. Control Panel: remote control allows initialization, compaction time and height control of the specimen. Also, data can be stored on a diskette and printed out, as desired.

2.3.2 Asphalt Vibratory Compactor

A photographic view of the Asphalt Vibratory Compactor (AVC), Model AVCII, used in this study is shown in **Figure 2.3**. AVC dimensions are 34 in (86.36 cm) x 50 in (127 cm) x 84 in (213.36 cm), and it weighs 2344 lbs (1063 kg). It requires compressed air of 3 SCFM @ 120 psi (827 kPa) and can be used for fabricating both cylindrical and beam samples, with the attachment of appropriate compaction heads. The AVC consists of the following components:

a. Compactor Assembly, which is a rigid steel frame mounted on noise absorbing isolators and supports.

b. Sample Table, where the compaction mold is placed. The AVC has provision for using two different steel molds, one for preparing beam samples, while the other for cylindrical samples.

c. Specimens Extractor is equipped with an air cylinder for the extraction of a compacted specimen.

d. Control Panel: remote control allows initialization, compaction time and height control of the specimen. The AVC is equipped with a power switch and button for emergency stop. It is also equipped with a switch for automatic operation.

The forward pressure should be kept at 14.5 psi (100 kPa) and the backpressure at 5.8 psi (40 kPa). The time to compact beam specimens can be fixed at 35 second. The Asphalt Vibratory compactor (AVC), developed by PTI, can be used to prepare beam or cylindrical samples with consistent bulk density values that can more closely simulate the compaction of asphalt mixes in the field than some other compactors (e.g., Texas Gyratory Compactor) (Jackson & Ownby, 1998).

2.3.3 SGC Versus AVC

In SGC compaction is achieved through gyration, while in AVC compaction is achieved through vibration. Vibratory compaction tends to result in more compaction at top and less compaction at the bottom of samples. This is generally true for both beam and cylindrical samples. Gyratory compacted samples, on the other hand, show less compaction in the top and the bottom of samples and significantly more compaction in the middle. In AVC, orientation of particles has been reported to be more representative of field situation. In SGC it is easier to achieve a desired level of compaction, while in AVC it is difficult to reach the desired level of compaction (Cooley & Kandhal, 1999).

Volumetric properties were observed to be relatively uniform throughout the vibratory compacted specimens (Jackson and Ownby, 1998). However, the vibratory parameters as ends in themselves. Rather, they are only useful if they can be related to pavement distress, or to pavement properties used in other models such as for overlay design. Consequently, the mechanistic-empirical type of deterioration modeling approach has been developed. In mechanistic-empirical models, a response parameter (stress, strain, or deflection) is related to measured structural deterioration (roughness, cracking, rutting etc.) or functional deterioration (PSI, safety etc.) through the regression equations. In this approach, mechanism of rutting is hypothesized and a structural response is assumed to be related o rutting. Primary responses such as surface deflection, horizontal tensile stress, strain and strain energy at the bottom of the asphalt layer, and vertical stress and strain at the top of the subgrade are calculated. Attempts are made to relate these responses to observed distress and pavement conditions such as roughness, cracking, rutting through regression analysis.

Sousa et al. (1992) presented a comprehensive, combined viscoelastic-plastic model to characterize the rutting behavior of asphalt mixes. Their model included numerous constants that made it difficult to use. *Gillespie et al. (1993)* analyzed pavement deformation in different layers using the physical pavement model. The viscoelastic Poisson's ratio was set to 0.5 in all the layers. The layer viscosity were chosen so that the proportion of the overall permanent deformation occurring within each layer was the same, as reported in AASHO Road Test. It was reported that 32% of the overall permanent deformation occurred in the asphalt layer, 14% in the crushed stone base, 45% in the subbase, and 9% in the subgrade. *Zaghloul and White (1994)* used a three-dimensional dynamic finite element (3D-DFEM) program (ABAQUS) to analyze flexible pavements subjected to moving loads at various speeds. A multilayer elastic analysis assuming static load and linear elastic material was used to verify 3D-DFEM predictions. A number of material models were used to represent actual material characteristics, such as viscoelasticity and elastoplasticity. They used two single-axle loads with dual wheels (80-kN and 258-kN) having a 2.8 km/hour speed. It was reported that the permanent deformation for the 80-kN load developed primarily in the asphalt layer, whereas 85% of the permanent deformation for the 258-kN axle load developed in the subgrade layer. Rutting in the base course and asphalt surface, as a result of the 258-kN axle load, was about 10 and 5 percent of the total rutting, respectively. *Collep et al. (1995)* presented a model to determine the rut depth of asphalt concrete under repetitive loading, treating it as a linear viscoelastic flow phenomenon. A list of some of the constitutive equations reviewed in this section, including the name of the researchers who developed them, is presented in **Table 2.2.** *Groenendijk et al. (1996)* indicated that all rutting in AC pavements could be ascribed to subgrade deformation. Their test results revealed that less than 1% of total rutting occurs in the AC layer. They conducted research on two test pavements of 0.15m and 0.08m gravel AC on a 5-m sand subgrade 75-kN super-single wheel load using the linear tracking device. No shear deformation within the asphalt layer was observed in their study. They reported a relationship between subgrade strains due to a wheel load as,

$$\varepsilon_{subgrade} = 2.8\times10^{-2}\times N^{-0.25} \quad \text{......................................(6)}$$

where, $\varepsilon_{subgrade}$ = permissible strain at the subgrade surface (m/m); and N = allowable number of load application. *Bonaquist and Witczak (1997)* used finite element approach with constitutive model to analyze pavement response including permanent deformation or rutting. The permanent strains for a given state of stress were represented as,

$$\xi = \left[\frac{0.002408\sqrt{\gamma}\left((I_1 + k/\sqrt{\gamma})/P_a\right)^{3.05}}{\gamma\left((I_1 + k/\sqrt{\gamma})/P_a\right)^2 - J_2/P_a} \right]^{2.22} \qquad (7)$$

where, ξ = plastic strain trajectory for load cycle N; I1 = first invariant of the stress tensor; J2 = second invariant of the deviatoric stress tensor; Pa = atmospheric pressure; k = Drucker-Prager cohesion parameter; γ = material parameter. According to these researchers, these permanent strains can be summed over the thickness of the pavement to obtain the permanent deformation in the pavement. With the total stresses known, the above equation can be solved for the corresponding permanent strains using the appropriate Drucker-Prager strength parameters. *Ali et al. (1998)* developed a mechanistic model to predict rut depth as a function of the vertical compressive elastic strain in all pavement layers. The model was derived from a well-established plastic deformation functional. To be compatible with mechanistic analysis, the model form allows the characterization of traffic in terms of loading groups, rather than ESALs. The proposed model form was developed based on the assumption that the relationship between the plastic and elastic strains is linear, for all pavement layers. It further assumes that this relationship is nonlinear in terms of the number of load applications. The model parameters indicate that the AC layer contribution to surface rutting is marginal. The combined base/subbase layer contributed the most to the measured rutting. The contribution of the subgrade to the measured rutting was greater than that of the AC layer, but less than that of the base layer. *Ramsamooj et al (1998)* predicted the stress-strain response of asphalt concrete pavement under cyclic loading using an elasto-plastic model. It was reported that the primary component of rutting at temperature up to 32°C is the plasticity of the asphalt concrete, and the amount of rutting can be predicted from the fundamental properties and the stress-dilatancy theory. It was concluded that selecting dense graded asphalt concrete or styrene-butadiene-styrene modified asphalt concrete with a higher value of coefficient of lateral earth pressure, which depends on aggregate interlocking and aggregate characteristics, could decrease the rutting.

2.5.3 Neural Network Rut Models

In recent years neural network (NN) modeling has emerged as a very powerful tool to find correlations between dependent and independent variables in a set of data. A typical deformation analysis deals with finding the stresses and displacements due to static and dynamic loads, and with the verification that the structure is sufficiently stable under such loads. Deformation analysis is a complex scientific domain incorporating many traditional methods or mathematical models. These models may be based on differential, variational or integral formulations. The first approach deals with (partial) differential equations, to be solved by integration, subject to some boundary conditions. The second approach uses test functions that find the stationary value of some functional, subject to satisfying the boundary conditions. The third approach is based on the reciprocity theorem and deals with integral equations to be solved on the structure boundary. All of these modeling techniques are useful only when the physics or mechanics of a problem is known or cab be expressed in a differential equation form. Rutting as the focus of the study is a complex problem and poorly understood. There are an infinite number of variables (some the variables are listed in Table 3) in the different types of aggregates, combination of aggregates, and the variety of binders used in making asphalt pavements which make modeling as well as accurate prediction of rutting very difficult. On the other hand, NN is modeling technique is particularly useful when physics or mechanics of a problem is too complex to express in a differential equation form, includes a large number of parameters or is poorly understood. It is a very powerful tool to determine correlations between dependent and independent variables in a large set of data. It has high-speed parallel processing property with an inexpensive simulation. Therefore, the choice of the study to employ such modeling technique to evaluate rutting is good decision.

A neural network (NN) is an interconnected assembly of simple processing units or nodes (called neurons) to represent the mapping or relationship embedded in any set of data. The architecture of a network allows it to approximate the mapping function in the absence of knowledge about the mathematical form of the mapping between an input signal and the corresponding output signal. The approximating ability of a NN is stored in the inter connections (called weights) obtained by a process of adaptation to or learning from a set of training patterns. In NN modeling procedure, a representative sample data set that includes a set of input signals and their corresponding output signals is used to determine the connecting weights in each mapping. The weights are updated in an iterative manner until the difference between the predicted output signals and the actual signals corresponding to the input signals is negligible. This weight updating process is called training. The trained network is then subjected for validation. The validated model can propagate a new input signal through the network and predict the resulting output signal.

Creating a neural net solution to a problem involves the steps of defining inputs, designing network architecture and algorithm, training the network on examples of the problem, and running the trained network to solve new examples of the problem. The input of a neural net consists of a series of known values. The values can vary from one to n-dimensional array of known numbers. The structure of NN mainly consists of an input layer made of several input nodes that are presumed by the designer to account for and explain the variability observed in the outputs of the problem. The output layer is designed to contain output nodes (variables). An intermediate layer (hidden layer) contains a number of units that have no interaction with the external environment but are interconnected with the nodes of other layer. The nodes in a certain layer are connected with the nodes of other layers. In NN architecture, each neuron consists of multiple inputs in which each input is connected to either the output of another neuron or one of the input numbers. The neuron consisting of single output is connected to the input of other neurons or to the final output. Each connection is assigned an initial 'synaptic strength. These weights can start out all the same, can be assigned randomly, or can be determined in evolutionary depending on the network algorithm. Once the neuron and connections are set up, each weighted input to the neuron is computed by multiplying the output of the other neuron (or initial input) that the input to this neuron is connected to by the synaptic strength of that connection. All of these weighted inputs to the neuron are summed. If this sum is greater than the firing threshold of this neuron, then this neuron is considered to fire and its output is 1. Otherwise, its output is 0. Repeated trials on sample problems are executed. After each trial, the synaptic strengths of all the inter-neuronal connections are adjusted to improve the performance of the neural net on this trial. Continue this training until the accuracy rate of the neural net is no longer improving. The dynamics of the network can be described perfectly by the state transition table or diagram. However, greater insight may be derived if the dynamics can be expressed in terms of energy function, and using the formulation, if it is possible to show that the stable states can always be reached in the developed network. Figure 2 represents a mechanism-based flow diagram, which will be incorporated for the development of a neural architecture. The study will employ the programming language MATLAB to carry out the training and prediction as well as for model development.

Simpson et al. (1995) developed a neural network (NN) model using the LTPP data. The independent variables as used by Simpson et al. (1995) are: AC thickness, air void, asphalt cement viscosity, annual precipitation, freeze-thaw cycles, plasticity index, subgrade moisture, subgrade passing #200 sieve, base thickness, and cumulative ESAL. According to this study, a strong relationship exists between the transverse surface rutting profile and the contributions of different layers to rutting. However, they did not provide the adequate information about the NN architecture, the training scheme used, and data sets used for training, and validation. Also, no information was given on the weighting matrix of the trained network that makes it difficult for others to use their NN model.

2.5.4 Other Rut Models

A number of procedures are available for the estimation of the amount of rutting from repeated traffic loading. They may be categorized as, (a) analysis by elastic layered theory (for stress and strain) with material characterization by repeated load triaxial test or creep test) (b) analysis by visco-elastic layered theory with material characterization by (creep test) Although several techniques have been proposed for the second approach, the approach has not been widely used because of the complexity in obtaining elasto-plastic or visco-plastic characterization for the various paving materials.

Elastic Layer Approach

A pavement system can be represented as a layered elastic system in the determination of the state stress or strain resulting from a surface loading. The total rut depth can be estimated by summing the contribution from each layer, i.e.,

$$\delta_i^p(x,y)=\sum_{i=1}^{n}(\varepsilon_i^p\,\Delta z_i)\ldots\ldots(8)$$

Where,

$\delta_i^p =$ rut depth in the ith position at point(x,y) in the horizontal plane

$\varepsilon_i^p =$ average permanentstrain at depth $[z_i + \Delta z_i/2]$

$\Delta z_i =$ differencein depth

Viscoelastic Layered Approach

Pavement is represented as a viscoelastic-layered system. The methodology requires determination of creep compliance of each material in each layer at given time.

VESYS Approach

Permanent strain due to a single load application is proportional to the elastic or resilience strain at 200th load repetition,

$$\varepsilon_p(N) = \mu\varepsilon_{200}N^{-\alpha} \quad \text{......................................} (9)$$

Where,

$\varepsilon_p(N)$ = Permanent or plastic strain at *N*th load application

ε_{200} = Elastic or resilience strains at 200th load repetition.

μ = constant of proportionality between elastic and plastic strain

N = Load application number, α = constant, representing the permanent deformation rate

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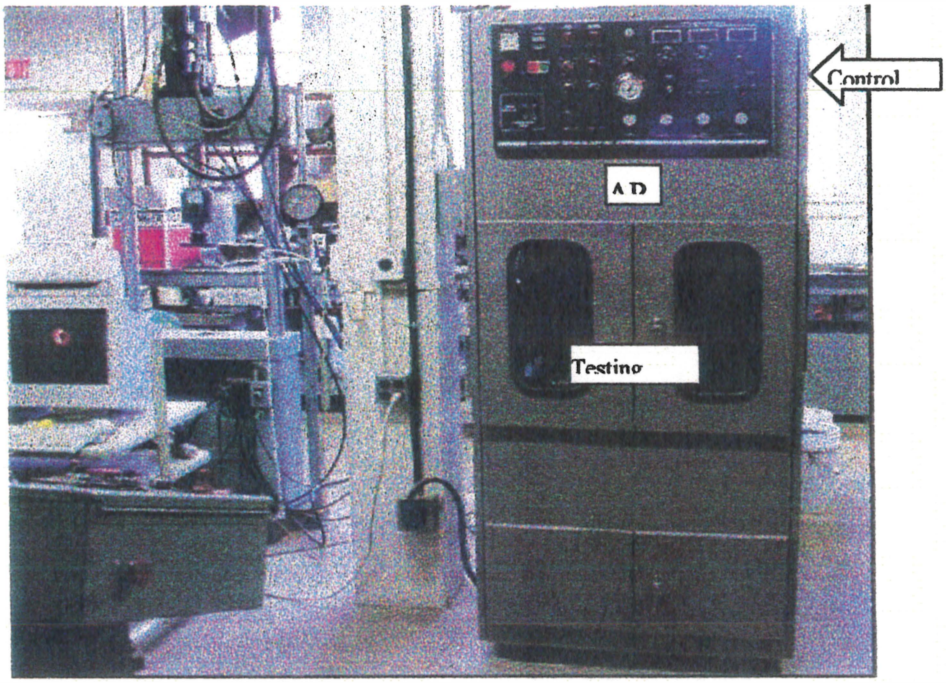
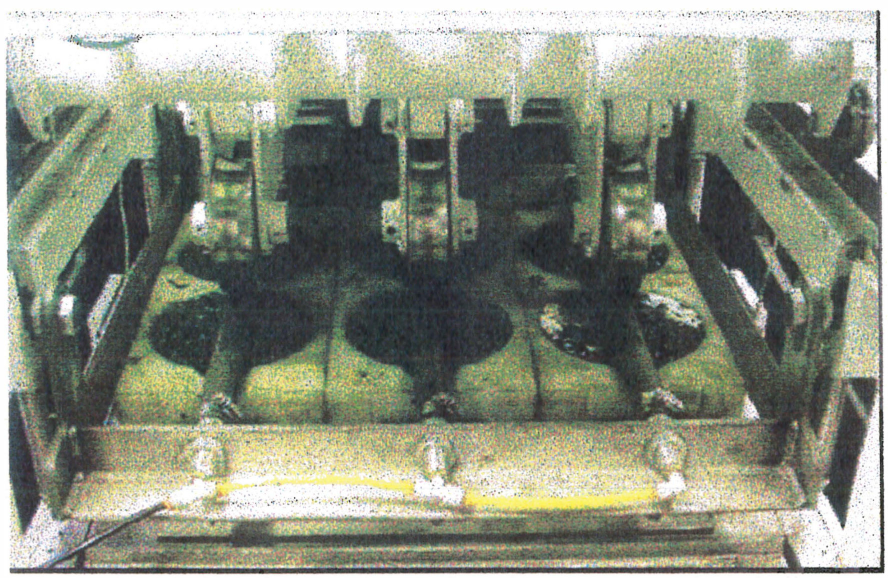
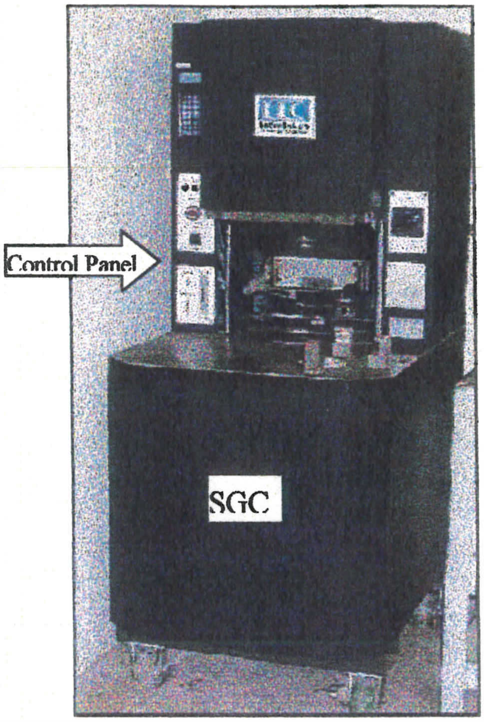


(a) Asphalt Pavement Analyzer (APA)



(b) Inside View of APA Chamber

Figure 2.1 Photographic View of Asphalt Pavement Analyzer (APA)



(b) Compaction Mold

(a) Superpave Gyratory Compactor (SGC)

Figure 2.2 Photographic View of Superpave Gyratory Compactor (SGC)

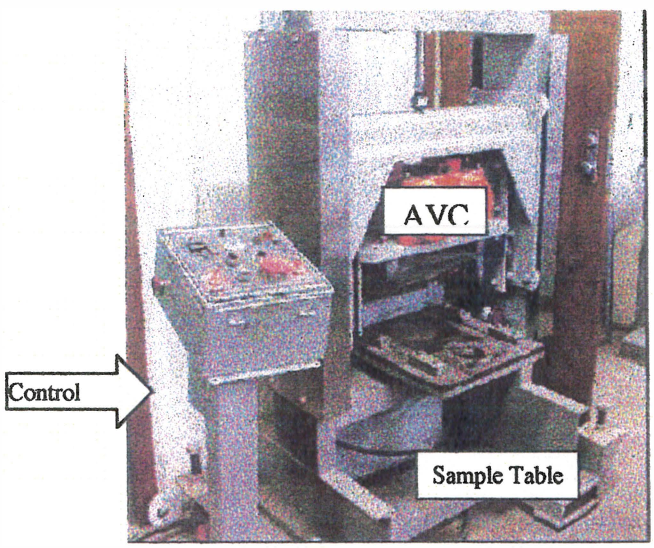


Figure 2.3 Photographic View of Asphalt Vibratory Compactor (AVC)

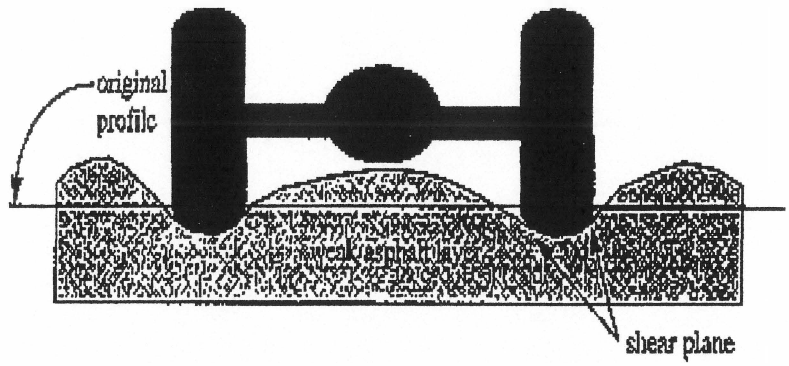


Figure 2.4 Rutting from Weak Mixture

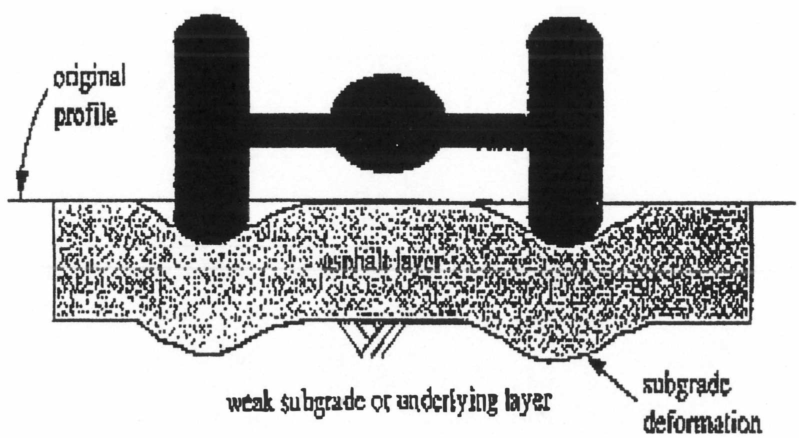


Figure 2.5 Rutting from Weak Subgrade

Table 2.1 APA Testing Protocol

Specimen Dimension		
Specimens type No. of specimens tested simultaneously Specimen size (mm)	Cylindrical 6 300x150x75	Beam 3 150x125x75
Environmental condition		
Range of test temperature Environmental condition	60-64 ^{0}C Dry cycle testing Wet cycle testing	
Wheel Configuration		
Wheel speed Wheel type Hose pressure Hose size Load Load cycle	0.6 m/ s Aluminum wheel on pressurized hose 100 (psi) 29 mm diameter 100 (psi) 80,000	
Measurement		
Rut depth measurement	Three locations centered □□90 mm about the center of the specimens (beam sample) or center of specimens (cylindrical sample).	
Method of rut depth measurement	Automatic by linear voltage displacement Transducers	
Acquisition of data Frequency of measurement	Automatic Every 250 wheel passes	

Table 2.2 Prediction Equations from Repeated load Tests

Developer	Material	Constitutive equation from repeated load tests
Snaith	Asphalt concrete	$\log\varepsilon^p = (a + b\log t)$
McLean and Monismith	Asphalt concrete	$\log\varepsilon^p = C_0 + C_1(\log N) + C_2(\log N)^2 + C_3(\log N)^3$
Freeme and Minismith	Asphalt concrete	$\varepsilon_z^p = cN^\alpha(\bar{\sigma})^{n-1}[\sigma_z - 1/2(\sigma_x + \sigma_y)]$ $\bar{\sigma} = 1/2[(\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2$
Barksdale	Granular material	$\frac{\varepsilon_p}{\bar{\sigma}} = \frac{(N/N_0)^m}{K}\{1 - [\bar{\sigma} R_f\,(1 - \sin\phi)]/[2(D\cos\phi + \sigma_3 \sin\phi)]\}$

III. EXPLORATORY AND BASELINE TEST

3.1 General

Initially, three mixes were selected for rut testing with the co-operation of ODOT. One mix (Project ID: NHY-8N (005) and Design ID: 3012-OAPA-99037) was selected to be evaluated by "Exploratory Tests". Another two-gravel mix (Project ID: NHY-8N (005) with Design ID: 3011-OK99-63070 and Design ID: 3011-OK99-63071) was selected for "Baseline Tests". Aggregates and asphalt binders were supplied by ODOT. The contractors supplied the source of materials and the proportions used for batching and mixing. The Job-mix formula (JMF) recommended by the contractors was followed for this research. However, combined aggregate gradation for selected percentages was computed and compared with the requirements as a counter check of contractor's specification. The Average daily traffic for the pavements constructed with these mixes was more than three million ESALs. The rut test temperature has to be represented of environment in which the paving mixture was utilized and ranged from 58°C to 64°C. Aggregate tests performed by the contractors include: Gradation, Los Angeles abrasion, sand equivalent, durability, insoluble organic contents, fractured faces, insoluble residue, effective specific gravity. Mix information is given in **Table 3.1.**

3.2 Aggregate Tests

Gradation test was performed for all mixes. It is perhaps the most important property of an aggregate. It affects almost all the important properties of a HMA, including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance, and resistance to moisture damage. Therefore, gradation is a primary consideration in asphalt mix design, and the specifications used by most of states limit on the gradations that can be used in HMA. **Figure 3.1** shows the gradation, which is a straight line on the 0.45 power gradation paper. The gradation used in the mixture a smooth curve and above the maximum density line and should have high resistance to deformation under load. **Figure 3.2** shows the gradation of two base mixes. Sieve analysis (ASTM C 136 or AASHTO T 27) was performed during mix production. The Los Angeles (L.A.) abrasion test was performed to check the design specifications. The Los Angeles (L.A.) abrasion test is most often used to obtain an indication of desired toughness and abrasion characteristics of aggregate. The test (ASTM C 131 or AASHTO T 96) is a measure of degradation of mineral aggregates of standard grading resulting from a combination of actions including abrasion or attrition, impact, and grinding for a prescribed number of revolutions in a rotating steel drum containing a specific number of steel spheres. This test has been widely used as an indicator of the relative quality or competence of various sources of aggregate having similar mineral compositions. Both the exploratory and the base aggregate have a L.A. abrasion value of about 29. Then the Sand Equivalent Test was performed to determine the relative proportions of plastic fines and dust in fine aggregates. Dust specially clay adhering to aggregate prevents good bond between the asphalt binder and aggregate. In this test, the amount of clay is measured (ASTM D 2419 or AASHTO T 176). The sand equivalent is the ratio of the height of sand to the height of clay times 100. Both aggregate showed a higher sand equivalent value than the minimum specified sand equivalent of 45. Aggregate particles with more fractured faces exhibit greater interlock and internal friction, and hence result in greater mechanical stability and resistance to rutting than do the rounded particles. Currently there is no ASTM or ASSHTO standard test procedure for measuring the percentage of fractured faces for an aggregate. A sample of coarse aggregate (retained sieve No. 8) is divided into 3 stacks. Count the particles that have none, one, and two or more fractured faces. A sample of coarse aggregate (retained sieve No. 8) is divided into 3 stacks. Count the particles that have none, one, and two or more fractured faces. One stack contains all the particles with 0 fractured faces. The second stack contains all particles with one fractured face, and the third stack contains all particles with two or more fractured faces are then determined. The percentage by weight of each stack with one or more fractured faces and with two or more fractured faces is then determined (OHD Designation: L 18). The exploratory mix had a higher fractured faces compared to the base mixes. All batch aggregate were tested for effective specific gravity. Specific Gravity of aggregate is the ratio of the mass (or weight in air) of a unit volume of coarse material to the mass of the same volume of water at stated temperatures. The specific gravity of coarse aggregate is useful in making weight-volume conversions and in calculating the void content (ASTM C 29) in a compacted. Absorption is the increase in the weight of aggregate due to water in the pores of material, but not including water adhering to the outside surface of the particles, expressed as a percentage of dry weight. The aggregate is considered dry when it has been maintained at a temperature of 110 ± 2^0C for sufficient time to remove all uncombined water. Absorption values are used to calculate the change in the weight of an aggregate due to water absorbed in the pores spaces within the constituent particles (ASTM C 127 and C 128or AASHTO T85 and T 84).

3.3 Mixture Test

Batch aggregate were dried and sieved into sizes (preferably individual sizes) and 3 percent moisture is added to minus no. 10 sieve aggregate to prevent segregation. Batch aggregate is then heated to mixing temperature. Asphalt cement must be heated to achieve a viscosity of 170±20 centistoke. For modified asphalt binders, use the compaction temperature recommended by the binder manufacturer. The temperature fore mixing and testing is listed in **Table 3.2**. Asphalt and aggregates are mixed using mechanical mixer. Laboratory prepared specimens shall be compacted to contain 7.0±1 percent air voids using AVC. The bulk specific gravity for each specimen is determined by weighing in air. This test is conducted in accordance with ASTM D 2726 (AASHTO T 166). Rice specific gravity on the loose HMA mix samples are measured in accordance with AASHTO T 209 (ASTM D2041). Air void contents of the test specimens are determined in accordance with ASTM D 3203 (AASHTO T 269). Rut test is performed in accordance with the OHD L-43 procedure. The bulk specific gravity of compacted bituminous mixture (lab-molded specimen) is used in calculating the unit weight of the compacted mixture (ASTM D 2726 or AASHTO T 166)e. The steps in determining bulk specific gravity involve in weighing the compacted specimen in air (W_D), submerging the samples in water and allowing saturation prior to getting submerged weight in SSD condition (W_{sub}) and removing the sample and weighing in air in saturated surface dry condition (W_{SSD}). Bulk Specific Gravity, $G_{mb} = W_D / W_{SSD} - W_{sub}$; The density of each specimen is the calculated using water density, $\rho_s = G_{mb} \, x \, \rho_w$; The air void content in the compacted dense-graded HMA specimen at optimum asphalt content is suggested by most agencies to lie between 3 and 5 percent (ASTM D 3203 or AASHTO T 269). Air voids in asphalt concrete cannot bear stress. Lower air void content result in greater stiffness because it reflects a more homogeneous structure with better stress distribution. Using the bulk specific gravity (G_{mb}) and the Rice Specific gravity (G_{mm}), the percent air void can be calculated as, *% Air Void* $= (1 - G_{mb}/ G_{mm}) \times 100$; VMA is the total volume of voids within the mass of the compacted aggregate. It is calculated using the bulk specific gravity of the aggregate (G_{ab}), the bulk specific gravity of the compacted mix (G_{mb}) and the asphalt content by weight of total mix (P_b). It can be calculated using the formula, $VMA = (1 - G_{mb} \times (1-P_b)/ G_{ab}) \times 100$; There are a number of states that include percent voids filled with asphalt cement. If a specifying agency includes a VMA requirement and exercises air void control during construction, percent VFA is a redundant requirement for dense graded HMA. Most states that include percent VFA requirements generally specify that the VFA range from 70 t0 85 percent. VFA for each specimen can be calculated using the percent void and VMA as, VFA = 100 x (VMA - %Void)/VMA.

3.4 Data Analysis

Figure 3.3 shows a typical rut versus number of cycles for exploratory mix. It can be seen that there is a small difference in rut value between the samples in left and middle. However, rut depth varies about 1 mm between the left and right samples. This is due to air voids difference. The testing parameters are listed in **Table 3.3.** A sample of rut versus cycles data is shown in **Table 3.4.** Both of this table data will be useful for neuron based model development. Initially, AVC was used for rut testing. The asphalt content was varied for different test and samples. From **Figure 3.3** it can be seen that rut depth at 64 degree centigrade is more than double of rut depth at 60 ^{0}C. There is no clear trend of increasing rut depth with the increasing air voids as in **Figure 3.4**. It is also seen that the SGC samples are more uniform in consideration of air voids. Actually, for samples with air void more than 5%, rut depth increases with the increase of air void. For samples with air void less than 4%, rut depth actually increases with the decrease of air voids. **Figure 3.5** shows air voids, percent asphalt content and rut depth for one of the base mix. The percent asphalt content is in the design range, therefore, the rut depth did not vary too much sample to sample. AVC samples shows higher rut depth when compare to the SGC sample. Here only 20 samples data are shown. Other data is included in chapter 6. Another 26 samples data was plotted in a bar chat as in **Figure 3.6**. It can be seen that the sample preparation using AVC was rejected gradually. The rut depth at 60 ^{0}C is about 4.5 mm. But the rut depth at 64 ^{0}C is about 6mm. The rut depth for the gravel mix is higher than the exploratory mix. Once again, the air void was not in the range 6-8%. However this data will be useful in developing a neural network model. **Figure 3.7** shows the correlation of rut depth with air voids. A poor correlation was obtained for this base mix. Therefore, air void is not the primary factor for rutting of gravel mix rather the round shape of particle might be responsible for higher rut. **Figure 3.8** shows the effect of gradation on rut depth for all of these three mixes. It can be seen that the mix (3011-OK-63072) gradation pass through the restricted zone shows maximum rut depth. Two mix passing above the maximum density line, exploratory mix showed less rut potential compared to the base gravel mix (3011-OK-63071). NCAT mix was added to enrich the baseline database. Two mixes one type B and another was superpave mix. Mix was collected for ODOT and a total of 12 samples (each mix with six samples) were tested for rut. The test result is plotted in **Figure 3.9**. SGC was used for compaction. It can be seen that the Type B mix showed a rut depth of 2 mm, whereas superpave mix showed a rut depth of about 2.2 mm. Therefore, from the APA data it can be concluded that the superpave mix is not performing better than traditional B mix. However, field data will be helpful in validating such performance of the mixes.

Table 3.1 Mix Information

Selected Mix Design No.		3012-OAPA-99037	3011-OK99-63070	3011-OK99-63071
Asphalt Concrete Type		B Insoluble	A	A
Project No.		NHY-8N(005)-10088(13)	NHY-8N(005)-10088(13)	NHY-8N(005)-10088(13)
Highway		US54	US54	US54
Avg. Daily Traffic		3M+	3M+	3M+
Contractor		Duit Construction Co., Inc	Duit Construction Co., Inc	Duit Construction Co., Inc
Producer		Highway Contractors Inc.	Highway Contractors Inc.	Highway Contractors Inc.
Blended Materials	**Source**		**% Used**	
1-1/2" Rock	Vega Sand & Gravel @ Oldham Co., Tx.		15	15
3/4" Chips	Vega Sand & Gravel @ Vega, Tx.	25	20	30
3/8" Chips	Vega Sand & Gravel @ Vega, Tx.	30		
Crushed Gravel	E.D. Baker Corp. @ Borger, Tx.		38	20
Screenings	Vega Sand & Gravel @ Vega, Tx.	30	27	35
Sand	Long Pit @ Texas County, Okla	15		
Asphalt Information				
Asphalt Type		PG70-28	PG64-22	PG64-22
Asphalt Content		5.0 ~ 6.0	4.5 - 5.5	4.3 - 5.3
Asphalt Source		Royal Trading @ Tulsa, OK	Total Petroleum @ Armore, OK	Total Petroleum @ Armore, OK
Asphalt Sp. Gr. @ 77		1.0177	1.0078	1.0078
Aggregate Property	**Required**			
Sand Equivalent	45 min.	48	61	46
L.A. Abrasion % Wear	40 max.	29.5	28.9	28.9
Durability (DC)	40 min.	76	78	78
IOC		0.34	0.42	0.53
Insoluble Residue (Ca)	40 min.	80	0	N/A
Fractured Faces	75 w/2	83	83	79.1
ESG		2.657	2.636	2.649
Mixture Property	**Required**			
Compaction (% of G_{mm})	94 - 96			
VMA, (Min. %)		15	13	13
Retained Strength (%)	75			
Hveem Stability (Min)	40			

Table 3.2 Mixing and Testing Temperature

Procedure\Temp. (^{0}F)	3012-OAPA-99037	3011-OK99-63070	3011-OK99-63071	Time (hr)
Oven drying of Aggregate	230	230	230	over-night
Gradation Test	77	77	77	> 2
Preheating Aggregate	325+/-10	325+/-10	325+/-10	>1.5
Mixing	325+/-10	325+/-10	325+/-10	3 minutes
Short-Term Aging	305+/-10	290+/-10	305+/-10	>2 < 4
Compaction	305+/-10	290+/-10	305+/-10	35 sec
Cooling	77	77	77	>4
Density and G_{mm} Test	77	77	77	0.5
Sample Conditioning	147.2	147.2	147.2	>10
Testing	147.2	147.2	147.2	2.5

Table 3.3 Rut Parameter for Mix ID: 3012-OAPA-99037

Design No. 3011-OK99-63037

Parameters to include	Left	Middle	Right
Asphalt content	5.75	5.75	5.25
Bulk Specific Gravity	2.333	2.364	2.372
Maximum Sp. Gravity	2.432	2.432	2.450
% Air void	4.1	2.8	3.2
% Material passing #200 sieve	6%	6%	6%
% Material passing #10	40%	40%	40%
Test Temp	64	64	64
Fractured Face	75 w/2%	75 w/2%	75 w/2%
% Natural Sand	15	15	15
Binder Specific Gravity at 77 degree Celsius	1.0177	1.0177	1.0177

Table 3.4 Rut-Cycle Relations

Cycle No	Rut (mm)		
Sample	Left	Middle	Right
1	0.000	0.000	0.000
2	0.000	0.000	0.000
3	0.003	0.001	0.005
4	0..0039	0.003	0.008
5	0.006	0.005	0.010
6	0.025	0.008	0.016
7	0.046	0.009	0.049
8	0.070	0.018	0.075
9	0.081	0.030	0.085
10	0.092	0.033	0.096
20	0.093	0.036	0.103
30	0.110	0.038	0.141
40	0.171	0.108	0.199
50	0.219	0.171	0.236
60	0.246	0.198	0.269
70	0.276	0.224	0.292
80	0.314	0.253	0.310
90	0.344	0.276	0.329
100	0.376	0.324	0.341
200	0.509	0.494	0.498
300	0.637	0.651	0.635
400	0.744	0.746	0.685
500	0.834	0.802	0.717
1000	1.139	1.145	1.016
1500	1.353	1.457	1.278
2000	1.553	1.646	1.472
3000	1.988	1.991	1.769
4000	2.453	2.462	2.072
5000	3.049	2.999	2.415
6000	3.712	3.625	2.867
7000	4.491	4.311	3.380
8000	5.266	4.965	3.987

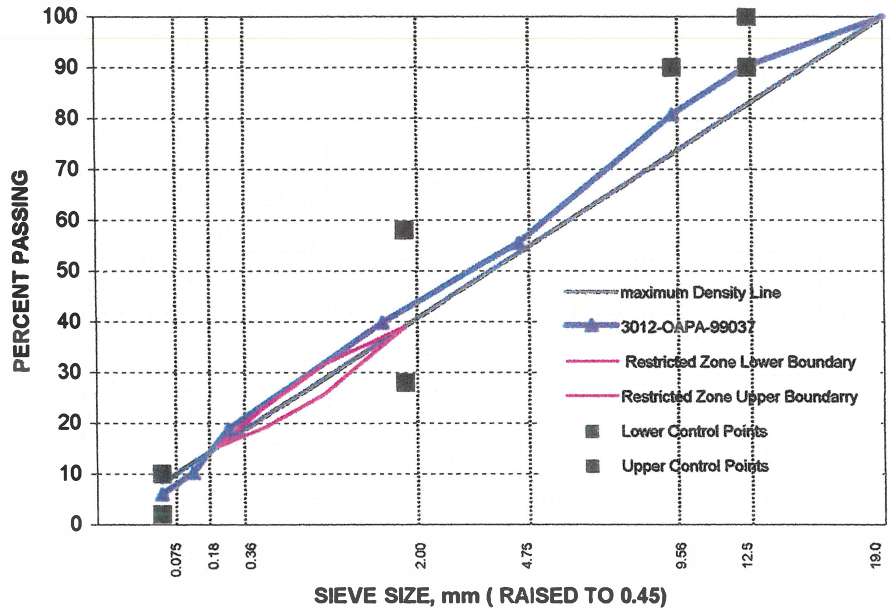


Figure 3.1 Gradation plot of Exploratory mix on 0.45 power chart

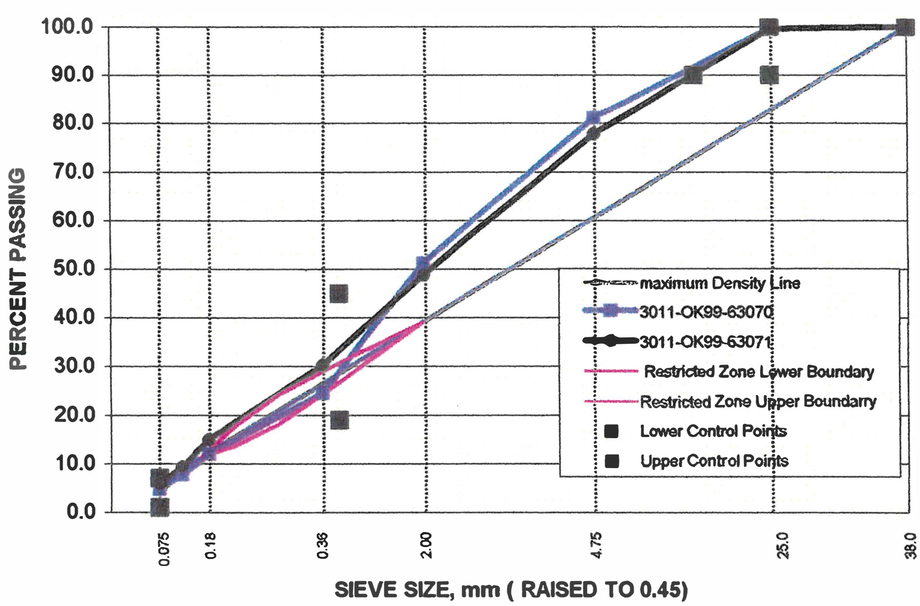


Figure 3.2 Gradation Plot of Base Mixes on 0.45 power chart

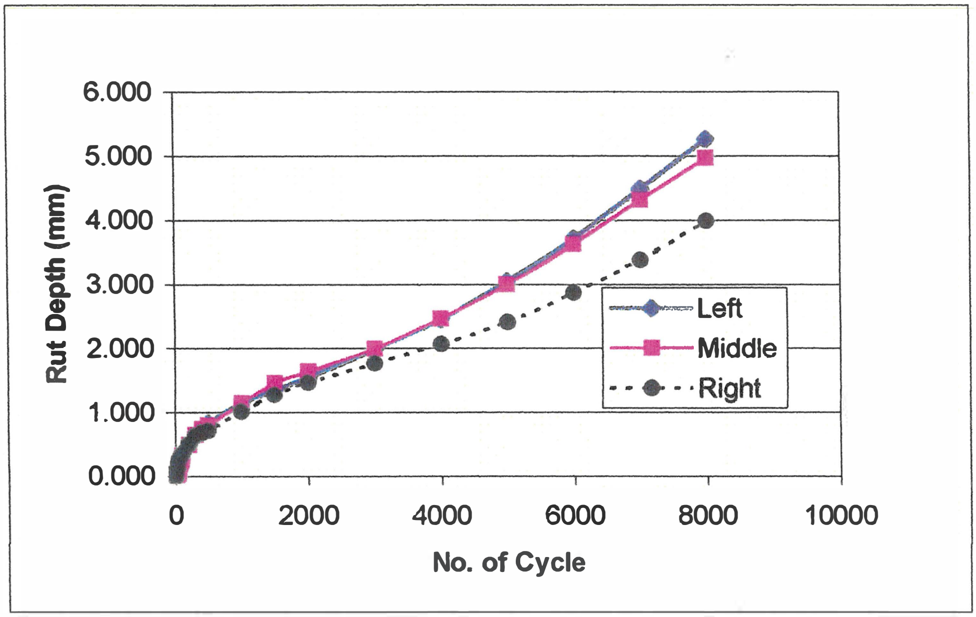
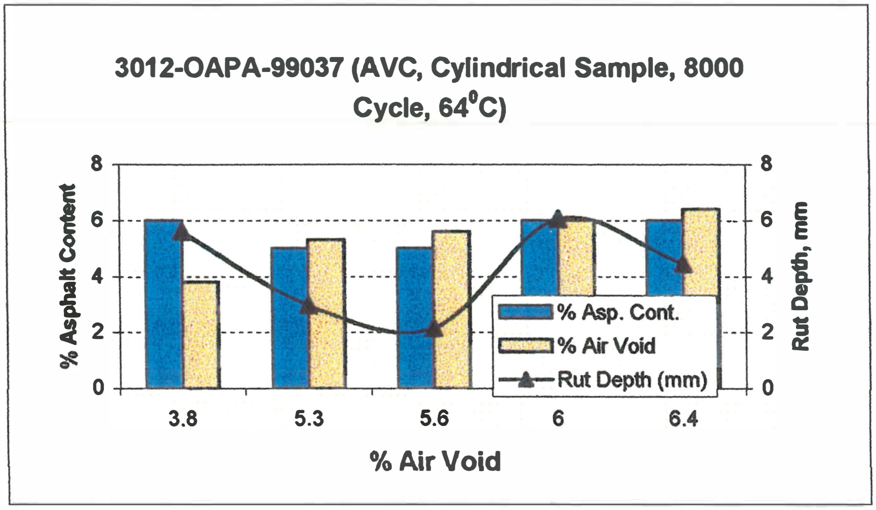
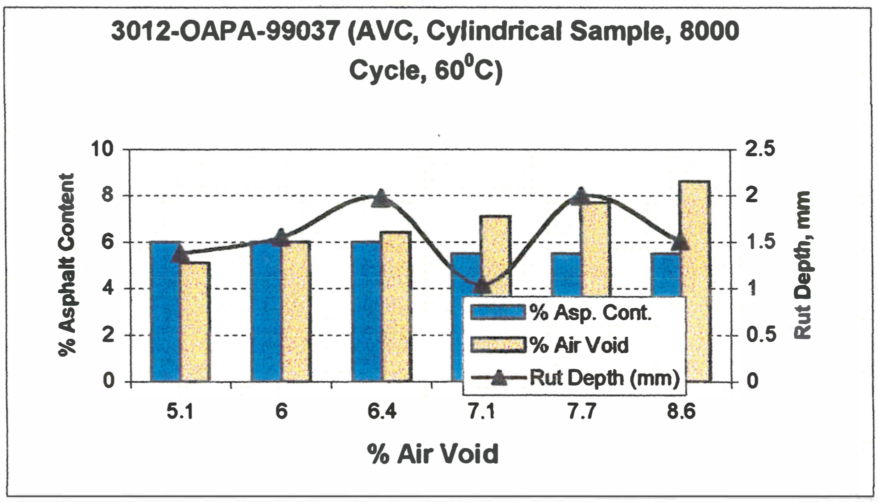


Figure 3.3 Typical Rut Plot of Exploratory Mix ID: 3012-OAPA-99037





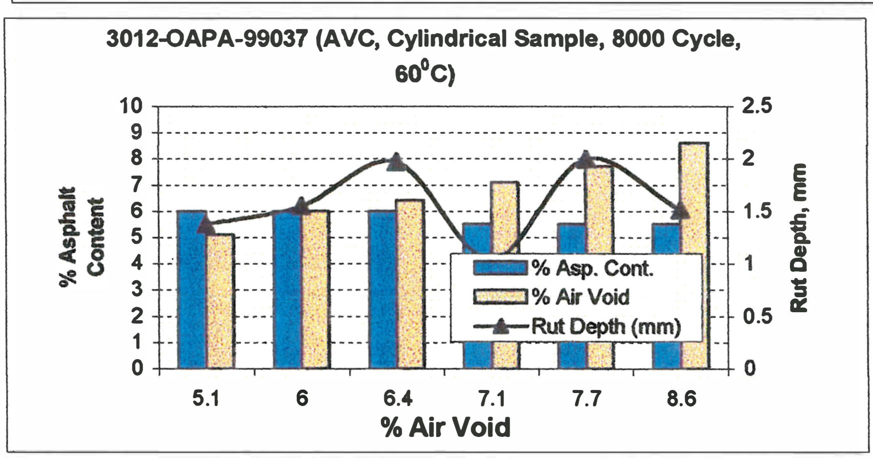
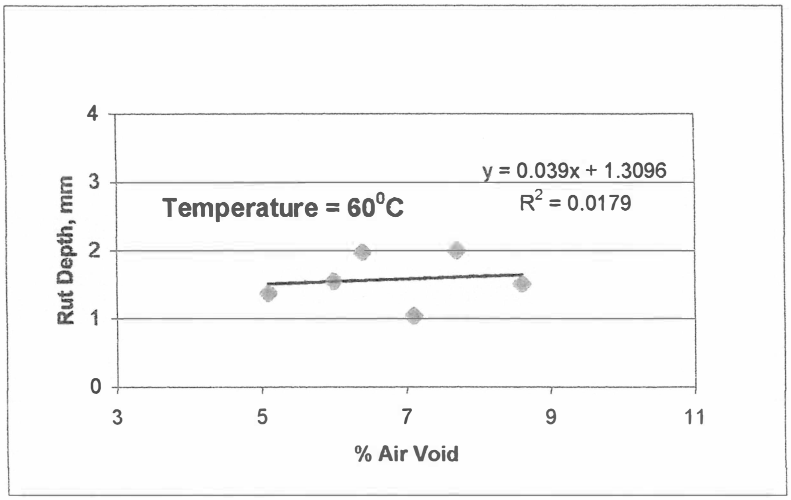


Figure 3.3 Rut Plot of Exploratory Mix



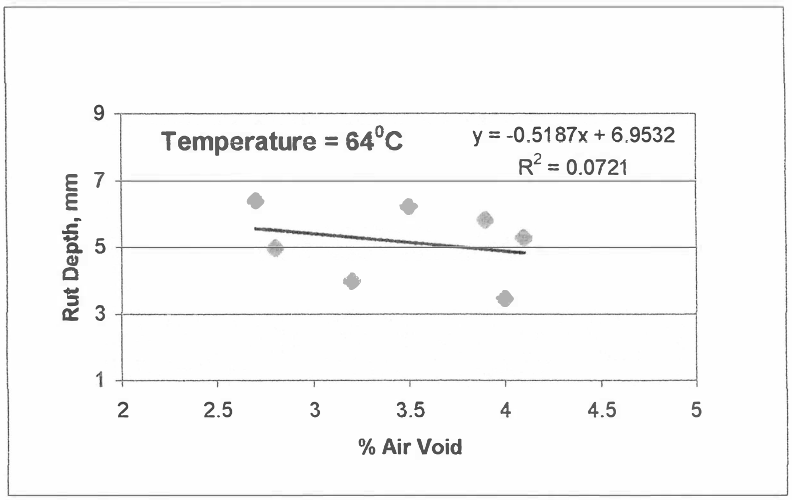
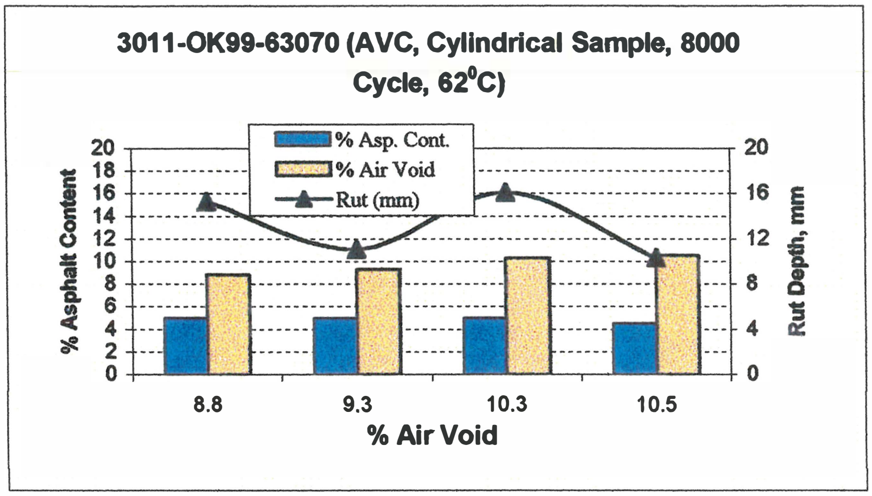


Figure 3.4 Correlations Between Rut And Air Void



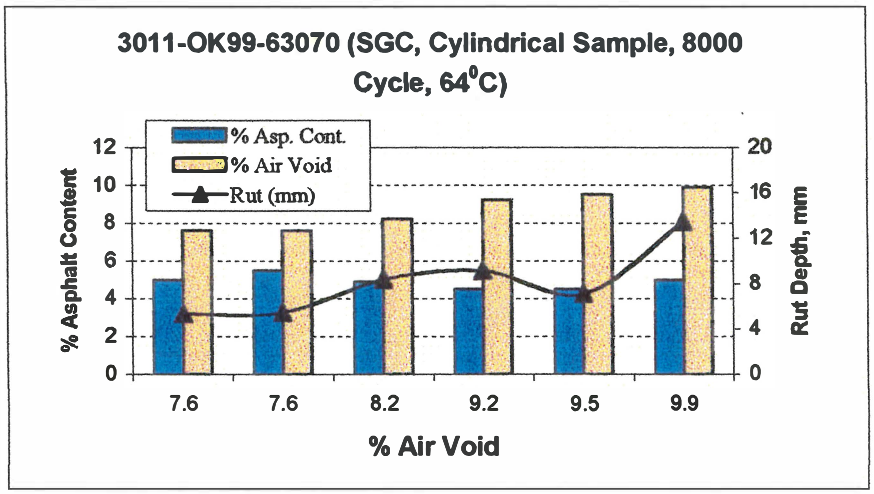
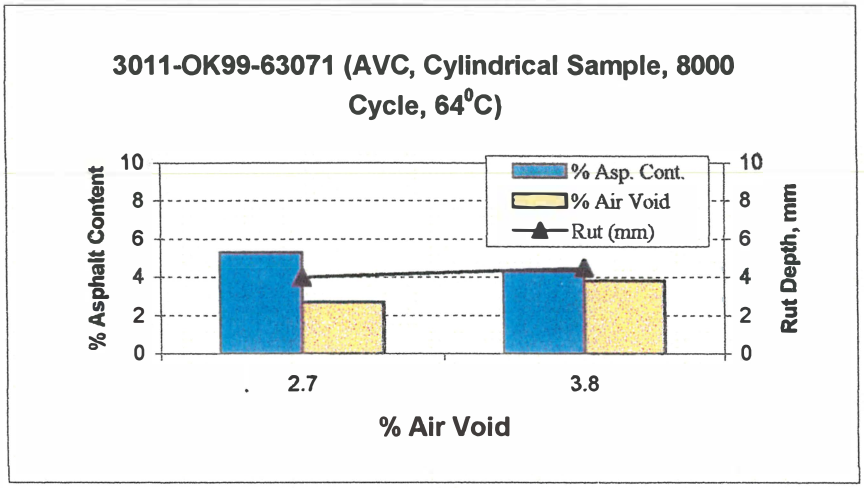
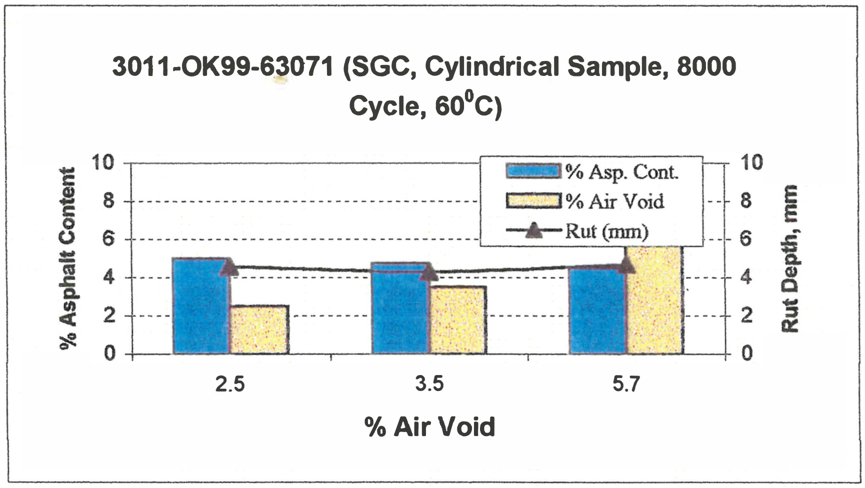


Figure 3.5 Rut Plot of Base Mix (ID: 3011-OK99- 63070)





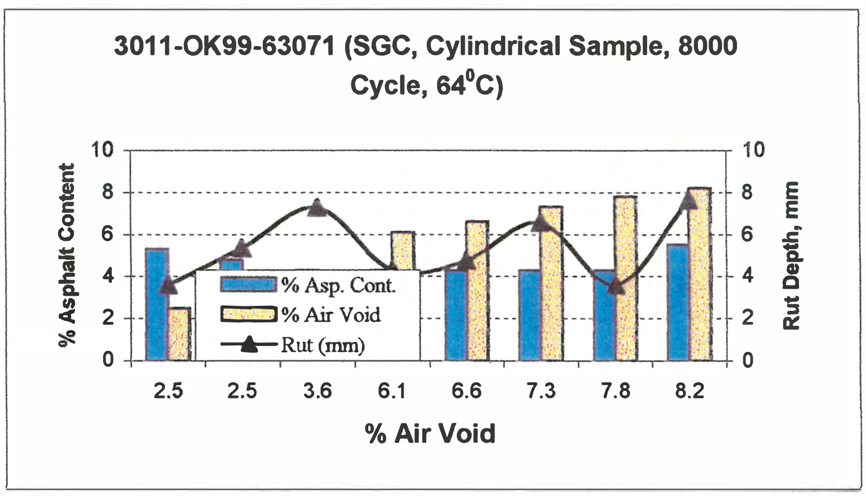
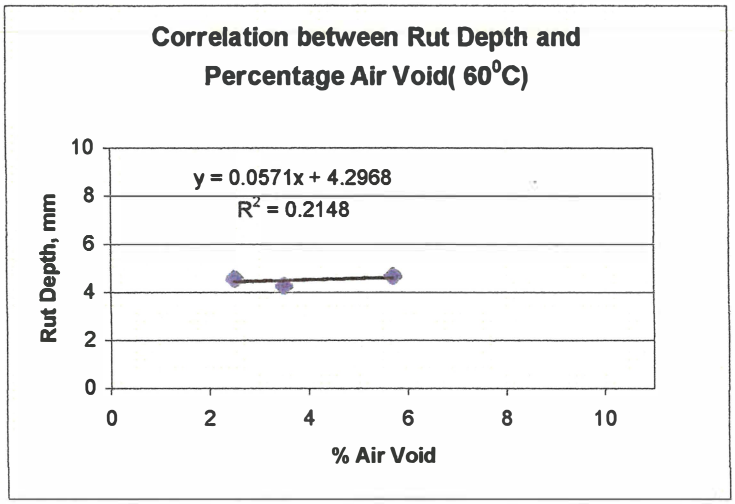


Figure 3.6 Rut Plot of Base Mix (ID: 3011-OK99- 63071)



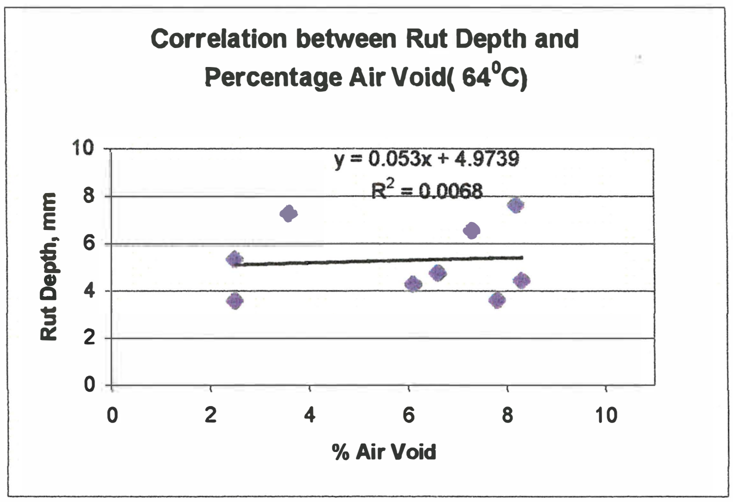
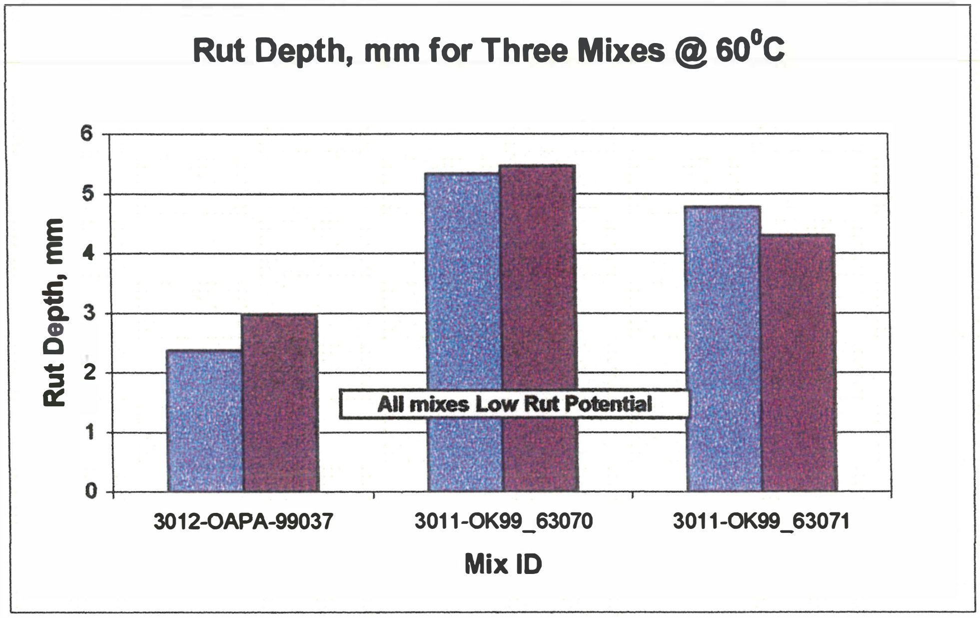


Figure 3.7 Correlation of Rut with Air Void



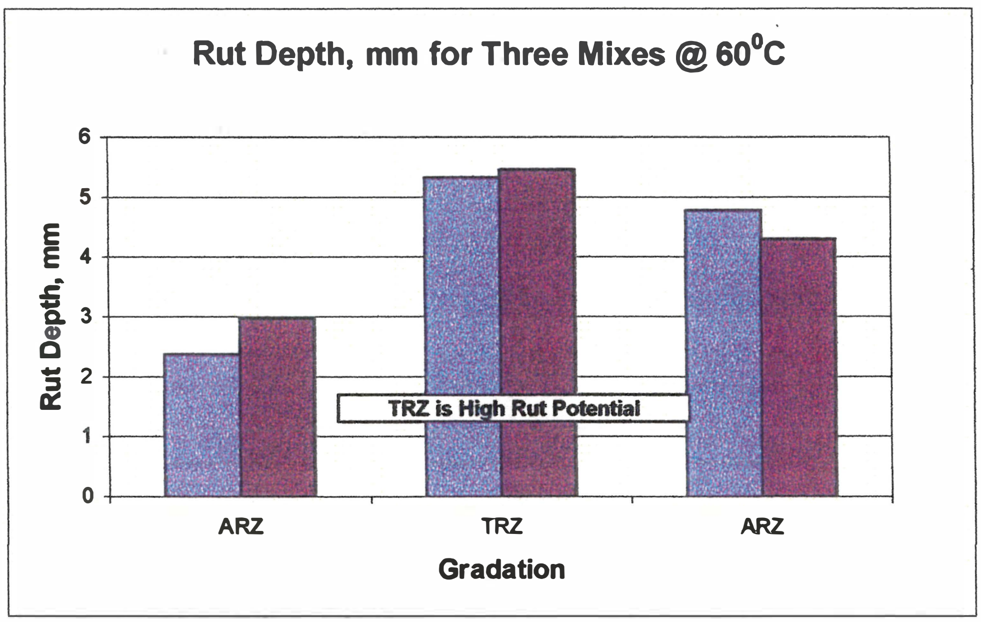


Figure 3.8 Comparison of Rut Potential of Exploratory and Base Mixes

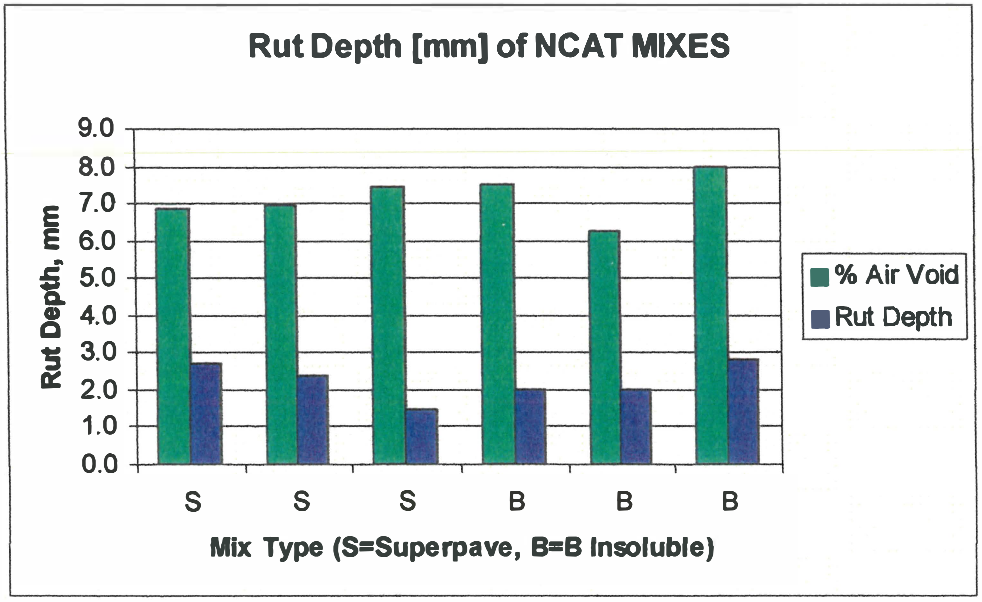


Figure 3.9 Rut Depths of Test Track Mixes

IV. PLANT MIX EVALUATION

4.1 General

The rutting potential of hot mix asphalt (HMA) samples can be evaluated in the laboratory during the design phase of a project using an Asphalt Pavement Analyzer. APA has the ability to rank mixture performance in the laboratory before costly surprises are encountered in the field (Brock et. al., 1999). This chapter deals with the rutting susceptibility of 10 selected HMA mixes that are commonly used in Oklahoma for pavement construction. The primary goal is to rank these mixes based on their rutting potential based on the APA data. The objective is to evaluate the rutting susceptibility of selected asphalt mixes based on the APA data, and to examine the pertinent mix parameters that lead to differential rutting potentials of HMA specimens.

4.2 Experimental Methodology

4.2.1 Mix Selection

A total of ten different HMA mixes were selected in cooperation with the Oklahoma Department of Transportation (ODOT). An attempt was made to select mixes that are representative of commonly used mixes in the State. The identification of mix, project identification number, design identification number, construction site (county), highway, and average daily traffic for each HMA concrete is listed in **Table 4.1**. The selected mixes are of types A and B of HMA. Mix 1, Mix 5 and Mix 7 are Recycled or Milled Asphalt Pavements (RAP or MAP) whereas the other mixes are Type B except

Mix 8 was Type C (ODOT 1999). Mix 2 was designed for less than three millions Equivalent Single Axle Loads (ESAL). Mix 1 Mix2, Mix 3 and Mix 8 were designed for more than 0.3 million ESALs. All of other mixes were designed for more than 3.0 million ESALs.

4.2.2 Material Collection

Materials from each project were collected in sufficient amount for rut testing. Each sample consisted of four bags with approximately 14 to 20 kg (30 to 44 lbs) of HMA materials. Two to three beam samples were fabricated from each mix; each beam sample required 6 to 6.5 kg (13 to 14 lbs) of HMA mixes, while six cylindrical samples were molded from each project, each sample requiring about 3 kg (6.5 lbs) of HMA mixes. The extra materials were burned in the NCAT ignition oven to determine the asphalt content and aggregate gradation as well as other properties of the mix.

4.2.3 Specimen Preparation

HMA mixes were heated first in a Blue M oven for about two hours, with all other tools such as spatulas, spoons, bowls, and molds at 149^0 C (300^0 F). Cylindrical specimens required about 3 kg (6.5 lbs) of HMA mix, while beam samples required about 6 to 6.5 kg (13 to 14 lbs) of the mix. For cylindrical specimen, the Superpave Gyratory Compactor (SGC) was used for compaction. In molding procedure, the cylindrical mold was filled with the heat HMA mix in three layers, each layer placed and speculated by spatula to make sure that the mix was placed homogenous in the mold according to standards and specifications (AASHTO PP28-00). Compaction specimens were compacted to height of 3 in (75 mm) to achieve the target air void of 7.0 ± 1.0%. For beam specimens, AVC was used for compaction with 700 kPa (100psi) forward pressure and 245 kPa (35 psi) backpressure for 35 second to achieve the target air void of 7.0 ± 1.0%. Compacted specimens were left at room temperature (approximately (25^0C) 77^0F) to allow the entire specimen to cool for ten hours. The bulk specific gravity of compacted specimens was determined (AASHTO T 166). The maximum specific gravity (G_{mm}) for all HMA mix was determined (AASHTO T 209). The percent air void was calculated for each specimen, and then the specimens were arranged and categorized according to their percent void before the rutting test was started (AASHTO T 269). A total of 54 cylindrical specimens and 14 beam specimens were prepared and tested for rutting susceptibility using the APA.

4.2.4 APA Rut Test

A typical test uses either three-beam specimen 75 mm x 125 mm x 300 mm (3 in x 5 in x 12 in) or six-cylindrical samples 150 mm diameter x 75 mm (6 in x 3 in). Specimens preconditioned at testing temperature of 64^0 C for minimum of 10 hours. The test temperature was representative of Oklahoma's environment in which the paving mixture will be utilized in the field. The preconditioned modeled specimens were tested in the APA. According to APA testing protocol, the vertical wheel load was kept at 445 N (100 lbs) and the pressure was adjusted to a pressure of 700 kPa (100 psi). APA was run for 8000 load cycles. The rut depth was measured as a function of load cycles. **Figure 4.1** shows a typical plot of rut depth versus load cycles prepared for Mix 6 from the APA data. It can be observed that the cylindrical specimens exhibited a rapid change in rut depth for the first 1000 cycles; as the number of cycles increased, the rut depth increased with a decreasing rate of rut. The cylindrical specimens for Mix 6 showed a maximum rut depth of 2.1 mm (0.82 inch). However, beam specimens of same mix exhibited a total rut depth less than 3.0 mm (1.2 inch) with basically a straight-line relationship between the rut depth and the number of cycles. Beam specimens when compared to the cylindrical specimens, exhibited low rut depth for the first 1000 cycles and then changed sharply; eventually it reached higher rut depths at 8000 loading cycles.

4.3 Mixture Analysis

Each Mix was burnt for asphalt content using National Center for Asphalt Technology (NCAT) ignition oven. Aggregate gradation based on sieve analysis was performed (AASHTO T 27). The proportions of the aggregate used in HMA mixes are listed in **Table 4.2**. Typically, three to four aggregates of different gradations are blended to achieve certain desirable gradation require for HMA mixes. **Table 4.2** also shows that Mix 1, Mix 5 and Mix 7 have used 37mm (1½ inch) rocks; therefore, the nominal maximum size is 25.4mm (1 inch). The gradation information for all mixes is listed in **Table 4.3**.

The blend gradations for 3 mixes are plotted in **Figure 4.2** representing the gradation by percent passing versus the sieve size raised to the 0.45 power. It can be seen that the Mix 2 is passing below the restricted zone whereas Mix 3 is above the restricted zone and Mix 8 is passing through the restricted zone. It is noted that the restricted zone is to control the percent natural sand in a typical HMA mix. The binder's Performance

Grade (PG), aggregate properties and mix volumetric properties are listed in **Table 4.4**. Asphalt cement Performance Grade (PG) PG 64-22 was used for Mix 1, Mix 2, and Mix 3 and Mix 8. Mix 6 was used with PG 76-28. Asphalt cement PG 70-28 was used for the other mixes. The percentage of asphalt cement used in the design mix varied from 4.4% to 6.3%.

4.4 Mix Ranking

Figure 4.3 is a histogram showing all mixes with increasing rut values for cylindrical samples. Mixes have been labeled E (Excellent), G (Good), F (Fair) and P (Poor) on the basis of rut value in millimeter. Four mixes exhibited rut values below 2 mm (0.79 inch) and are labeled as excellent. Three mixes exhibited rut depth more than 2 mm (0.79 inch) and less than 3 mm (1.18 inch) and are classified as good. Mixes with rut potential of 3 mm to 4 mm (1.18 inch to 1.6 inch) have been characterized as fair mix. Mix 3 has showed rut depth more 4 mm (1.6 inch) and is classified as poor mix. **Figure 4.4** is a histogram for ranking the mixes based on beam specimen's rut values. For all cases, beam specimens rutted more than the cylindrical specimens. The ranking criteria for beam samples were fixed by increasing the rut depth criteria of cylindrical samples by 1 mm. Therefore, it can be seen that 2 mixes are excellent, one is good and others are poor performing mixes out of seven mixes. It can be seen that Mix 3 is poor performing in both cases. Some of the cylindrical excellent performing Mixes are showing poor performance when tested as beam. Achieving target air void for beam samples is tedious. Beam specimens show higher variability in rut for two identical samples. Therefore, this study proposed mixes ranking based on test results from cylindrical specimens.

4.5 Rut Parameter Interpretation

The APA data were analyzed carefully to establish any correlations between rutting and other parameters. Specifically, compaction method and sample geometry, mix type, aggregate size, asphalt content, binder grade, dust content, aggregate gradation and air void on the rutting susceptibility were evaluated.

4.5.1 Asphalt Concrete Type

Figure 4.5 shows rut depth versus asphalt mix type for the cylindrical samples. Three of the ten mixes used in this study are Type A (RAP) mixes and six mixes are of Type B insoluble and one is C insoluble. Type A mixes exhibited a mean rut of about 2.3 mm (0.90 inch) with standard deviation of 0.45, while the Type B mixes exhibit a mean rut depth of 2.5 mm (.98 inch) with a standard deviation of 1.1. Type C mix exhibited rut depth of 3.2 mm (1.2 inch). This is because the Type A mixes combine larger aggregates (nominal maximum size of aggregate 19.0 mm) compared to Type B mixes (nominal maximum size of aggregate 12.5 mm) or Type C mixes (nominal maximum size of aggregate 9.5 mm). The coarse aggregate provides the shear strength to resist rutting where as the fines are used to fill the voids in coarse aggregates.

4.5.2 Asphalt Content and PG

Table 4.5 illustrate that for Type A mixes, mix 7 with a percent asphalt content of 4.1 of PG 70-28 has the lowest rut depth, where as Mix 1 with a percent asphalt content of 4.6 of PG 64-22 has highest rut depth of 2.8 mm. If comparing the Mix 7 with Mix 5, rejection of HMA, there is a need to correlate the results from the APA test and actual rut depths in pavements.

Acknowledgement

The authors would like to express their deep appreciation to the Oklahoma Department of Transportation. The authors are thankful to Kenneth Hobson for his valuable help in material collection, and for proving mix design data. Thankful acknowledge to colleague Emad Al Namasy for his valuable help.

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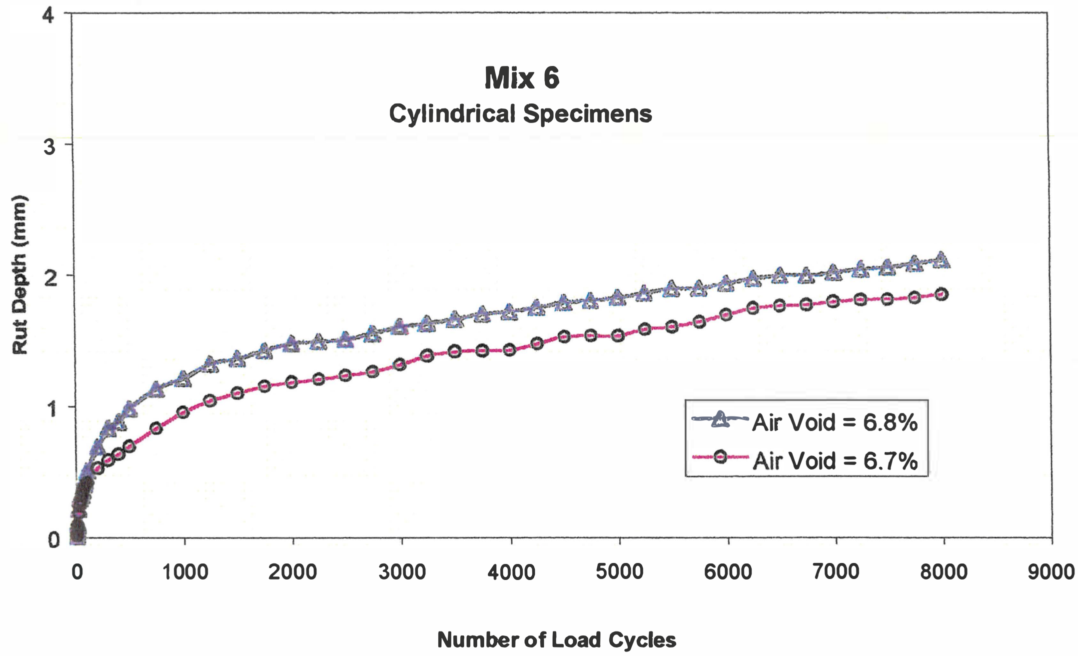

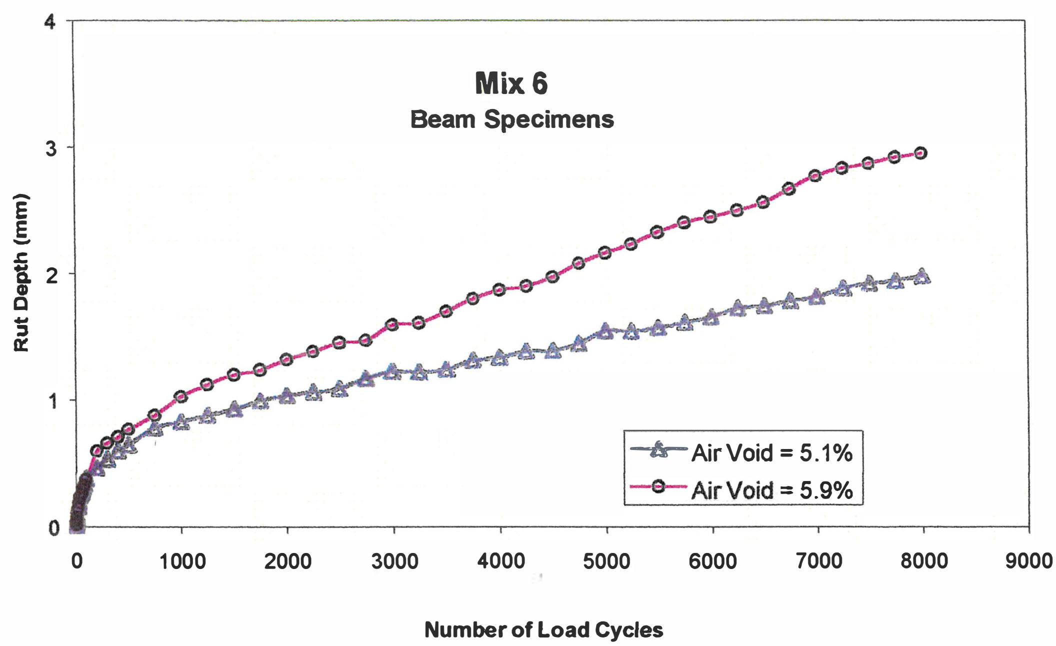

Figure 4.1 Typical Rut Depth Versus Loading Cycle Plot by APA

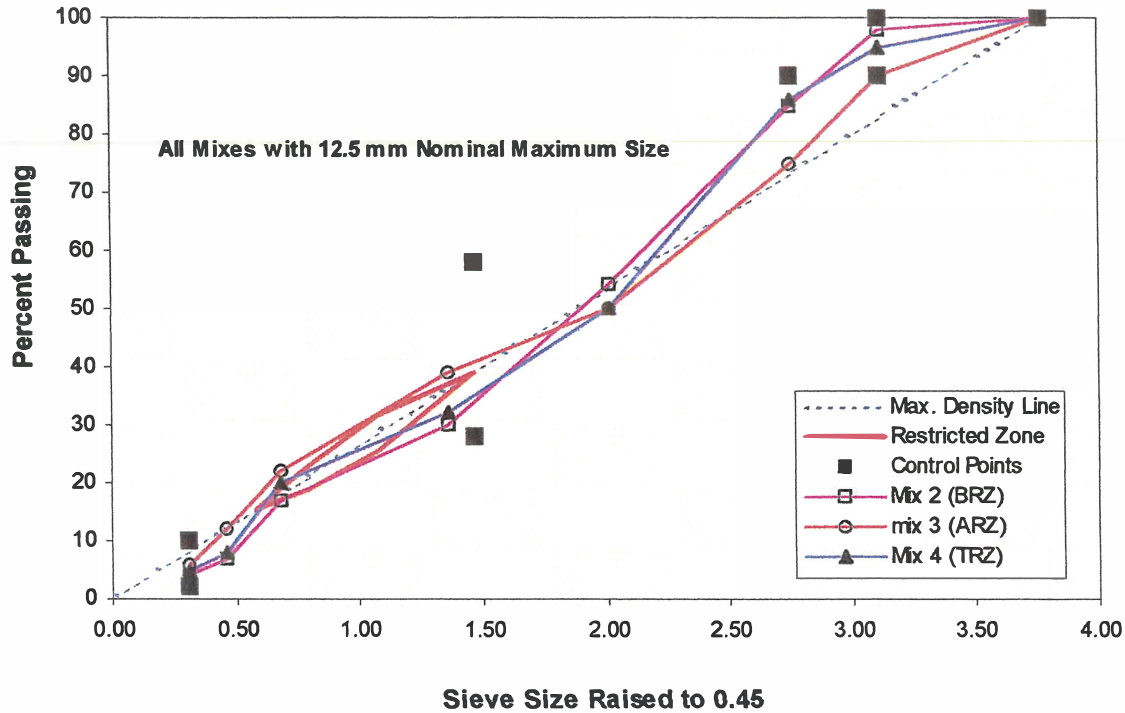

Figure 4.2 Characteristics of Mixes on the 0.45 Power Gradation Chart

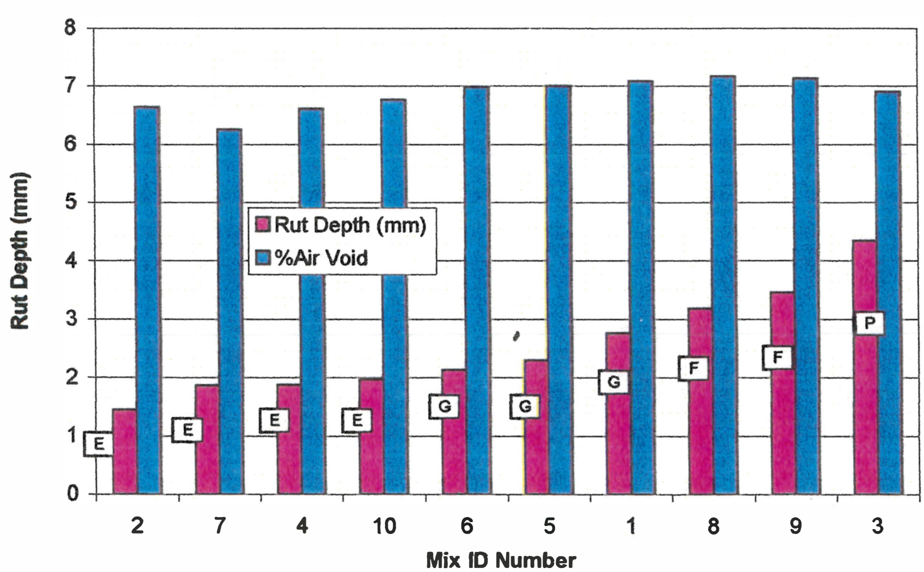

Figure 4.3 Mix Ranking Based on Rutting Potential of Beam Specimen

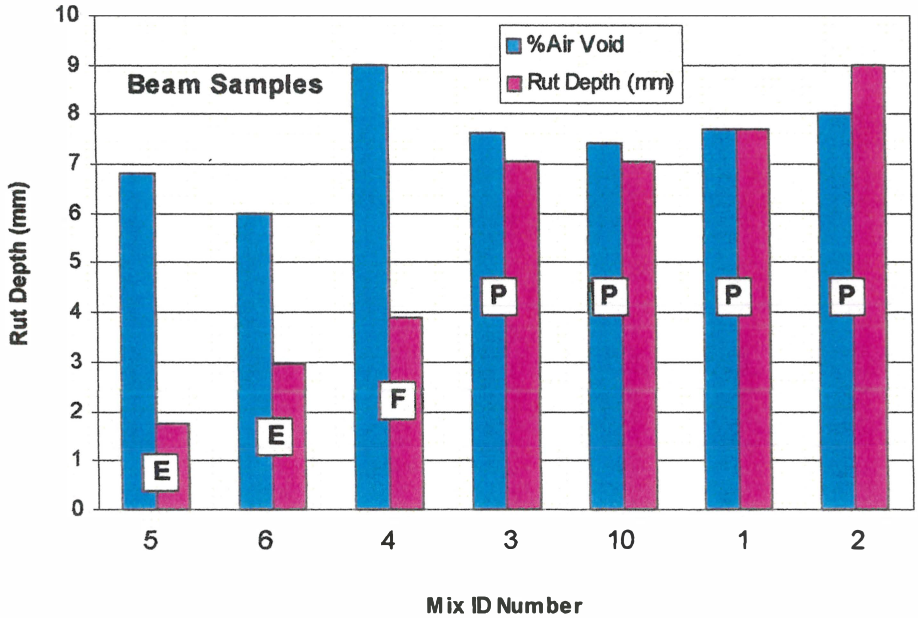

Figure 4.4 Mix Ranking Based on Rutting Potential of Beam Specimen

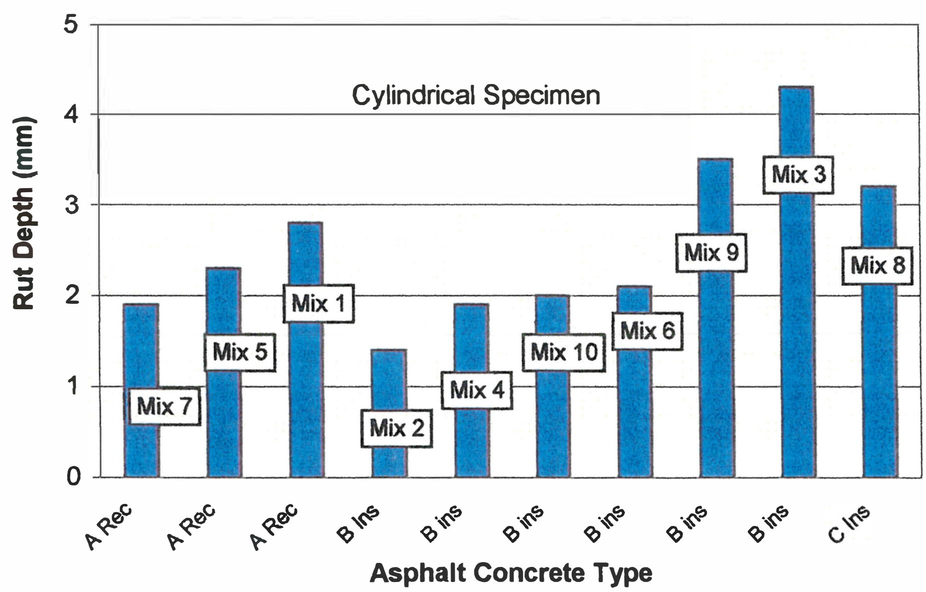

Figure 4.5 Effect of Asphalt Concrete Type on Rut Depth

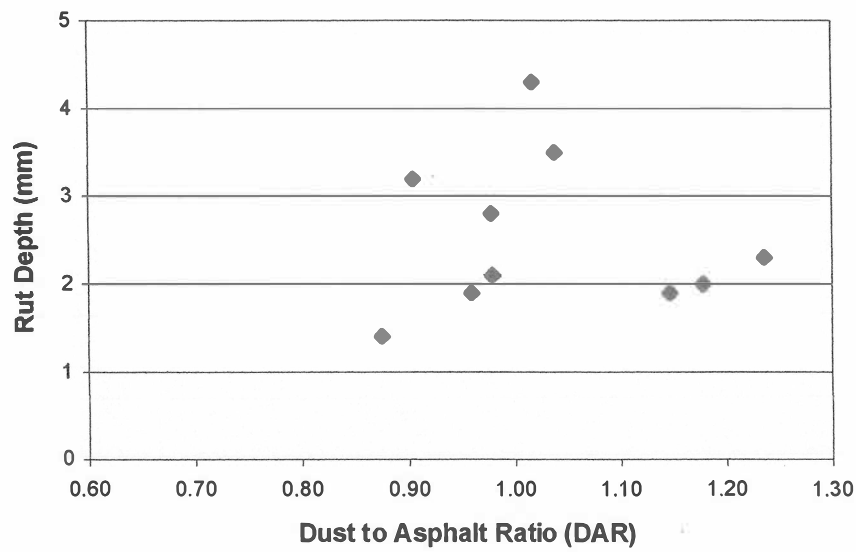

Figure 4.6 Effect of DAR on Rutting

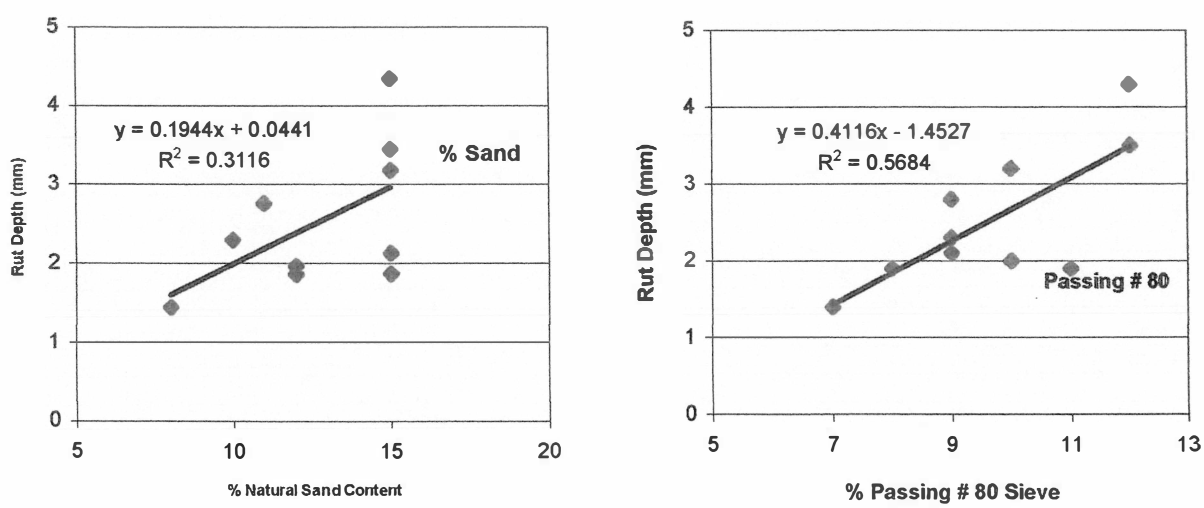

Figure 4.7 Effects of Sand and Passing # 80 Sieve Materials on Rutting

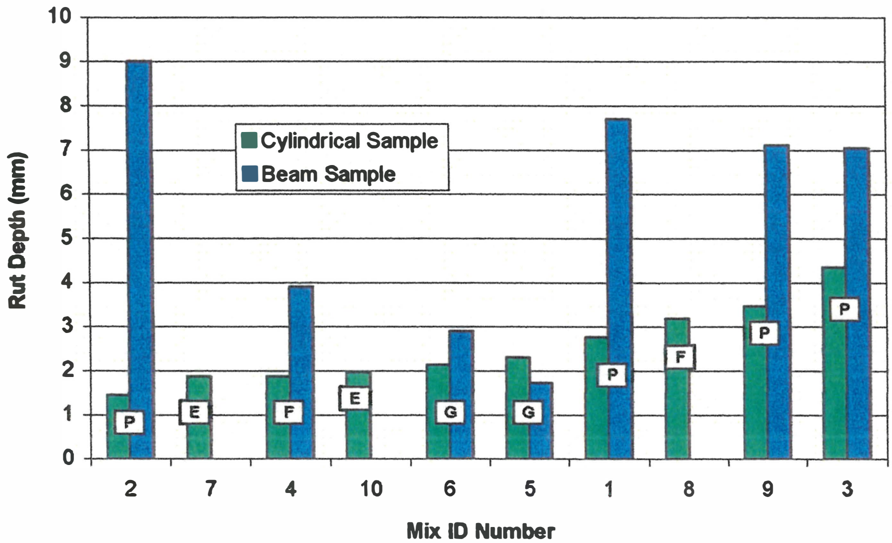

Figure 4.8 Mix Ranking Considering Both Beam and Cylindrical Specimen

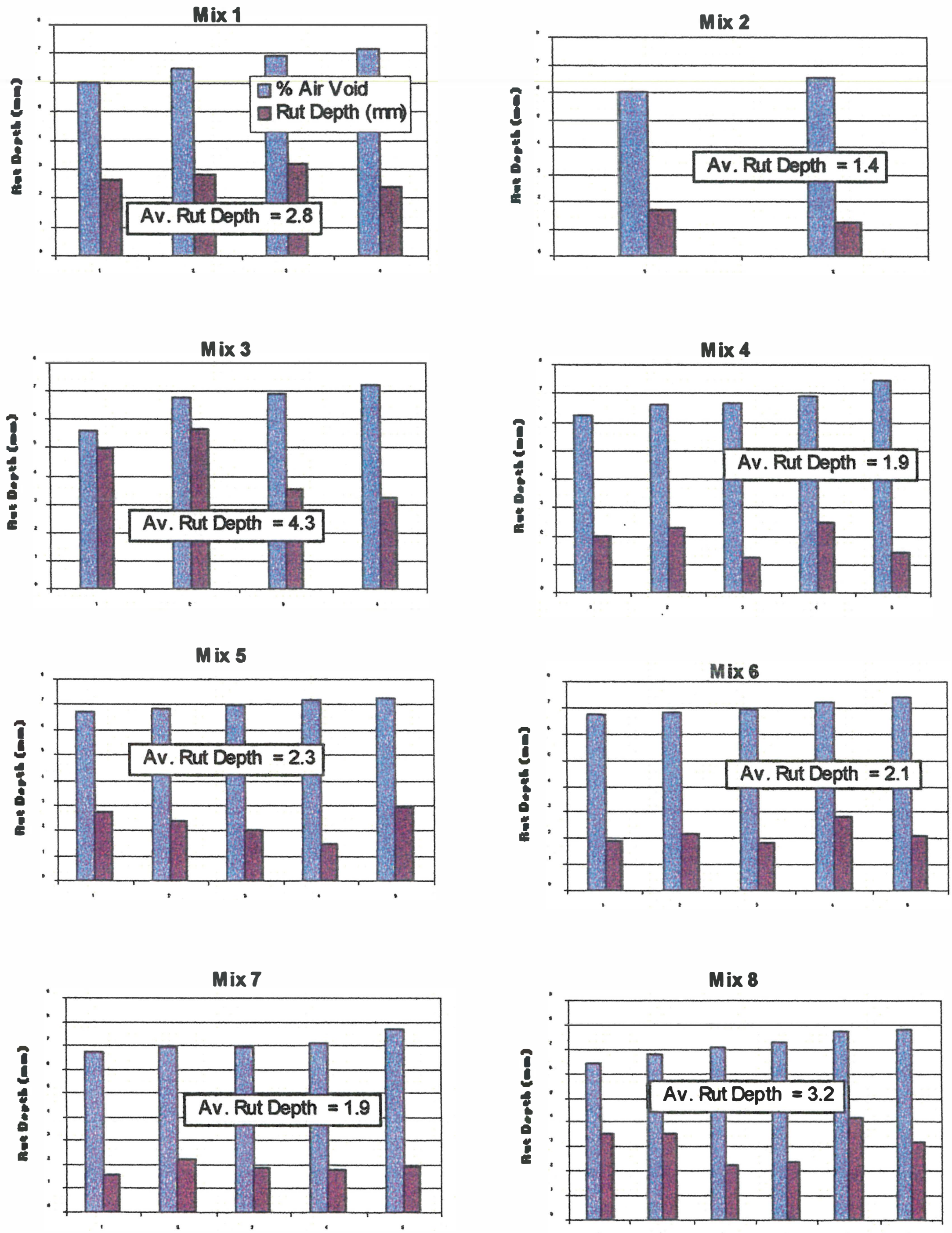

Figure 4.9 Effect of Air Void on Rut Depth for Cylindrical Samples

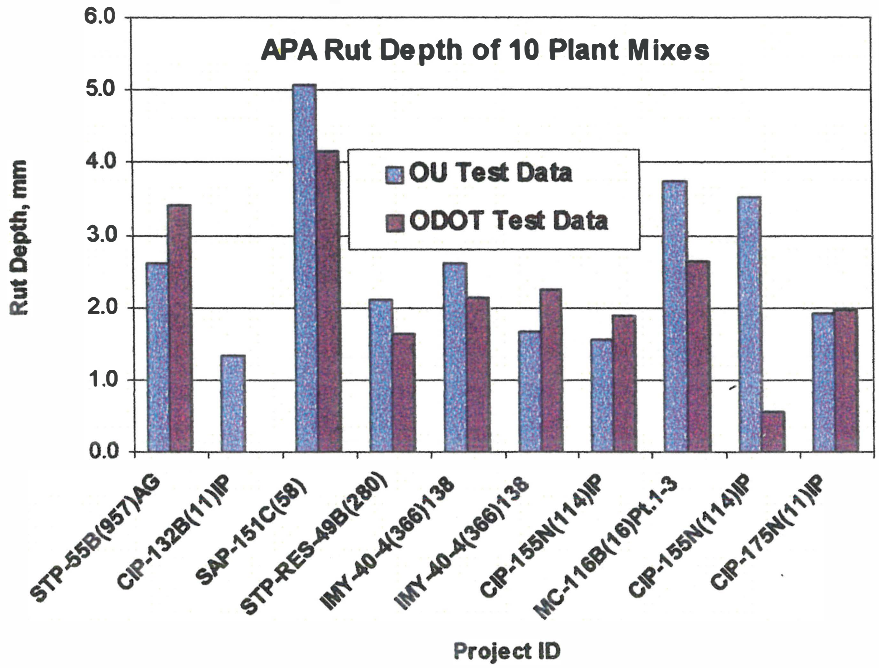

Figure 4.10 Comparison of OU Rut Data with ODOT Rut Data

Table 4.1 Mix Information

Mix ID	Project ID	Design ID	County	Highway	AC Type	A.D.T
1	STP-55B(957)AG	3011-56875	Oklahoma	City Street	A Rec	0.3M+
2	CIP-132B(11)IP	3012-OAPA-99048	Hughes	US75	B Ins	0.3M+
3	SAP-151C(58)	3012-OAPA-20095	Muskogee	Lake Road	B ins	0.3M+
4	STP-RES-49B(280)	3012-APAC-99018	Mayes	SH-20	B ins	3M+
5	IMY-40-4(366)138	3011-OAPA-20048	Canadian	I40	A Rec	3M+
6	IMY-40-4(366)138	3012-OAPA-20049	Canadian	I40	B ins	3M+
7	CIP-155N(114)IP	3011-OAPA-20090	Oklahoma	City Street	A Rec	3M+
8	MC-116B(16)Pt.1-3	3013-OAPA-20225	Cimarron	City Street	C Ins	0.3M+
9	CIP-155N(114)IP	3012-OAPA-20095	Oklahoma	City Street	B ins	3M+
10	CIP-175N(11)IP	3012-OAPA-20033	Oklahoma	US183	B ins	3M+

AC= Asphalt Concrete; A.D.T = Average Daily Traffic; Rec= Recycled; Ins= Insoluble

Table 4.2 Types of Aggregate

Mix ID	1-1/2" Rock	3/4" Chips	5/8" Chips	5/8" Mill Run	3/8" Screenings.	1/4" Chips	Shot	Stone Sand	Chat	No.4 Screening	Screening	MAP	Sand
1	22						20				22	25	11
2			30	34		28							8
3		17	35								33		15
4		26							36		23		15
5	39				13			15				23	10
6			42		18			25					15
7	24						18				21	25	12
8		25	30								30		15
9			28					10			47		15
10		12	30							26	20		12

Table 4.3 Mix Aggregate Gradation

Sieve Size (mm)	1 1/2"	1"	3/4"	1/2"	3/8"	# 4	# 10	# 40	# 80	# 200
Mix ID	**(37.5)**	**(25.4)**	**(19.5)**	**(12.5)**	**(9.5)**	**(4.75)**	**(2.0)**	**(0.425)**	**(0.18)**	**(0.075)**
1	100	99		84		60	35	20	9	4.5
2			100	98	85	54	30	17	7	4.2
3			100	90	75	50	37	22	12	5.7
4			100	95	86	50	32	20	8	4.7
5	100	98		76		54	40	20	9	4.7
6			100	99	86	60	45	22	9	4.6
7	100	99		82		61	36	23	11	4.7
8				100	95	66	44	18	10	5.7
9			100	99	89	62	44	25	12	5.4
10			100	89	73	57	40	20	10	5.3

Table 4.4 HMA Mix Properties

Mix ID	Binder Properties			Aggregate Properties						Mix Properties		
	PG	**Source**	**Sp. Gr.**	**S. E.**	**L.A.**	**Durability**	**IOC**	**IR**	**FF**	**P_b**	**VMA**	**Hveem Stability**
1	PG64-22OK	a	1.0100	70	23.5	69	0.22	87.4	100	4.6	13.7	41
2	PG64-22	d	1.0201	70	27.3	83	0.14	87.4	100	4.8	15.4	48
3	PG64-22OK	e	1.0119	56	34.7	58	1.04	90.0	100	5.6	15	49
4	PG70-28OK	c	1.0198	71	23.4	73	0.22	40.4	100	4.9	16	45
5	PG70-28OK	b	1.0100	77	23.2	73	0.10	87.4	100	3.8	13.7	59
6	PG76-28OK	b	1.0232	79	26.4	77	0.23	40.0	100	4.7	15.7	50
7	PG70-28OK	a	1.0100	62	20.7	72	0.22	79.3	100	4.1	14.5	62
8	PG64-22OK	f	0.9943	75	20.0	84	0.3	80.9	100	6.3	15.5	51
9	PG70-28OK	a	1.0128	59	20.9	77	0.78	70.5	100	5.2	17.2	59
10	PG70-28	c	1.0245	68	25.2	84	0.12	63.5	100	4.5	16.2	53

S.E = Sand Equivalent; L.A. =Los Angeles Abrasion; P_b = Percent Asphalt Content; IOC = Ignition Oven Calibration Factor; IR = Insoluble Residue; FF = Fractured Face; VMA = Void in Mineral Aggregate

Table 4.5 Effect of Asphalt Concrete Type

Mix ID	AC Type	Gradation	Nominal Maximum Size (mm)	% Passing # 200 Sieve	% Asphalt Content	DAR	Rut Depth (mm)
7	A Rec	ARZ	19.0	4.7	4.1	1.15	1.9
5	A Rec	ARZ	19.0	4.7	3.8	1.24	2.3
1	A Rec	ARZ	19.0	4.5	4.6	0.98	2.8
2	B Ins	BRZ	12.5	4.2	4.8	0.88	1.4
4	B ins	TRZ	12.5	4.7	4.9	0.96	1.9
10	B ins	ARZ	12.5	5.3	4.5	1.18	2.0
6	B ins	ARZ	12.5	4.6	4.7	0.98	2.1
9	B ins	ARZ	12.5	5.4	5.2	1.04	3.5
3	B ins	ARZ	12.5	5.7	5.6	1.02	4.3
8	C Ins	TRZ	9.5	5.7	6.3	0.90	3.2

Table 4.6a Comparison of OU APA Data with ODOT APA Data

Mix1	% Air Void	Rut (mm)	Mix6	% Air Void	Rut (mm)	Mix9	% Air Void	Rut
OU	6.0	2.6	OU	3.9	1.1	OU	6.2	4.1
OU	6.5	2.8	OU	6.7	1.9	OU	7.5	2.5
OU	9.5	2.3	OU	7.4	2.1	OU	7.7	3.8
ODOT	6.9	3.2	ODOT	6.8	2.1	ODOT	6.9	0.7
ODOT	7.1	2.4	ODOT	6.9	1.8	ODOT	7.1	0.7
ODOT	7.2	4.7	ODOT	7.2	2.8	ODOT	8.1	0.3
Mix3	**% Air Void**	**Rut (mm)**	**Mix7**	**% Air Void**	**Rut**	**Mix2**	**% Air Void**	**rut**
OU	5.5	5.1	OU	7.1	1.7	OU	6.0	1.7
OU	5.5	5.1	OU	7.7	1.9	OU	6.5	1.2
OU	5.6	4.9	OU	7.8	0.9	OU	9.5	1.1
ODOT	6.8	5.6	ODOT	6.7	1.6	**Mix5**	**% Air Void**	**rut**
ODOT	6.9	3.5	ODOT	6.9	2.2	OU	6.7	2.7
ODOT	7.2	3.3	ODOT	7.0	1.9	OU	6.8	2.4
Mix4	**% Air Void**	**Rut**	**Mix8**	**% Air Void**	**Rut**	ODOT	7.0	2.0
OU	5.9	1.8	OU	6.4	3.6	ODOT	7.2	1.5
OU	6.2	2.0	OU	6.8	3.5	ODOT	7.2	2.9
OU	6.9	2.5	OU	7.7	4.1	**Mix10**	**% Air Void**	**Rut**
ODOT	6.6	2.3	ODOT	7.0	2.2	OU	2.7	1.1
ODOT	6.7	1.2	ODOT	7.3	2.4	OU	4.2	2.1
ODOT	7.5	1.4	ODOT	7.8	3.2	OU	4.6	2.6

Table 4.6b Comparison of OU APA Data with ODOT APA Data

10 Plant Mixes			8000 Cycle Rut, mm	
Mix No.	**Project**	**AC Type**	**OU**	**ODOT**
1	STP-55B(957)AG	A Res	2.6	3.4
2	CIP-132B(11)IP	B Ins	1.3	*
3	SAP-151C(58)	B ins	5.1	4.1
4	STP-RES-49B(280)	B ins	2.1	1.6
5	IMY-40-4(366)138	A Res	2.6	2.1
6	IMY-40-4(366)138	B ins	1.7	2.2
7	CIP-155N(114)IP	A Rec	1.5	1.9
8	MC-116B(16)Pt.1-3	C Ins	3.7	2.6
9	CIP-155N(114)IP	B ins	3.5	0.6
10	CIP-175N(11)IP	BH ins	1.9	2.0

Table 4.6a Comparison of OU APA Data with ODOT APA Data

Mix1	% Air Void	Rut (mm)	Mix6	% Air Void	Rut (mm)	Mix9	% Air Void	Rut
OU	6.0	2.6	OU	3.9	1.1	OU	6.2	4.1
OU	6.5	2.8	OU	6.7	1.9	OU	7.5	2.5
OU	9.5	2.3	OU	7.4	2.1	OU	7.7	3.8
ODOT	6.9	3.2	ODOT	6.8	2.1	ODOT	6.9	0.7
ODOT	7.1	2.4	ODOT	6.9	1.8	ODOT	7.1	0.7
ODOT	7.2	4.7	ODOT	7.2	2.8	ODOT	8.1	0.3
Mix3	% Air Void	Rut (mm)	Mix7	% Air Void	Rut	Mix2	% Air Void	rut
OU	5.5	5.1	OU	7.1	1.7	OU	6.0	1.7
OU	5.5	5.1	OU	7.7	1.9	OU	6.5	1.2
OU	5.6	4.9	OU	7.8	0.9	OU	9.5	1.1
ODOT	6.8	5.6	ODOT	6.7	1.6	Mix5	% Air Void	rut
ODOT	6.9	3.5	ODOT	6.9	2.2	OU	6.7	2.7
ODOT	7.2	3.3	ODOT	7.0	1.9	OU	6.8	2.4
Mix4	% Air Void	Rut	Mix8	% Air Void	Rut	ODOT	7.0	2.0
OU	5.9	1.8	OU	6.4	3.6	ODOT	7.2	1.5
OU	6.2	2.0	OU	6.8	3.5	ODOT	7.2	2.9
OU	6.9	2.5	OU	7.7	4.1	Mix10	% Air Void	Rut
ODOT	6.6	2.3	ODOT	7.0	2.2	OU	2.7	1.1
ODOT	6.7	1.2	ODOT	7.3	2.4	OU	4.2	2.1
ODOT	7.5	1.4	ODOT	7.8	3.2	OU	4.6	2.6

Table 4.6b Comparison of OU APA Data with ODOT APA Data

10 Plant Mixes			8000 Cycle Rut, mm	
Mix No.	Project	AC Type	OU	ODOT
1	STP-55B(957)AG	A Res	2.6	3.4
2	CIP-132B(11)IP	B Ins	1.3	*
3	SAP-151C(58)	B ins	5.1	4.1
4	STP-RES-49B(280)	B ins	2.1	1.6
5	IMY-40-4(366)138	A Res	2.6	2.1
6	IMY-40-4(366)138	B ins	1.7	2.2
7	CIP-155N(114)IP	A Rec	1.5	1.9
8	MC-116B(16)Pt.1-3	C Ins	3.7	2.6
9	CIP-155N(114)IP	B ins	3.5	0.6
10	CIP-175N(11)IP	BH ins	1.9	2.0

V. BINDER EVOLUTION

5.1 Background

The concept of creating Hot Mix Asphalt (HMA) concrete with increased resistance to permanent deformation or rutting was a major driving force behind much of asphalt-related research performed under the Strategic Highway Research Program (SHRP). The provisional binder specification AASHTO MP1-98 (1) generally better known as the SHRP or Superpave binder specification represents a historic and logical steppingstone on the path to a truly performance-related specification for binders. In the 40's and 50's the penetration grading system, ASTM D 946 (2) was primarily used for specifying binder. The penetration value can not describe pavement distress, as it is not a fundamental property of binder. The next evolutionary step was the viscosity grading system, ASTM D 3381 (3). The performance of pavements built with viscosity-graded asphalt binders were thought to be controlled by their viscosity-temperature susceptibility (4). Asphalt cements classified on the basis of viscosity does not adequately reflect the rheology of the binder. Viscosity does not give a true indication of how asphalt cement will perform within a pavement over its yearly temperature range. A binder can be non-Newtonian (and visco-elastic), therefore, requires further characterization in addition to the viscosity. In the late 80's and early 90's, a new specification, so-called Performance-Based Asphalt (PBA) Specification, attempted to include regional climate variations and long-term aging in the field (5). The Superpave binder specification adopted many of the concepts in PBA specifications. The most significant advancement in Superpave Binder

(SB) specification is the move from empirical testing to advanced performance based testing where a binder can be characterized at a controlled rate and temperature to obtain the engineering properties of binder. In the Superpave binder specification, the Dynamic Shear Rheometer (DSR) (6), Bending Beam Rheometer (BBR) (7) and Direct Tension (DT) (8) replaced such tests as the viscosity, penetration and ductility testing to specify nine binder grade-classification under the asphalt cement grading system. Oklahoma Department of Transportation (ODOT) adopted the PG (Performance Graded) binder specification in July 1997. ODOT supplemented the AASHTO MP1 (1) specifications in 1999 (9).

The new grading system, AASHTO MP1 (1) more appropriately relates the grade of the asphalt binder to the pavement temperature and traffic loading for a construction project than the previous grading systems. Under a true PG grading system binders classified the same should have similar performance characteristics. Mixture containing these binders should show similar performance characteristics. PG binders of same grade, produced from different crudes and manufacturing process and meeting the specification requirements of MP1-98, may show different performance in HMA mixes (10). If different binders of the same PG grade do not perform similarly, then the binder specification may lose its significance. It should be noted that the PG system is a purchase specification. A real attempt was made by the SHRP researchers to relate the various PG grades to actual performance. No binder grading system may fully identify the full mixture performance when binder characteristics alone are considered.

Rutting and fatigue failure models were developed during the SHRP research but these models continue to be refined. The Superpave Shear Test (SST) (11) and Indirect

Tensile Test (IDT) (12) machines are expensive. Only five Superpave centers had these machines in the early 1990's. The cost of these machines makes full use of the SHRP research using the SST and IDT cost and time prohibitive for full implementation of Superpave using theses machine by State and local agency and governments. ODOT and the University of Oklahoma purchased APA and Asphalt Vibratory Compactors (AVC) in 1999. An Oklahoma HMA contractor purchased an APA in 2001 and some contractors have used the APA to determine rutting potential independent of ODOT requirements. Superpave testing equipment and procedures to fully evaluate the permanent deformation resistance of a given mixture are still under development. Recently, the APA has become increasingly popular in evaluating rutting potential of HMA mixes (13). Accordingly, many state agencies have started using the APA to evaluate rutting potential. The present study has employed APA to investigate the performance of different binders based on mixture rut potential. The main objective is to evaluate and compare the performance of these binders in the context of rut potential of mixtures with these binders. A subsequent objective is to examine the performance of binders with the same high temperature PG grade (unmodified binders or modified binders) as well as the performances of binders with different high temperature PG grade (comparison modified and unmodified binders). The primary goals of this study are to develop rutting prediction equations of HMA mixes and to examine whether MP1-98 specified binders could produce a low rut potential mix.

5.2 Binders Description

This paper investigated thirteen different unmodified and modified binders from different sources and PG grades HMA mixtures. These binders are currently being used in different projects within Oklahoma. The unmodified binders referred to as PG1 are PG 64-22 or PG 64-22 OK graded binders and are from eight different sources. These binders are produced from crude oil that is high in asphaltenes as so known base asphalt. The modified binders PG2 are of type PG 70-28 and PG 70-28 OK graded binders typically contains 2% styrene-butadiene-styrene (SB) polymer. These two binders were obtained from two different sources. The modified binder PG3 is a PG 76-28 OK graded binder from one of PG2 sources. It typically contains 5% SB polymer with 0.05% chemical anti-strip additive. The modified binders are produced from same base asphalts but contain relatively with low asphaltenes. PG 64-22 OK, PG 70-28 OK and PG 76-28 all meet the requirements for PG 64-22, PG 70-28 and PG 76-28 in accordance with AASHTO MP1, as well as the additional requirements of ODOT specification (9).

5.3 Binders Properties

Tests were conducted to determine G^* and δ values using a Dynamic Shear Rheometer (DSR) at the high PG temperature and at 10 radian/sec frequency of loading. The DSR tests were performed on the original and Rolling Thin Film Oven (RTFO) samples. The Superpave binder specification uses a factor called rutting factor, $G^*/\sin \delta$ to characterize binder stiffness or rut resistance at high pavement service temperature. The rutting factor reflects the total resistance of a binder to deform under repeated loading (G^*), and the relative energy dissipated into non-recoverable deformation ($\sin \delta$)

during the loading cycle (14). A higher value of G*/sin δ implies that the binder behaves more like an elastic material, which is desirable for rutting resistance. As the binder ages, the G* increases and the δ decreases and binders become more viscous. The SHRP rutting factor G*/sin δ for unaged and aged binders is listed in **Table 1**. From this table it can be seen that all binders are within the Superpave specification for the rutting factor, $G^*/\sin\delta$, which is a minimum of 1.00 kPa and 2.20 kPa for unaged, and RTFO aged binders, respectively. The mean rutting factor for the unmodified binder is 1.40, where as for the modified binder the corresponding value is 1.57 at unaged condition and the mean rutting factor for unmodified binder of 3.3 and for the modified binder of 3.10 after RTFO aging indicates there is not a significant improvement of rutting factor due to modification. The rutting factor can be compared at the same temperature assuming linear behavior. For example, rutting factor for modified binder (i.e. PG2) of 3.10 at 70 ^{0}C would be 6.2 at 64 ^{0}C. Therefore, all the modified binders have high rutting factors when compared with unmodified binder at 64 ^{0}C. A study by Bahi et al., (15) showed that polymer modification increases the elastic responses and dynamic modulus of bitumen at intermediate and high temperatures, and influence complex and stiffness modulus at high temperature. Polymer can reduces the temperature susceptibility, the glass transition and limiting stiffness temperatures of bitumen (15).

The binders were also tested for viscosity at 135^0 C using a rotational viscometer (AASHTO TP48-97) and the values are listed in **Table 5.1**. Although the test is usually conducted for mixing and handling performance, this study has attempted to correlate viscosity with rutting performance. The higher viscosity values for modified binders as shown in **Table 5.1** indicates that polymer modification makes binders more resistance to disturbance. The table also shows that the viscosity is different for various modified binders depending on the source. The degree of improvement in binder quality generally increases with polymer content, but varies with base bitumen, bitumen source, PG grade and polymer type (16)

5.4 Aggregate and Mix Design

Four mineral aggregates consisting of 5/8" chips, screenings, shot and sand were incorporated into the Superpave method of mix design to produce asphalt concrete. Aggregate information is listed in **Table 5.2**. In the experimental procedure, aggregates were evaluated and gradation tests were performed to obtain the desired blend that met all of the Superpave gradation criteria. The final blend gradation plotted on the 0.45 power chart, as shown in **Figure 5.1,** passes below the maximum density line with a Nominal Maximum Size (NMS) of 12.5 mm. The blended aggregate properties are summarized in **Table 5.3.** Mix designs were performed using a traffic level of more than 3 and less than 30 million Equivalent Single Axle Loads (ESALs). Although the binder grades of PG 64-22 and PG 64-22 OK are recommended for less than 3 million ESALs in ODOT specification, this study used 3 million ESALs as the design criteria and for volumetric properties. The maximum gyration, N_{max} was 160 and the design gyration, N_{design} was 100. Design mixtures were mixed at 163^0 C, aged at 149^0 C for 3 hours and compacted at 149^0C using a Superpave Gyratory Compactor (SGC). The SGC was set at 600 kPa load and 1.25^0 gyratory angle. The optimum asphalt content was determined at 4% air void at N_{design}. **Figure 5.2 and Table 5.4** represents typical examples optimum asphalt content of four binders and volumetric properties as well as Superpave volumetric criteria. After each mix design was completed, the mix was tested for water susceptibility (AASHTO T 283). Only mixtures with a Tensile Strength Ratio (TSR) more than 0.80 were used in the final mix design. In addition, some binders were mixed at lower and higher optimum asphalt contents to examine the effect of asphalt binder on rutting performance of mixtures.

5.5 Rut Testing

Cylindrical specimens of 75 mm height were compacted in the SGC at a target air void of 6 to 8%. Specimens were preconditioned at 64^0 C for 10 hours before rut testing. In the APA testing procedure, the cylindrical samples were subjected to repeated passes of 45 kg (100 lb) loaded wheel through 690 KN/m^2 (100 psi) pressurized hose. Specimens were tested at 64^0 C temperature. The rut depth was measured in millimeters as a function of number of wheel passes. Ninety specimens were prepared and tested for rut depth at 8000 loading cycles. **Figure 5.3** shows the typical variations of rut depth in millimeter with the number of load cycle for mixtures containing various modified and unmodified binders. Three modified binders out of four showed rut depth of less than 3 mm. Others showed more than 4.5 mm rut depth at 8000 cycles of loading. From the figure it can be observed that more that 50% of the final rutting had occurred within 1000 loading cycles for all mixtures. The initial higher rate of rutting can be attributed to the initial densification or compaction of materials. After completion of initial densification, the rate of rutting (slope of rutting curve) decreases with the increase in loading cycles for each mixture. The slope of rutting curves in the range of 2000 cycle to 8000 cycles is almost equal for all mixtures. Therefore, it can be concluded that the major difference in final rut depth is primarily due to densification of materials and not for plastic flow at higher cycles.

5.6 Analysis of Test Results

5.6.1 Overall Ranking

Figure 5.4 is a histogram showing all binders with increasing rut depth for samples with 6 to 8 percent air voids. A threshold value of rut depth for classifying a mix as good or poor performing has yet to be developed by ODOT. This study considered a rut depth of 6 mm as threshold between excellent and good mixtures to poor mixtures. Accordingly, in **Figure 5.4**, the binders were classified as E (excellent), G (good) and P (poor) on the basis of the threshold value associated with rutting performance. It is evident that 3 mixtures fall in the category of excellent, 6 mixtures are in good category and 4 mixtures exhibit poor rutting performance rating out of 13 mixtures prepared with various binders. It is also evident that the APA can be used for screening of poor mixture or as a proof tester.

5.6.2 Effect of PG

Figure 5.5 shows that most PG2 and PG3 modified binder mixtures have lower rut potential (excellent) compared to the rutting performance of PG1 (unmodified binders). The mean rut depth for the modified binders is 3.4 mm with a standard deviation of 1.8 mm. The unmodified binders show a mean rut depth of 5.8 mm with a standard deviation value of 0.78 mm. The higher standard deviation for the case of modified binders is due to poor performance of S8-PG 70-28 OK. From the binder's PG point of view, it can be shown that the overall performance of the modified binders is much better than the unmodified binders. This agrees with what is expected from Superpave binder's specification point of view. However, there is no significant difference when the performance of the modified binder S8-PG 70-28 OK mixture is compared with the performance of unmodified binders. Again, the rutting performance of S7-PG3 does not differ when compared with the performance of the S7-PG2 binder mixture. From the test results, it is evident that the binder's higher performing grade is not a sufficient criterion to conclude that the mixture will perform well. A polymer-modified binders' performance should be evaluated in the mixtures for performance.

5.6.3 Effect of Source

One of the objectives of the present study was to examine whether the performance of mixtures with same PG binder grade differs with the source. For the PG1 binder, the following source ranking is S6>S5>S3>S1>S8>S4>S7>S2, based on the low to high rutting potential. From **Figure 5.5,** it is shown that the rut potential for PG1 binders differs very little by source. But, in the case of the PG2 binder the performance of S8 was worst compared to the source S7. Based on the APA test results, it is evident that APA is sensitive to a binder's PG grade and source. A simple APA rut test can facilitate the prediction of binder's actual behavior in a HMA mix. Therefore, binders meeting the specification requirements of MP1-98 should also be evaluated by APA rut testing.

independent does not increase the R-squared value by a significant amount (or until all variables are entered, of course). The dependent variable (rut depth, RD in millimeter) was multiplied by 100 and transferred to a logarithmic scale prior to incorporation into the linear model. The loading cycle was also transferred to logarithmic scale. The established terminal simplified form of the equation is,

$$Ln\,(RD\,.1000) = -2.51 - .20\,(R_v) + 5.29\,(P_b) - 4.92\,(P_{be}) - 0.59(G^*/sin\delta)_u + 0.608\,Ln(Cycle) \qquad (5.1)$$

Summary statistics are reported in **Table 5.5.** The sample multiple correlation coefficient R =. 951 measure the degree of relationship between the actual Ln (RD.1000) and the predicted Ln (RD.1000). The value indicates that the relationship between Ln (RD. 1000) and the five independent variables is quite strong and positive. The sample Coefficient of Determination R-square or R^2 measures the goodness-of-fit of the estimated Sample Regression Equation (SRP). It explains the proportion of the variation in the dependent variable predicted by the fitted SRP. The value of R^2 = .905 simply means that about 90% of the variation in Ln (RD.1000) is explained or accounted for by the estimated SRP that uses Ln (cycle), R_v, P_b, P_{ba}, DSR_u as the independent variables. Adjusted R-Square is the sample Coefficient of Determination after adjusting for the degrees-of-freedom lost in the process of estimating the regression parameters. In this case, adjusted R^2 = 0.904 is a better measure of the goodness-of-fit of the estimated SRP than its nominal/unadjusted counterpart. Standard Error of Estimate S_e = 0.507 means that, on an average, the predicted values of the Ln (RD.1000) could vary by ±0.507 about the estimated regression equation for each value of independent variables during the sample period and by a much larger amount outside the sample period.

5.7.2 NR Model

The present study also employed the iterative estimation of Levenberg-Marquardt method for nonlinear model development. A regression model is called nonlinear, if the derivatives of the model with respect to the model parameters depend on one or more parameters. The specific advantages such as the parameters of a nonlinear model usually have direct interpretation in terms of the process or mechanism under considerations. In the modeling procedure, a nonlinear equation is studied to fit observed rutting giving initial values of parameters. The adjustment of all parameters is considered in one iteration. In the next iteration, the program attempts to improve on the fit by modifying the parameters. If any further improvement is not possible, the fit is considered converged. Iterations are stopped when the relative reduction between successive residual sums of squares is at most 1.000E-08. Several models with different parameters were examined. A model (for example, one with more parameter) was satisfactory, if the relative increase in sum-of-squares (going from one to another model) was greater than the relative increase in degrees-of-freedom, i.e. $(SS1-SS2)/SS2>(DF1-DF2)/DF2$, where, SS = regression sum of square and DF = degrees-of-freedom. In a linear regression model, the quality of fit of a model is expressed in terms of the coefficient of determination, R^2. In nonlinear regression, such a measure is unfortunately not readily defined. One of the problems with the R^2 definition is that it requires the presence of an intercept, which most nonlinear models do not have. A measure, relatively closely corresponding to R^2 in the nonlinear case is Pseudo-R^2=1–SS (residual) /SS ($Total_{Corrected}$). The final form of the nonlinear model with Pseudo-R^2 =0.806 is,

$$RD = -2.57 + 0.35\,(V_a) - 1.09\,(R_v) + 1.68\,(P_b) - 0.41\,(VMA) - 0.71\,(G^*/\sin\delta)_u + 0.2442\,(Cycle)^{0.3359} \quad (5.2)$$

Table 5.6 contains the partitioning of the total sum of squares for the model and data into a regression sum of squares explained by the model and a residual sum of squares. The mean square error of this fit 0.5697 is the estimate of variability in the data when adjusted for the nonlinear model.

5.8 Comparison of Measured Rut Depth with Model Predictions

Figure 5.11 is a typical plot of measured versus model predicted rut depth for unmodified binder, S8-PG1-OK. The figure illustrates that the nonlinear prediction is closer to the measured rut depth and better than linear prediction. In this case, linear prediction is 3 mm more than the measured rut depth as well nonlinear prediction. A poor nonlinear prediction for the case of unmodified binder, S2-PG1 as in **Figure 5.12** shows that the nonlinear prediction follows the trend of measured rut depth with a rut depth about 2 mm less than the measured values. Linear prediction is higher than nonlinear predictions. **Figure 5.13** and **Figure 5.14** are the plots for modified binders S7-PG2 and S7-PG3, respectively. Both figures show that both nonlinear and linear predictions cannot explain the measured rut depth. The linear and nonlinear prediction equations include the viscosity and G*/sin δ (unaged), but these values do not vary significantly with modified binders. Although the final rut depth for the linear prediction is better than the nonlinear prediction, the slope of the nonlinear prediction at higher load cycles is almost equal to measured rut depth.

5.9 Cycle-500 Versus Cycle-8000 Rut

APA rut depth at 500-cycle can be a transition between consolidation and plastic flow of materials. The preceding analyses indicate that the visco-elastic properties of binder is dominant at lower number of load cycles. At higher load cycles, binder properties are less significant and rate of rutting is almost equal for all binders. Therefore, the study has attempted to correlate 8000-cycle APA rut depth to 500-cycle rut depth. From the linear regression analysis, the following relation was obtained with a $R^2 = 0.83$:

$$RD = 1.96 + 1.8\,(RD_{500}) + 0.93\,(G^*/\sin\delta)_u - 2.3\,(G^*/\sin\delta)_a \tag{5.3}$$

where, RD_{500} is the APA measured rut depth at 500-cycle. A nonlinear analysis is found to give better correlation with $R^2 = 0.89$. The following equation was obtained:

$$RD = 15.76 + 0.53(V_a) - 0.17(R_v + 2.67(P_b) - 0.8\,(VMA) - 2.16(G^*/\sin\delta)_u + 7.2(P_{ba}) - 19.62(RD_{500})^{-0.17} \tag{5.4}$$

The predicted 8000 cycle rut depths for all mixes are plotted against measured rut depth in **Figure 5.15 and Figure 5.16** for linear and nonlinear prediction, respectively. These model prediction show that nonlinear prediction has less scatter along a 45^0 line drawn between the measured and predicted rut values. One of the basic idea behind establishing this kind of relation is to extract rutting performance of a pavement at the end of pavement life from its early life.

5.10 Concluding Remarks

- This study ranked 13 different binders based on their mixture's performance and also on their properties. The binders' ranking based on their properties do not match with the mixture performance. A binders PG grade do not ensure the performance of mixture containing the binder. Therefore, a binder satisfying the Superpave specification requirements should be evaluated by the HMA mixture's rutting performance.

- The performance of modified binders having the same PG grade can vary significantly with the combining process or source. If the binders are unmodified or neat asphalts then the changing source will not vary in rutting depth more than 1 mm if the binder satisfies AASHTO MP1-98. As the binders' source is a changing target, the ranking of unmodified binder depending on the source become less significant.
- On the basis of the measured predicted results presented in this paper, the authors do not support the theory that a higher rutting factor can ensure lower rutting potential for mixtures containing that binder. Rather, a binder's viscosity showed good correlation with the mix performance.
- If rut depth of 6.00 mm is the divider between good and poor mixes, then ODOT's restriction, for using of unmodified binders in roads with 3M+ ESALs, on some sources should be reinvestigated.
- The study found that if the air void of laboratory produced rut specimens are kept within 6 to 8%, then air voids play an insignificant role in the contribution to rut potential. 500-cycle APA rut depth is a better predictor of 8000-cycle rut depth both for modified and unmodified binders' mix for both linear and nonlinear regression models.
- The study developed two models based on APA rut data on laboratory-produced samples. Nonlinear model is much more reliable than the linear prediction model.

However, both models over predicted rut depth for mixtures with modified binders.

- The study included one gradation of aggregate in the mixture. No consideration for wet rut testing on laboratory specimens was investigated.
- Rutting is a complex phenomenon. It involves many parameters. A neural network model could be very efficient for a complex phenomenon such as rutting.

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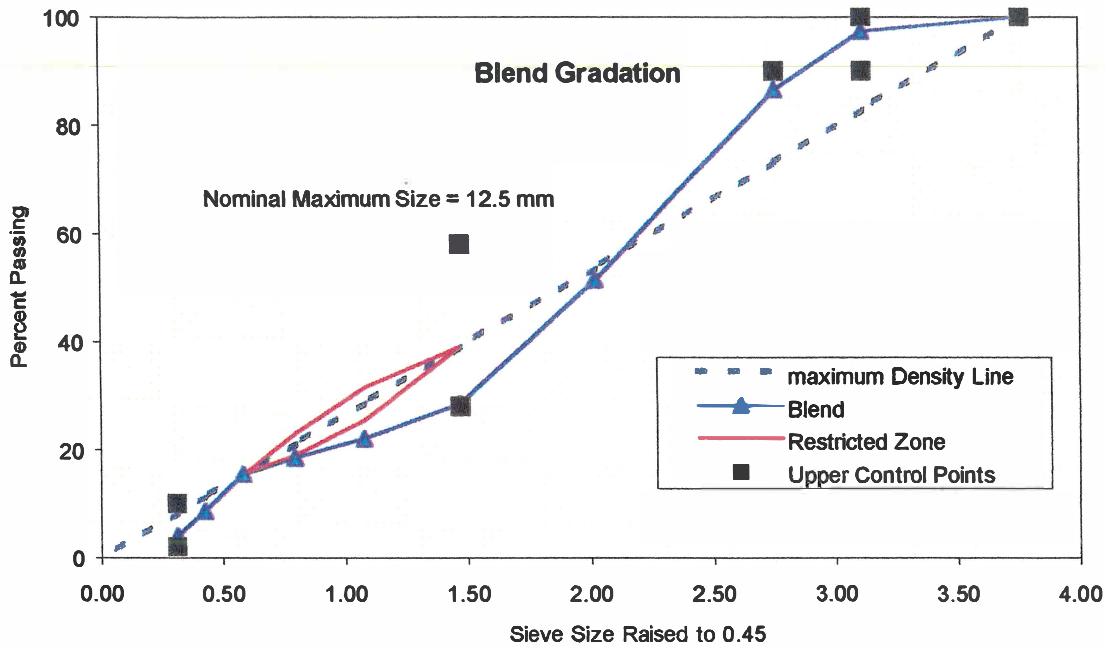

Figure 5.1 Blended Aggregate Gradation Used for Mix Design

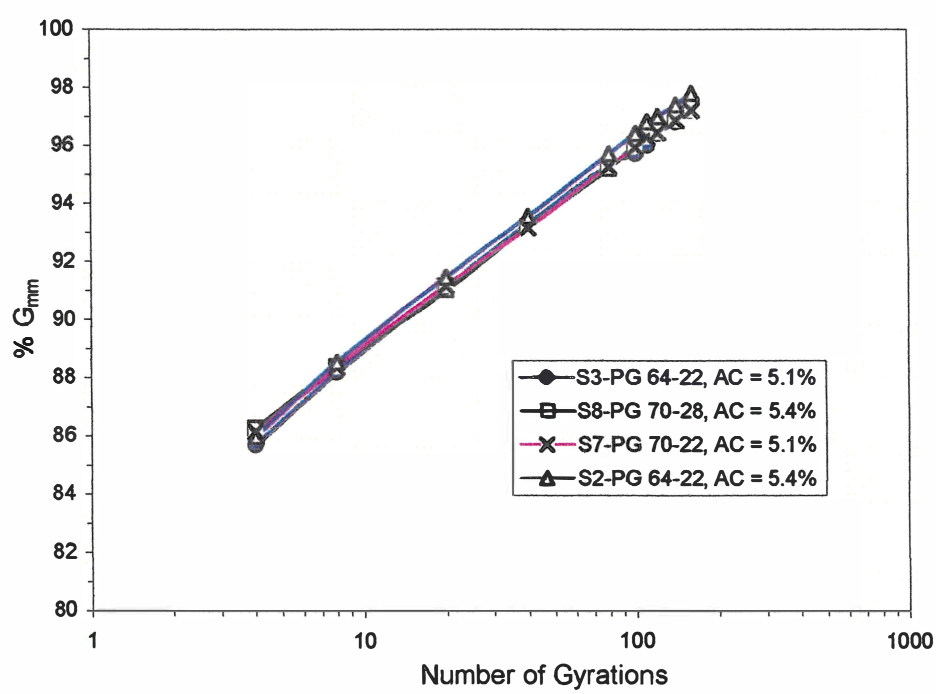

Figure 5.2 Average Densification Curve with Optimum Asphalt Content

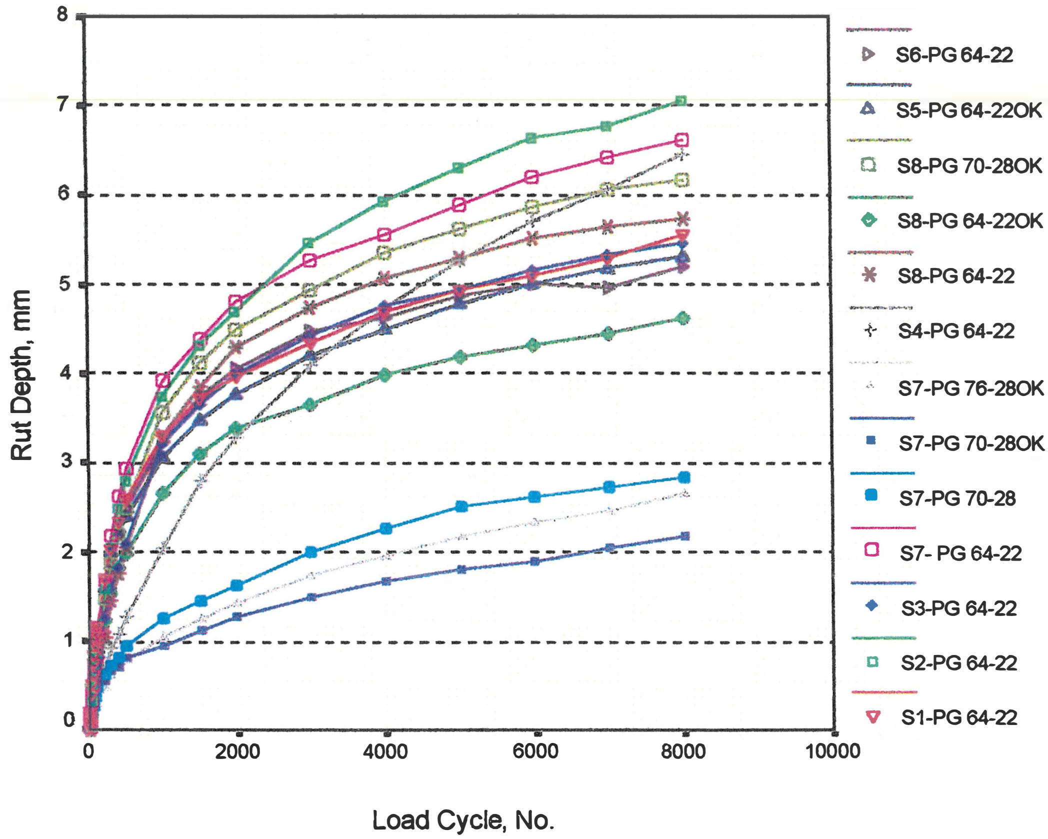

Figure 5.3 Typical Rut Depth versus Load Cycle

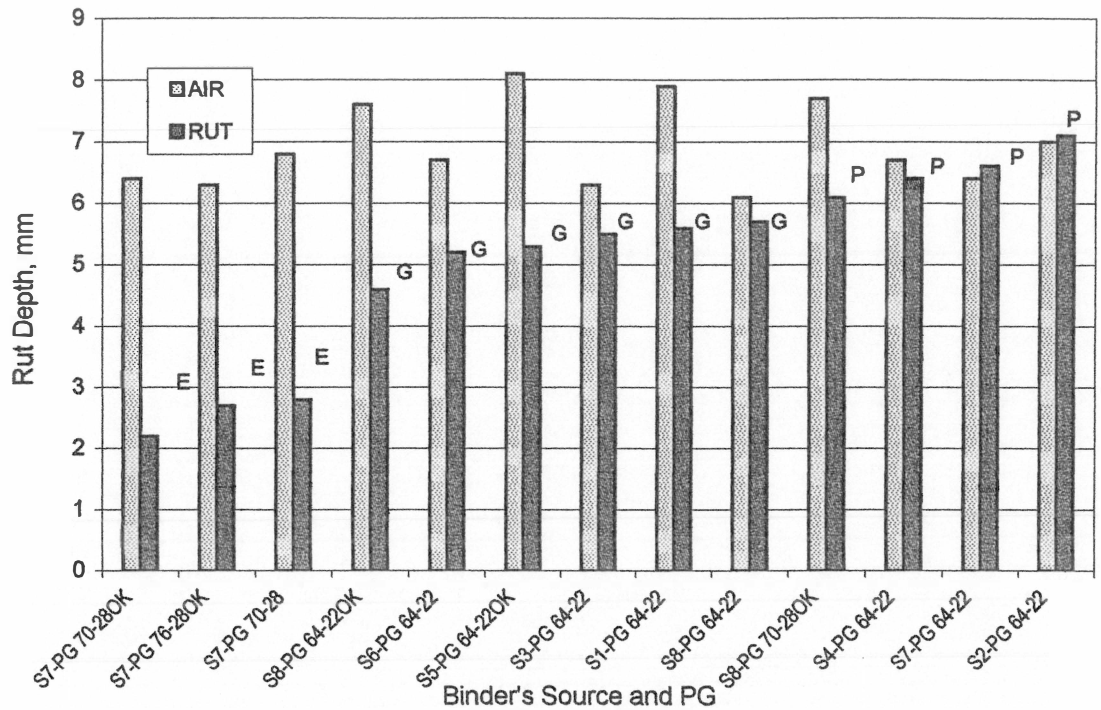

Figure 5.4 Overall Ranking of Mix

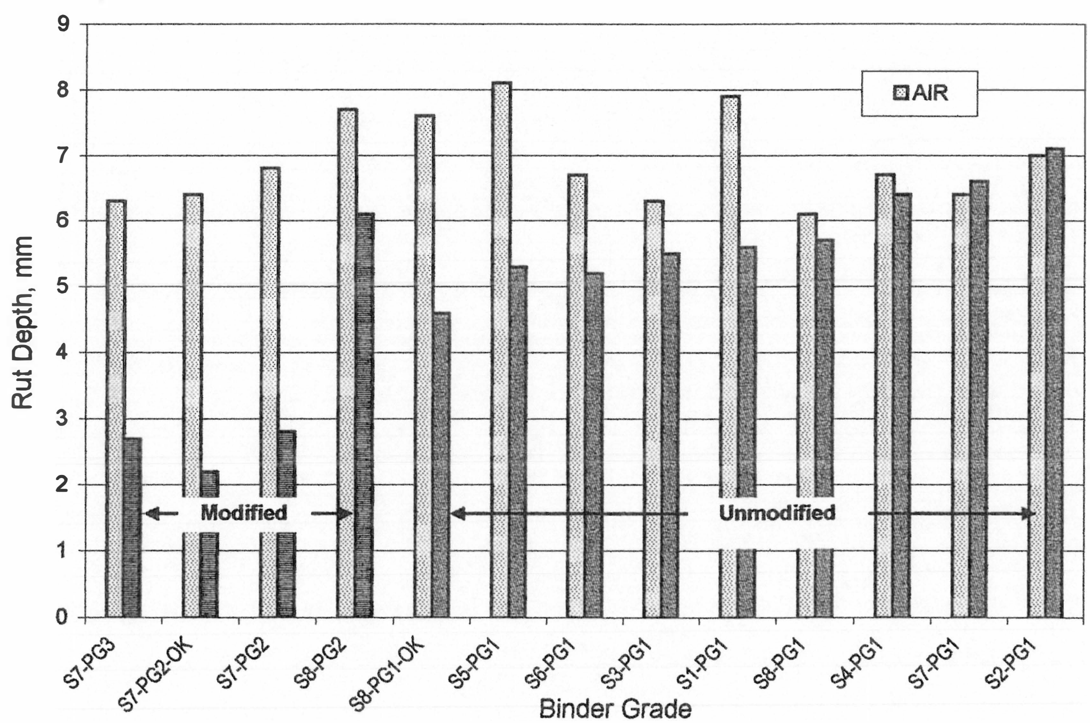

Figure 5.5 Comparison of Modified with Unmodified Binder's Performance

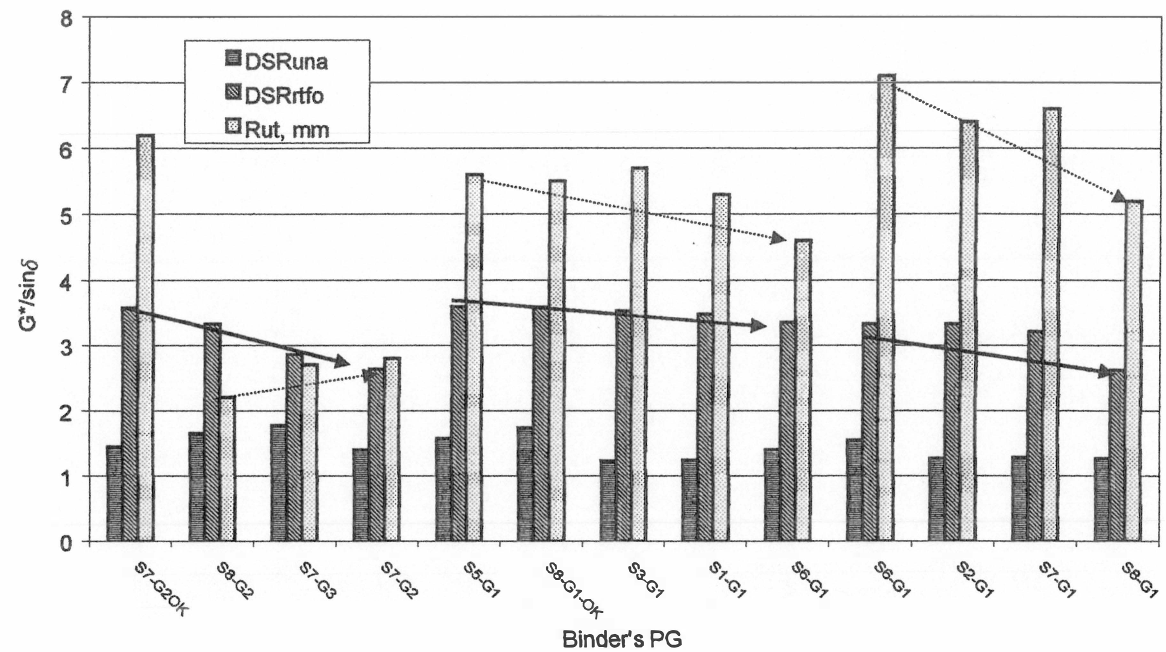

Figure 5.6 Effect of Rutting Factor on Rutting Performance

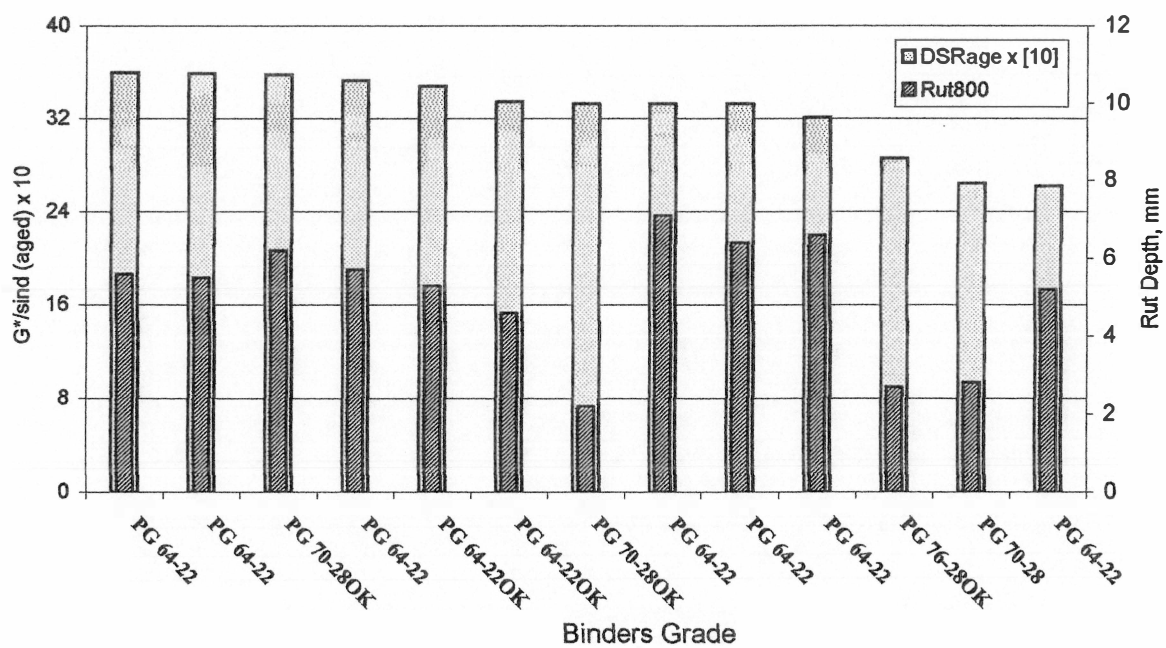

Figure 5.7 Overall Ranking of Binder based on G*/sinδ (aged) Values

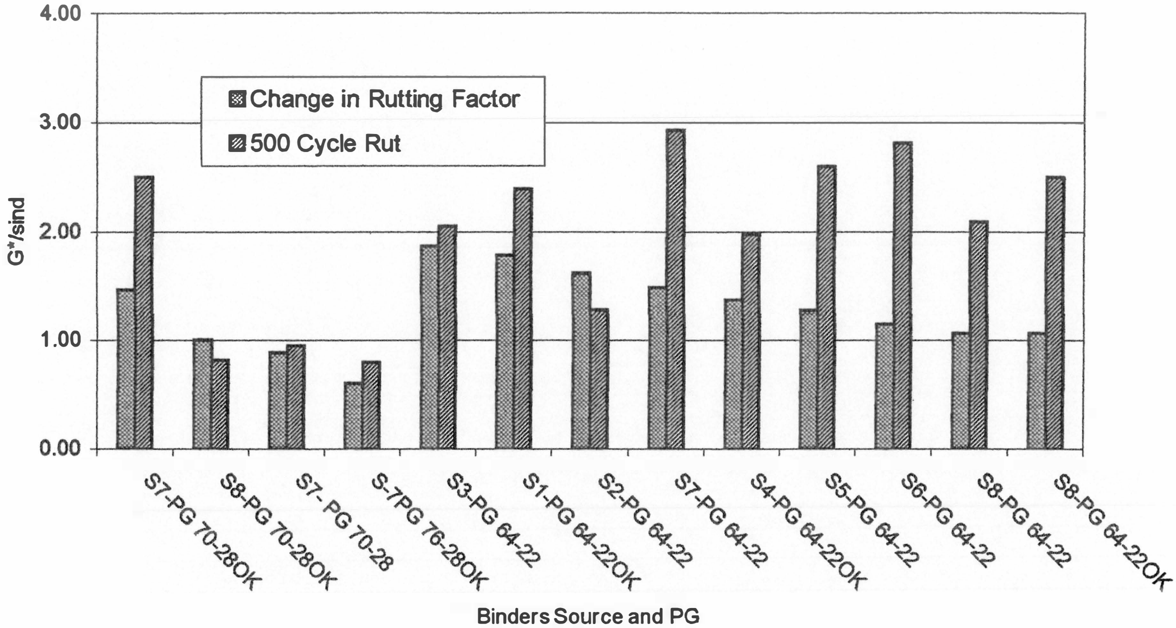

Figure 5.8 Effect of RTFO Aging on Binder's Performance

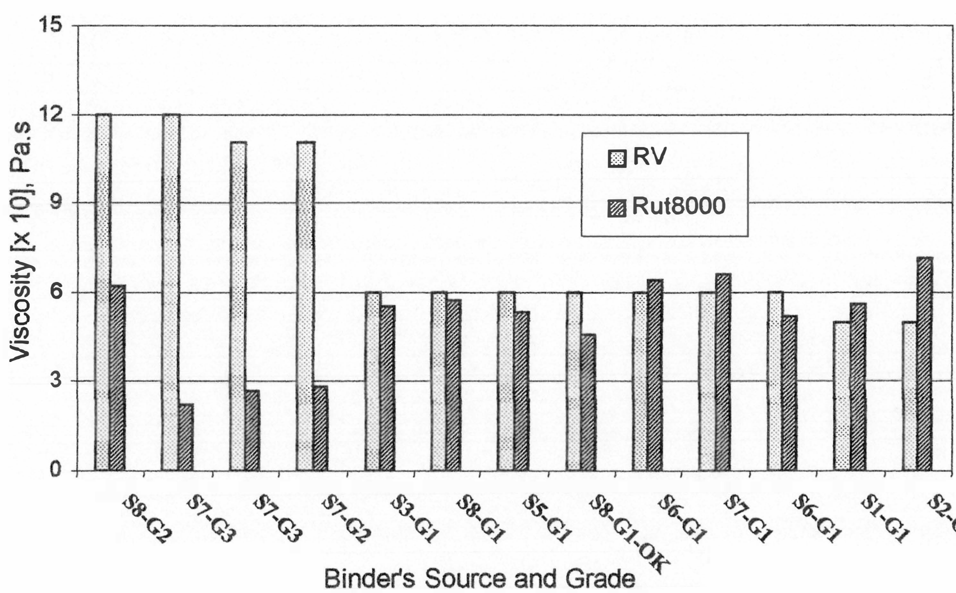

Figure 5.9 Effect of Viscosity on Rut Performance

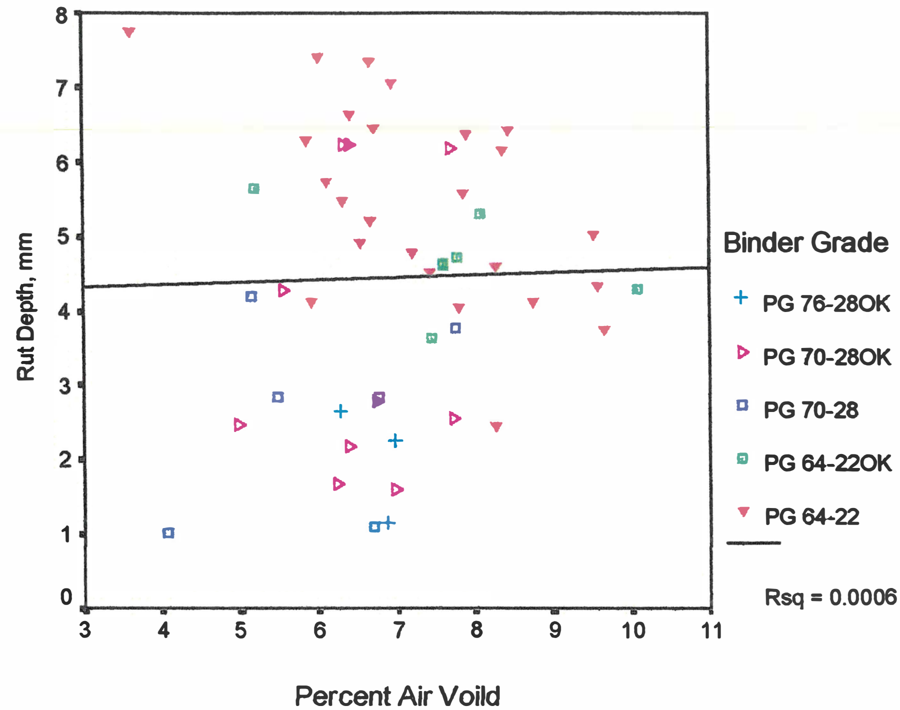

Figure 5.10 Correlation of Rut Depth with Percent Air Void

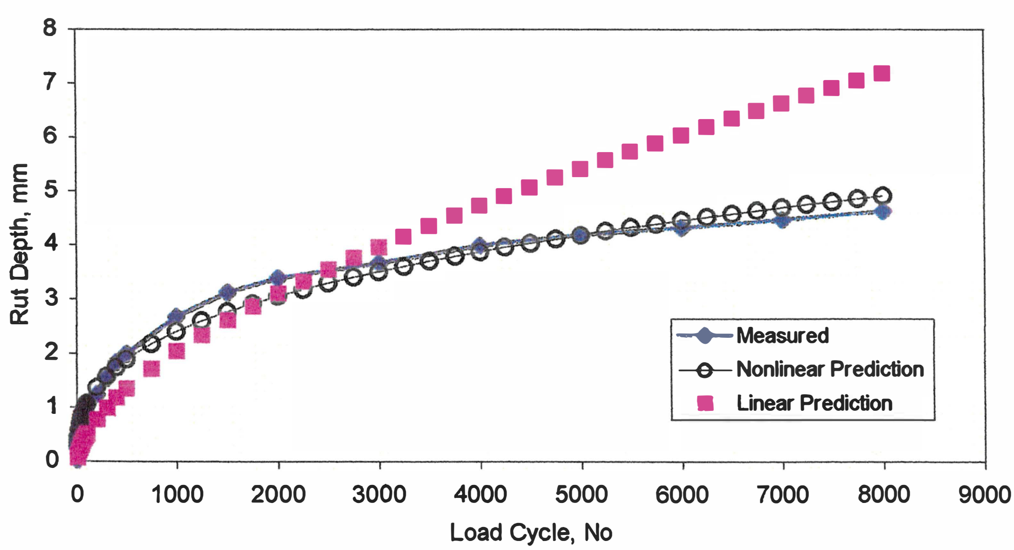

Figure 5.11 Prediction versus Measured Rut Depth for Binder S8-PG 64-22OK

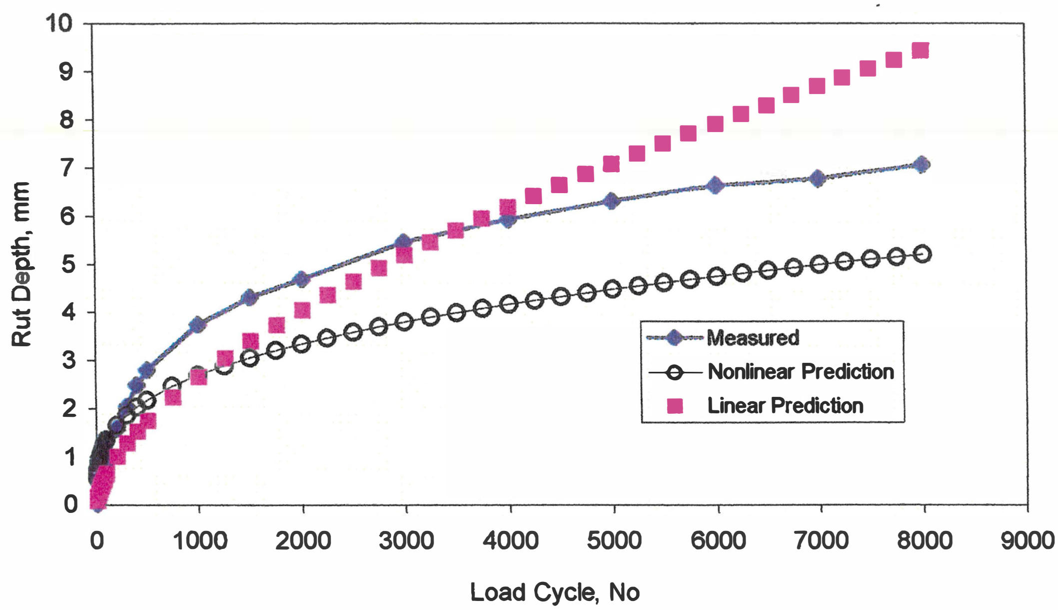

Figure 5.12 Prediction versus Measured Rut Depth for Binder S2-PG 64-22OK

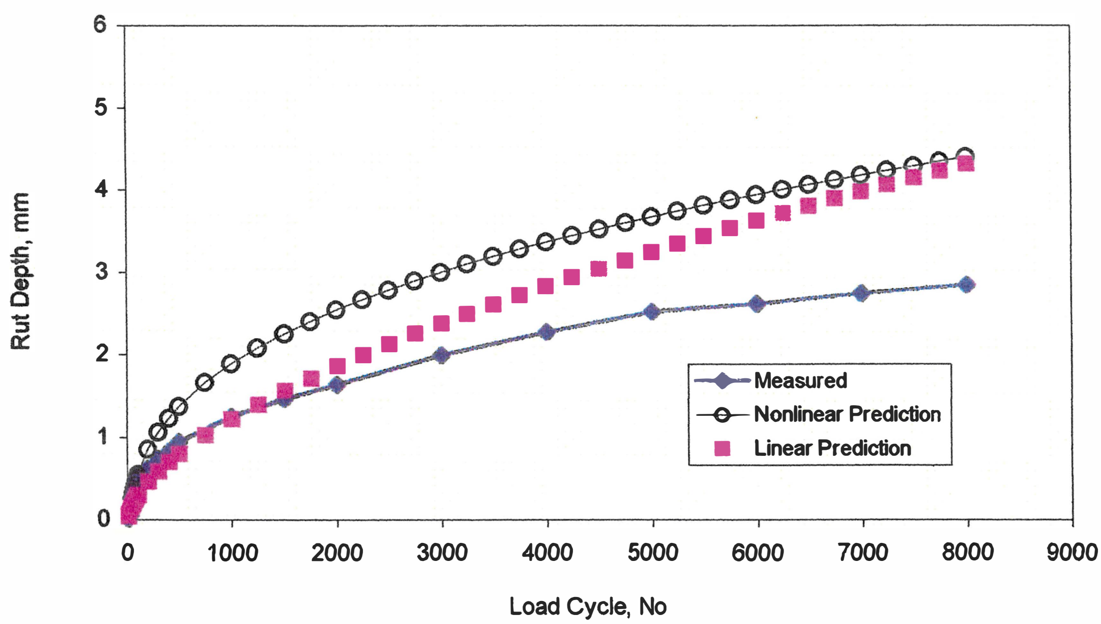

Figure 5.13 Prediction versus Measured Rut Depth for Binder S7-PG 70-28

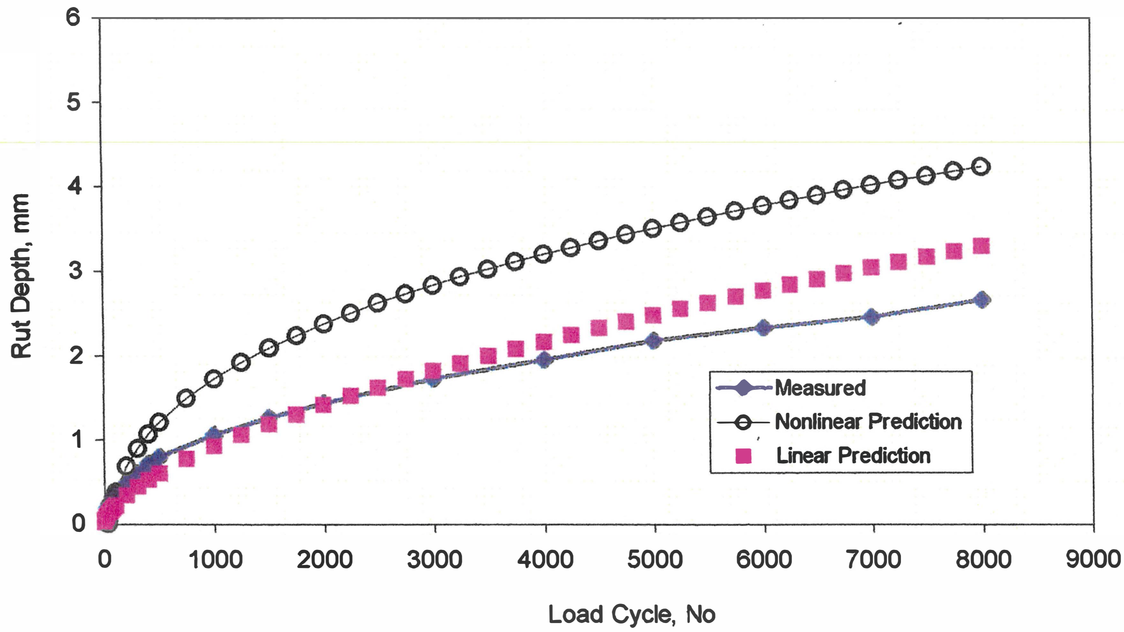

Figure 5.14 Prediction versus Measured Rut Depth for Binder S7-PG 76-28OK

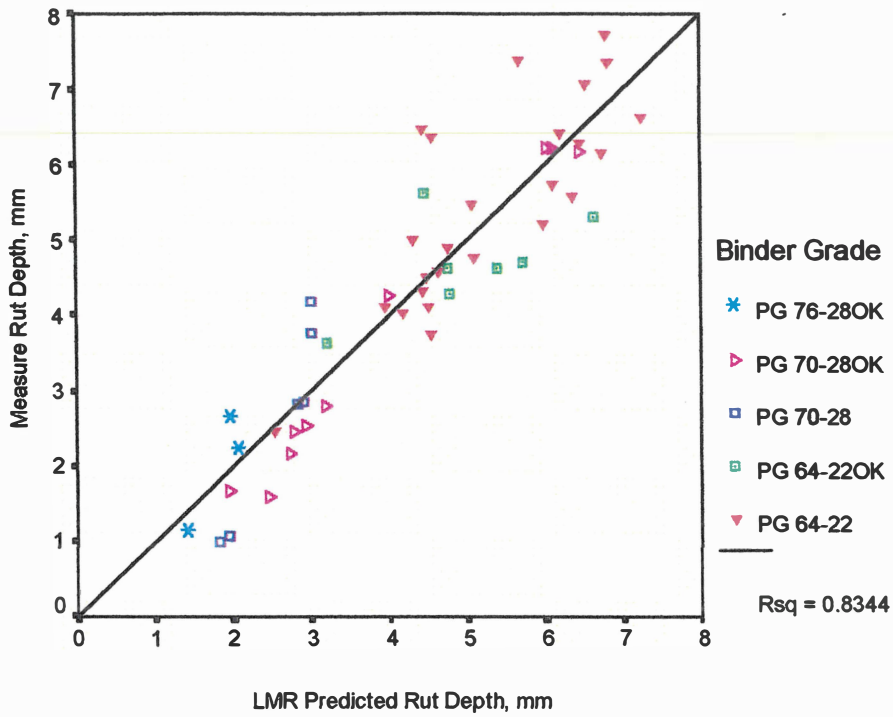

Figure 5.15 LMR Model Predicted 8000-Cycle Rut from 500-Cycle Rut

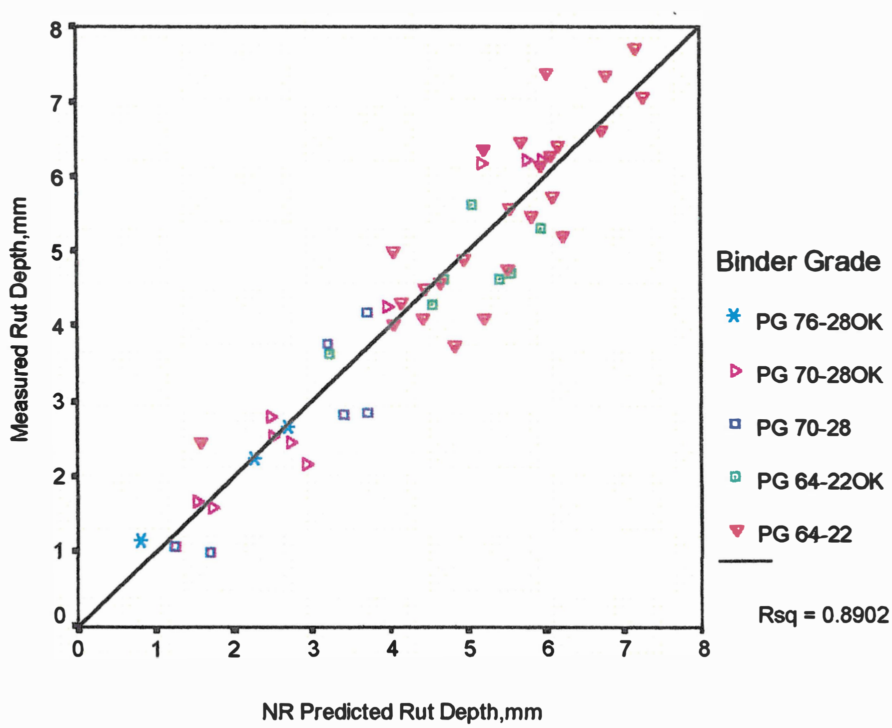

Figure 5.16 NR Model Predicted 8000-Cycle Rut from 500-Cycle Rut

Table 5.1 Properties of Unaged and RTFO Aged Binder

Binder Type	Binder Source	Binder PG	Specific Gravity	Viscosity $(R_v)^a$	$^b(G^*/\sin\delta)_{unaged}$	$^b(G^*/\sin\delta)_{RTFO}$	% Increase $(G^*/\sin\delta)$
Unmodified	S1	PG 64-22	1.0152	0.47	1.58	3.60	128
	S2	PG 64-22	1.0315	0.45	1.55	3.33	115
	S3	PG 64-22	1.0254	0.61	1.74	3.59	106
	S4	PG 64-22	1.0159	0.63	1.27	3.33	162
	S5	PG 64-22 OK	1.0103	0.64	1.25	3.48	178
	S6	PG 64-22	1.0076	0.59	1.27	2.62	106
	S7	PG 64-22	1.0151	0.60	1.29	3.21	149
	S8	PG 64-22	1.0110	0.60	1.23	3.53	187
	S8	PG 64-22OK	1.0160	0.56	1.41	3.35	138
Modified	S7	PG 70-28	1.0122	1.11	1.40	2.64	89
	S7	PG 70-28 OK	1.0150	1.20	1.66	3.33	101
	S8	PG 70-28 OK	1.0087	1.17	1.45	3.58	147
	S7	PG 76-28 OK	1.0258	1.08	1.78	2.86	61

$^a 135^0$ C and 10 radian/second $^b G^*/\sin\delta$ at high PG temperature

Table 5.2 Aggregate Information

Material	Source	Type	% Used
5/8" Chips	Western Rock at Davis, Oklahoma	Rhyolite	35
Screening	Western Rock at Davis, Oklahoma	Rhyolite	35
Shot	Dolese Co. at Davis, Oklahoma	Limestone	20
Sand	Dolese Co. at Oklahoma City, Oklahoma	Quartz	10

Table 5.3 Blended Aggregate Properties

Properties	Measured	Required
L.A. Abrasion, % wear	23	40 Max.
Durability Index	74	40 Min.
Insoluble Residue (%)	68.7	40 Min.
Fractured Faces (%)	100	95/90 Min.
Sand Equivalent (%)	52	45 Min.
Fine Aggregate Angularity (%)	46	45 Min.
Specific Gravity (SSD)	2.639	
Absorption (%)	0.189	

Table 5.4 Volumetric Properties for Optimum Asphalt Content

Binder	Optimum AC	% V_a @ N_d	% VMA @ N_d	% VFA @ N_d	% G_{mm} @ N_i	% G_{mm} @ N_d
S3-G1	5.4	4.0	14.2	72.0	88.8	96.0
S8-G2	5.4	4.1	14.7	72.3	88.5	95.9
S7-G2	5.1	4.0	13.9	70.9	88.2	96.0
S2-G1	5.1	4.1	14.0	70.7	89.0	95.9
Superpave Requirement		4.0	14 min	65-76	Less than 89	96.0

Table 5.5 LMR Model Summary

Model	Independent Variables (Predictor)	R	R^2	Adjusted R^2	Std. Error of The Estimate
1	(Constant), LNCY	0.931	0.867	0.867	0.5989
2	(Constant), Ln (cycle), R_v	0.944	0.892	0.891	0.5409
3	(Constant), Ln (cycle), R_v, P_b	0.948	0.899	0.899	0.5219
4	(Constant), Ln (cycle), R_v, P_b P_{be}	0.950	0.902	0.902	0.5137
5	(Constant), Ln (cycle), R_v, P_b P_{be} DSR_u	0.951	0.905	0.905	0.5068
6	(Constant), Ln (cycle), P_b P_{be} DSR_u VFA	0.952	0.906	0.906	0.5038
7	(Constant), Ln (cycle), R_v, P_b P_{be} DSR_u, VFA	0.952	0.906	0.906	0.5039
8	(Constant), Ln (cycle), P_b P_{be} DSR_u VFA DSR_a	0.952	0.906	0.906	0.5031

Dependent Variable: Ln (RD. 1000)

Table 5.6 NR Model Summary Statistics

Source	DF	Sum of Squares	Mean Square
Regression	8	6456.02	807.00
Residual	1522	867.09	0.5697
Uncorrected Total	1530	7323.11	
(Corrected Total)	1529	4473.71314	
R squared = 1 - Residual SS / Corrected SS = 0.80618			

VI. RUTTING FACTOR

6.1 General

This chapter screened and evaluated the relative weights of parameters influencing rutting performance of a mixture. The objective was to identify the most significant factors. A fractional factorial design was employed to implement experiments and statistical analysis considering seven influencing parameters for rutting. Mixture rutting performance was determined in the Asphalt Pavement Analyzer (APA). Initially, seven rutting parameters for a Superpave mixture (limestone) were investigated in a two level-designed experiments in the laboratory. The included parameters were asphalt content, binder's grade, testing condition, temperature, compaction type, wheel load, and hose pressure. The test data were analyzed statistically. The results from this study showed that binder's Performance Grade (PG), specimen-testing condition (moisture sensitivity of mixture), test temperature, and sample type affects a mixture's rutting performance significantly. Wheel load, hose pressure and percentage asphalt content at their chosen levels were shown to be less significant when compared to other factors. A most likelihood value of rut depth under the influence of aforementioned significant factors at a specified level were also postulated and verified by confirmation experiments. Next, the study investigated two gravel mixtures with five rutting parameters at different levels. Identical statistical approaches were used to evaluate these parameters. Wet condition, temperature and gradation were found to be significant. Rutting was highly affected by the introduction of moistures for all cases.

6.2 Background

Rutting is influenced mainly by loading, environment and time dependent material behavior under loading, especially, cyclic loading. A list of factors affecting rutting in flexible pavement is shown in **Table 6.1a** and **Figure 6.1a**. A detail discussion of the factor list is given below:

6.2.1 Loading

It is an important factor for rutting. Overstressing of the underlying pavement layers due to heavy loading is considered as a significant cause of rutting. The contact area between the tire and the pavement increases with increasing wheel load and decreasing tire pressure. The average stress under the wheel is not proportional to the contact stress. Again, the actual traffic does not move in a single wheel path, but is laterally distributed over the traffic lane. Some of the material that is pushed sideward to the lateral swelling is also pushed backwards by the wheel moving along the edge of the central wheel path. Corte, et al. (1997) found that the rutting magnitude was increased from 20 to 40% going from dual wheels to the singlewide wheels. Several traffic variables can influence rutting and some of those are listed below.

- Wheel load, axle load and total vehicle load.
- Number of load applications, and their sequence
- Vehicle speed
- Lateral and lane distribution of load
- Tire pressure
- Wheel configuration

High-pressure truck tires and increased wheel loads are primary causes of increased rutting. Studies by Middleton et al (1886) and Kim et al (1988) have shown that truck tire inflation pressures have increased substantially above the 482 to 551 kPa (70 to 80 psi). Hudson et al (1988) have shown truck tire pressures to be as high as 965 kPa (140 psi). Temperature is another major factor to influence rutting.

6.2.2 Material Behavior

HMA layer contains both asphalt binder and mineral aggregate. The properties of the individual components and how they react with each other in the system affect its behavior. The rutting performance of the HMA primarily depends on the properties of the mixture and not so much upon the individual properties of the binders or aggregate. There are occasions when the asphalt binder and aggregate are adequate but the mix fails to exhibit desired performance because of poor compaction, use of incorrect binder content, poor adhesion or some other problems associated with the mixture. Also, mixture properties alone are not sufficient to ensure satisfactory performance. The effect of the asphalt mixture, asphalt binder and aggregate on rutting is discussed in this section.

6.2.2.1 Asphalt Cement Properties

Asphalt cement is a visco-elastic or thermoplastic material. Its consistency changes with temperature and rate of loading. Its properties can change during HMA production and can continue to change subsequently in service. Factors that contribute to age heardening are oxidation, volatilization, polymerization, thixotropy, syneresis, separation etc. The consistency (viscosity or penetration) of asphalt cement plays relatively small role in the rut resistance of HMA if well graded, angular and rough textured aggregates are used. Some increased resistance to rutting can be obtained by using stiffer (high viscosity or low penetration) asphalt cements. However, stiffer asphalt cements are more prone to cracking during winter in cold regions especially if they are used in the surface courses. The current specification uses a performance grade (e.g., PG 64-22) or viscosity grade (e.g., AC-30) notation for the selected binder. The physical properties remain constant for all performance grades, but the temperature at which these properties must be achieved varies from grade to grade depending on the climate in which the asphalt binder is expected to perform. For example, a PG 64-28 grade is intended for use in an environment where an average seven-day maximum pavement temperature of 64 ^{0}C and a minimum pavement design temperature of –28 ^{0}C, are likely to be experienced. Some states in the southeastern portion of the US have started to use higher viscosity AC-30 grade in place of AC-20 to improve the resistance of the mix to rutting (Roberts, et al., 1996).

6.2.2.2 Mineral Aggregate Properties

Shear strength dependent on aggregate properties-such as coarse and fine aggregate angularity, elongation, flatness and clay content etc. For an example, by specifying a sufficient angularity, it is possible to achieve a high degree of internal friction and thus, high shear strength for rutting resistance. Angular-shaped particles exhibit greater interlock and internal friction; hence, result in greater mechanical stability than do rounded particles. On the other hand, mixtures containing rounded particles, such as most natural graves and sands, have better workability and require less compactive effort to obtain the require density. This ease of compaction is not necessarily an advantage, however, since mixtures that are easy to compact during construction may continue to be densified under repeated traffic loading, ultimately leading to rutting due to low voids and plastic flow. **Button et al. (1990)** studied aggregate characteristic through creep-recovery performance of HMA mixture and concluded that the rutting susceptibility of the mixture increases dramatically when natural fine aggregate particles replace crushed particles for a given aggregate gradation. Aggregate gradation is perhaps the most important property of aggregate. It is the distribution of particle sizes expressed as a percent of the total weight and can be determined by sieve analysis. It affects almost all the important properties of a HMA, including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance, and resistance to moisture drainage. **Hughes and Maupin (1987)** reported that the binder type of asphalt concrete mixtures does not appear to be as important as the gradation of aggregates and possibly the type of aggregates in minimizing the early rutting of pavement. Aggregate gradation provides more sufficient aggregate interlock that is an effective way to improve the rutting response of the asphalt concrete pavements.

6.2.2.3 Mix Properties

The properties of asphalt mix depend on percent air void, asphalt content, asphalt to dust content and compaction effort. The Strategic Highway Research Program (SHRP) recommended that asphalt concrete mixes be designed based on maximizing the overall mechanical properties of the mix (Sherif, 1997). Air voids in asphalt concrete cannot bear stress. Lower air void content result in greater stiffness because it reflects a more homogeneous structure with better stress distribution. The fine-graded, 50-blow Marshall-designed mixes have experienced a significant number of failures due to rutting (Musselman, 1998). Aggregate properties have little effect on rutting when the void contents are low, but when the voids are above 2.5%, mixes with higher fractured face counts and more angular fine aggregate are more resistant to premature rutting (Cross and Brown, 1992)

The density of HMA mix is usually expressed as a percent of theoretical maximum density. Increased compaction, asphalt content, filler content or any method that reduces the void can achieve the required density. When voids filled exceed approximately 80% to 85%, the asphalt mixture typically becomes unstable and rutting is likely to occur. Therefore, it is important how the density is achieved. Satisfactory compaction effort on a properly designed mixture produces a mixture with shear strength, while modifying the mixture to reduce in-place voids will provide a mixture with low shear strength with a tendency for high permanent deformation. Filler materials (passing No. 200 sieve) fill the void in an asphalt mixture and lower the optimum asphalt content. Some filler is necessary to obtain the desired stability, but excess filler results in a mixture at optimum asphalt content that is brittle and which tends to crack. The asphalt content must be adjusted for higher filler contents; otherwise, rutting will occur. Filler characteristics also vary with the gradation of the filler. The filler smaller than 10 microns act as an extender of the asphalt cement since the thickness of most asphalt films in dense-graded HMA is less than 10 microns. The filler, larger than 10 microns act as an aggregate. If excessive amount of this larger sized mineral filler is present, the asphalt demand may increase because of increased VMA. Certain mineral fillers can increase the apparent viscosity of asphalt cement at 60 °C and thus make the mix more resistance to rutting. Therefore, care must be taken to consider not only the amount of mineral filler, but also its type and size in evaluating design mix **(Anderson, 1987).** Asphalt cement content is probably the single largest contributor to rutting in HMA. Higher asphalt content increase the percent density and the thickness of the binder film between aggregates, which results in lower stress in the binder but is not be good for rutting. High asphalt content in HMA results in insufficient compactive effort during mix preparation. **Barksdale (1973, 1987)** concluded that the permanent deformation in dense-graded asphalt concrete, caused by both densification and shear distortion, is directly related to the asphalt content and was not sensitive to the material types, the gradation of aggregate and the level of compaction used in mix design.

Another test parameter that can significantly affect test results is the type and compaction method of test samples (West 1999). The two predominant "types" of test specimens are cylinders and beams/slabs. Cooley et al (1999) evaluated the density gradients in terms of variation in air voids within samples common to the APA and compared the two types of compactive effort used for APA samples: vibratory and gyratory compaction. Vibratory compaction tends to result in more compaction at the top and less compaction at the bottom of samples. Gyratory samples showed less compaction in the top and bottom of samples and significantly more compaction were noted in the middle. The vibratory specimens exhibited greater variability throughout a given specimen than was observed in gyratory specimens (Cooley et al., 1999 and Masad et. al., 1999). They found that the sample type could also influence APA rutting.

6.2.3 Environment

Temperature, moisture, water table, frost can influence rutting. Among these, temperature has the greatest effect on rutting of HMA pavement. It was verified that if the temperature in the asphalt does not reach 30°C, no rutting is produced. When the temperature is close to 60°C to 65°C, the rut depth is doubled to the rut depth at 40°C to 45°C (Corte', et al., 1997). At high temperatures (e.g., > 100°C), asphalt cement acts almost entirely as a viscous fluid. At low temperature (e.g., < 0°C), asphalt cement behaves mostly like an elastic solid. Brown and Snaith (1974) studied the effect of stress, strain and temperature on the rutting of asphalt concrete triaxial specimen subjected to dynamic loading for both deviatoric and the confining stress. They reported temperature as a major rut causative factor. Moisture is another factor that contributes to rutting performance. Rutting rates accelerate when moisture-induced damage is observed. Moisture susceptibility of a mix can be determined by conducting tests for rutting susceptibility on both dry and preconditioned specimens. The precondition is achieved by vacuum saturating a sample and then subjecting the sample to static saturation under water for at least 10 hours. The preconditioned specimens are then tested under water in the APA. This method compares favorably with AASHTO T-283 (1996) standard procedure for evaluating moisture susceptibility.

6.3 Experimental Design

Four mineral aggregates consisting of 16 mm chips (5/8 inch), screenings, shot and sand were incorporated in a Superpave method of mix design to produce specimens for testing in this study. The aggregate information is listed in **Table 6.1**. In the experimental procedure, aggregates were evaluated and gradation tests were performed to obtain the desired blend that met all of the Superpave gradation criteria. The final blend gradation was plotted on the 0.45 power chart, as shown in **Figure 6.1,** which passes Below the Restricted Zone (BRZ) with a nominal maximum size (NMS) of 12.5 mm (1/2 inch). The blended aggregate properties are summarized in **Table 6.2.** Two different binders, PG 62-22 and PG 70-28, were used in this study. The Superpave method of mix design was used with roadway traffic levels of more than 3 and less than 30 million Equivalent Single Axle Loads (ESAL). The maximum number of gyrations, N_{max} was chosen to be 160 and the design number of gyrations, N_{design} was 100 (ODOT, 1999). Mixing temperature was kept at 163° C (325° F). Mixtures were aged at 149° C (300° F) for minimum of two hours but less than four hours. The optimum asphalt contents were determined. **Table 6.3** summarizes the optimum asphalt content of the two binders used in this study and volumetric properties as well as the Superpave volumetric criteria (AASHTO D PP3-00, 1998). Two gravel mixtures consisting of 25 mm (1 inch) rock, 19.0 mm (3/4 inch) chips, screenings and crushed gravel were also designed by varying the gradations as shown in **Figure 6.2**. Other design criteria such as average daily traffic, average high air temperature, mixing temperature etc. were the same as mentioned above. Cylindrical samples of 75 mm (3 inch) height were compacted with the SGC at target air voids of 6 to 8%. Beam samples of the same height were prepared with the AVC at the same target air voids. Samples were preconditioned either dry or wet for 10 hours before rut testing. For rut testing under water, samples were vacuum saturated to 55-75% saturation.

6.4 Identification of the Rutting Factors

HMA is a composite material composed of graded aggregates embedded in a matrix of asphalt cement that fills part of the space between the aggregate particles and binds them together. The properties of the individual components and how they react with each other in the system affects the behavior of a mix. There are occasions when asphalt binders and aggregates are adequate but the mix fails to exhibit a desired level of performance because of poor compaction, use of incorrect binder content, poor adhesion or some other problem or combination of problems associated with the mixture. Again, mixture properties alone are not sufficient to ensure satisfactory performance. A pavement material is subjected to three dimensional stress induced by repeated loads. This stress-response depends on the time or rate of loading, temperature, and material properties.

6.5 Selection of the Factor's Levels

Aggregate affects almost all the important properties of a HMA, including stiffness, stability, durability, permeability, workability, fatigue resistance, frictional resistance, and resistance to moisture drainage. Aggregate factor includes aggregate size (i.e., NMS of 12.5 mm [1/2 inch] or 19.0 mm [3/4 inch]), type (i.e., limestone or gravel), and shape (i.e., rounded or angular). The properties of asphalt mix depend on percent air void, asphalt content, asphalt to dust content and compaction effort. Mix factors includes percent air void (i.e., 4% or 7%), percent asphalt content (i.e., optimum, more or less than optimum), Voids in Mineral Aggregate (i.e., VMA of 15 or 18), mixture gradation (above, through or below the restricted zone). Asphalt cement is a visco-elastic or thermoplastic material. Its consistency changes with temperature and rate of loading. Binder factors include stiffness (i.e., soft or stiff binder), source (source A or Source B) and Performing Grade (i.e., PG 64-22 or PG 70-22). Load is also an important factor for rutting. Overstressing of the underlying pavement layers due to heavy loading is considered a significant cause of rutting. The contact area between the tire and the pavement increases with increasing wheel load and increasing tire pressure. The average stress under the wheel is not proportional to the contact stress. Load factor includes wheel load (i.e., 100 or 110 lb), hose pressure (i.e., 100 or 110 psi), and load repetition (i.e., 8000 cycles or 10000 cycles). Temperature, moisture, water table, and frost can also influence rutting. Among these, temperature has the greatest effect on rutting of HMA pavement. Environmental factors include temperature (i.e., 60° C, 62° C or 64° C, 66° C), testing condition (i.e., wet or dry), and aging (i.e., no aging, short term aging or long term aging). The sample type (i.e., AVC for beam samples or SGC for cylindrical samples) also influences laboratory rutting.

6.6 Optimization of the Test Matrix

Seven factors were incorporated into orthogonal arrays of L_8 balanced design (Kyle, 1995). Designations for orthogonal arrays include the letter 'L' first then the subscript number second. The subscript after the L denotes the number of trials that must be executed in a given design. For example, in an L_4 array, four trials would be required to complete the experiment. It was decided to explore the following seven factors: wheel load, hose pressure, test temperature, test condition, sample type, asphalt content and binder's grade (see **Table 6.4** for details). Each factor in the array was compared to all other factors in equal number of times. The selected factors were assigned to the designed array, as shown in the **Table 6.5** to develop experimental matrix**. Table 6.6** summarizes the rutting averages for two selected experiments. A total of 8 beam samples and 16 cylindrical samples were tested in accordance with the test matrix. **Table 6.7** summarizes the rutting averages achieved over two trial experiments. **Table 6.7** also summarizes the trials that need to be added together to obtain the Level 1 and Level 2 totals for each factor. This parameter is needed to calculate the sums of squares.

6.7 Analysis of Data

Consider factor F. In an L_8 array factor F or sample type is set at level 1 in trials 1, 4, 5, and 8. Therefore, calculation of F_1 at level sum is accomplished by adding together the totals for each of these trials as shown in **Table 6.8.** Level sums for other factors can be performed in a similar way.

Table 6.9 shows the level sum for each factor. The totals for each factor are also calculated and recorded in this table. The sum of level 1 and level 2 was equal to the total of the experiment. The next step is to perform the sums of squares (SS_x) calculation. The modified sums of squares were calculated by the following formula:

$$SS_x = \left(\frac{Level\,Sums^2_{Level1} + Level\,Sums^2_{Level2}}{n} \right) - \left[\frac{\left(\sum X_i\right)^2}{N} \right] \qquad (1)$$

where

SS_x = Sum of squares for factor x,

Level $Sum_{Level\ 1}$ = Level sum for factor x at level 1,

Level $Sum_{Level\ 2}$ = Level sum for factor x at level 2,

n = Sum of data points used in calculating the level sums for either level 1 or level 2, and

N = Total number of data points in the experiment.

Table 6.10 summarizes the sum of squares calculations for each factor and the total variation, SS_{Total}, in the experiment. This study adopted the simplest way that is to make a significant plot as shown in **Figure 6.3**. The SS_x for each factor are plotted in descending order of magnitude from the left to the right and points are connected by solid line. It is evident from the plot which factors are expected to have the greatest effect on the quality characteristic (i.e., the dependent factor) and which would not. The factors along the steepest section of the graph are the more important ones and those along the flat portion or the bottom of the slope are the least important. From **Figure 6.3,** factor A (i.e., binder's grade) was considered the most significant followed by factors F (sample type), and C (test temperature) and B (sample conditioning). All remaining factors, D (wheel load), G (percentage asphalt), and E (hose pressure), were not considered significant.

An Analysis of Variance (ANOVA) calculation was also performed. The premise of an ANOVA calculation is to compare the contribution by each factor to the explained variation to that of the unexplained variation (i.e., experimental error). The factors that had little or no effect on rutting were grouped. Factors that were grouped together were those calculated to have the smallest sums of squares. The factor that resulted from the

6.10 Gravel Mix

Five factors: wheel load, hose pressure, test temperature, test condition, mixture gradation were selected for evaluation in two-designed experiments of gravel mixture. The selected factors were assigned to the designed array, as shown in the **Table 6.13 and Table 14** to develop experimental matrices**.** Statistical analysis as described above was performed. From significance plot of **Figure 6.5 and Figure 6.6,** it is evident that the effect of wheel load and hose pressure can be neglected selected range of load and hose pressure. The gradation has the second highest effect on rutting among these five parameters. Results of the statistical analysis are summarized in **Table 6.15. The** confidence interval for gravel mixture with temperature level 60-64° C is CI = 11.55± 1.79 mm, where as CI = 11.53± 3.47 mm. This means that the predicted rutting value will be between 8.0 mm to 15.0 mm if the level of parameters in **Table 6.14** is used in APA rut testing. Predicted value will be 9.7 to 13.3 mm if the parameters in Table 13 are used. It is evident that gravel mixture has higher rut potential compared to the Superpave Mix. It was noticed that the gravel mixture during testing under water creates lots of uncoated fines or dust.

6.11 Conclusions

This study employed a factorial design for screening several APA rutting factors. Knowledge of underlying physics was used to choose the levels of factors. Seven factors were chosen to examine their relative effect on APA rutting. It was found that four factors out of nine have important effects on laboratory prediction of rutting for the case of the limestone mixture used in this study. Based on the results of this study, it was evident that the beam samples yielded collectively higher rutting in the APA under wet condition. A testing temperature of 64° C (147.2° F) with a PG 64-22 binder showed the highest average rut depth. Wheel load, hose pressure and asphalt content at their chosen level did not show any significant effects on rutting. However, the estimate of the effect of these insignificant factors on rutting is associated with setting the low and the high value of that factor. A prediction of rut depth for limestone mix using these significant factors was found to predict a rut depth between 8.6 mm to 9.7 mm and was verified by confirmation experiments. Two other test matrices were covered for gravel mixture. Gravel mixture passing through the restricted zone showed higher rut potential when compared to the rut potential of gravel mix passing below the restricted zone. From the test result, it was found that temperature affects significantly for the case of gravel mixture. For the case of gravel mixture, a lot of dust or fines produced during rut test under water. For some cases, aggregates under APA hose showed no coating for gravel mix under water testing. Therefore, stripping has to be investigated carefully before using any gravel mix in the field. The limitation of the study is that it has considered selected parameters with two selected levels. However, rutting can be affected by other parameters such as aggregates type, size, boundary and loading conditions in the test setup as well as other factor-levels not considered here.

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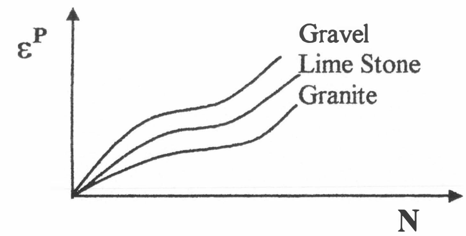
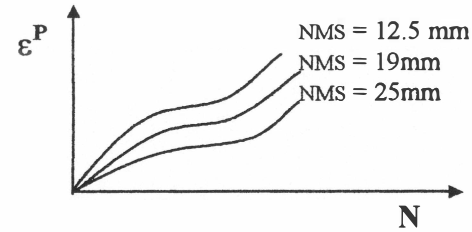
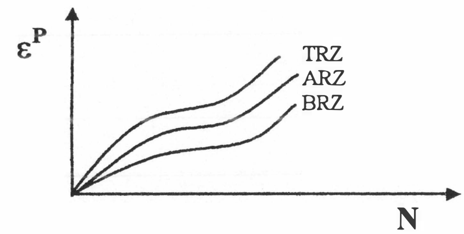
- **Type of Aggregate**



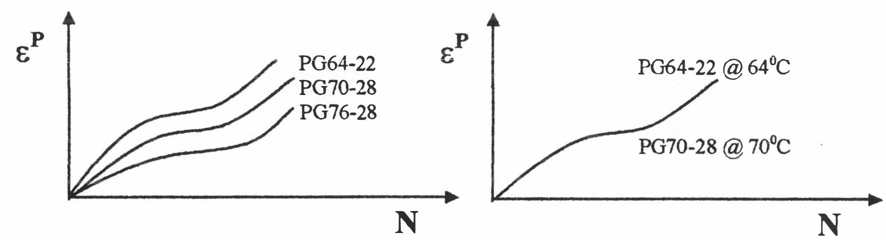
- **Nominal Maximum Size**



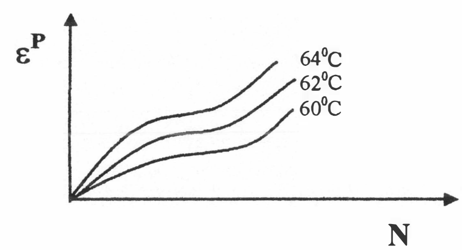
- **Gradation**



- **Binder Type**



- **Temperature**



- **Air Void Content**

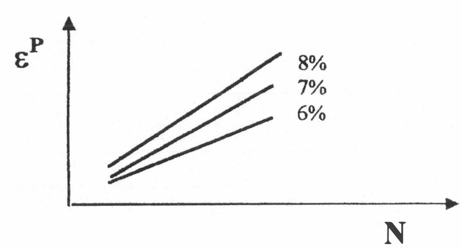
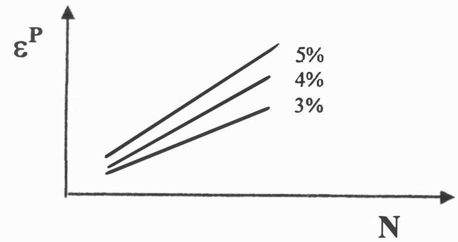
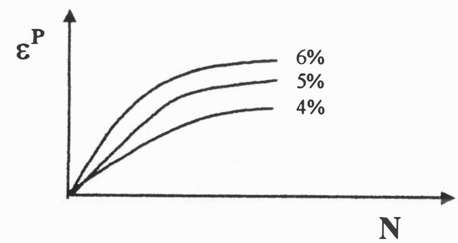


Figure 6.1a Factors Affecting Rutting (Fig. 6.1a continue)

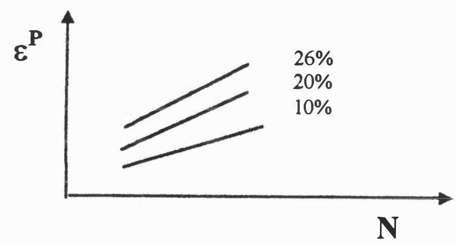
- **Dust Content**
Or Dust to Asphalt Ratio



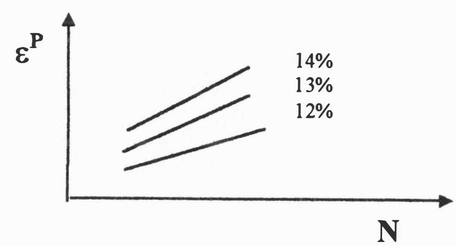
- **Asphalt Content**



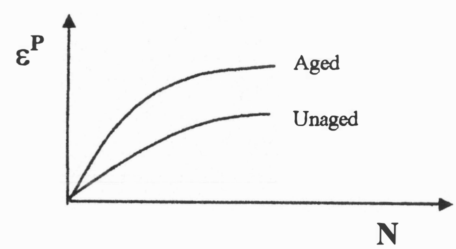
- **Natural Sand Content**



- **VMA *f*(NMS)**



- **Short Term Aging**



- **Compaction Temperature**

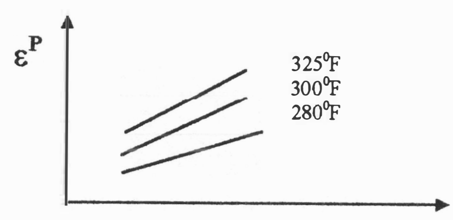
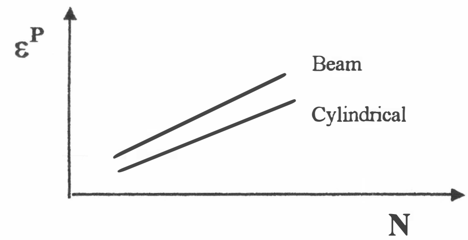
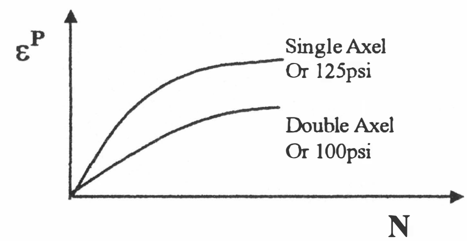


Figure 6.1a Factors Affecting Rutting (Fig. 6.1a continue)

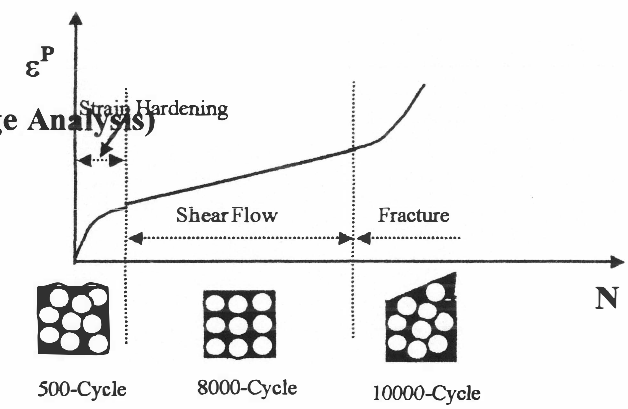
- **Sample Type**



- **Wheel Load**



- **Density gradient Analysis**
    1. **Particle orientation (Image Analysis)**
    2. **Mold Effect**
    3. **Specimen Geometry**



- **Other Factors**
    - **VFA *f*(Traffic level)**
    - **Effective Asphalt Content**
    - **Effective of Absorptive Aggregate**
    - **Effect of incorporating RAM**
    - **Compaction Energy (NG or vibration-time)**
    - **Hose Pressure**
    - **Specimen Conditioning**
    - **Manual measurement vs. Auto measurement**
    - **Seating Cycle**
    - **Fractured face**
    - **Fine Aggregate Angularity**
    - **Percent Passing Sieve No. 4 and No. 40**
    - **Specific Gravity of Binder (Source)**
    - **Liquid Antis trip (w/o lime)**
    -

Figure 6.1a Factors Affecting Rutting

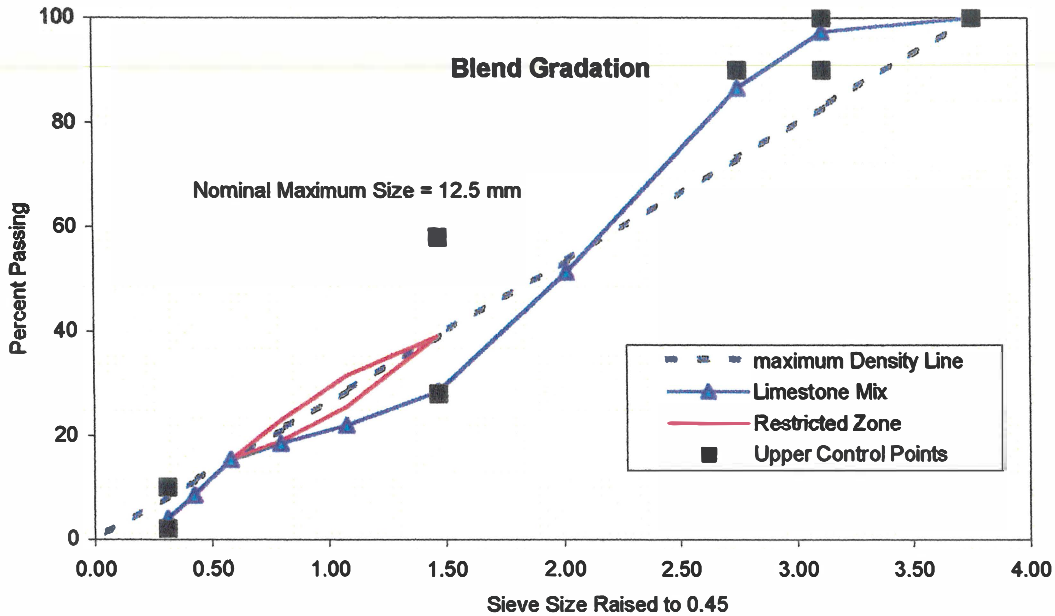


Figure 6.1 Blended Aggregate Gradation for Limestone Mix

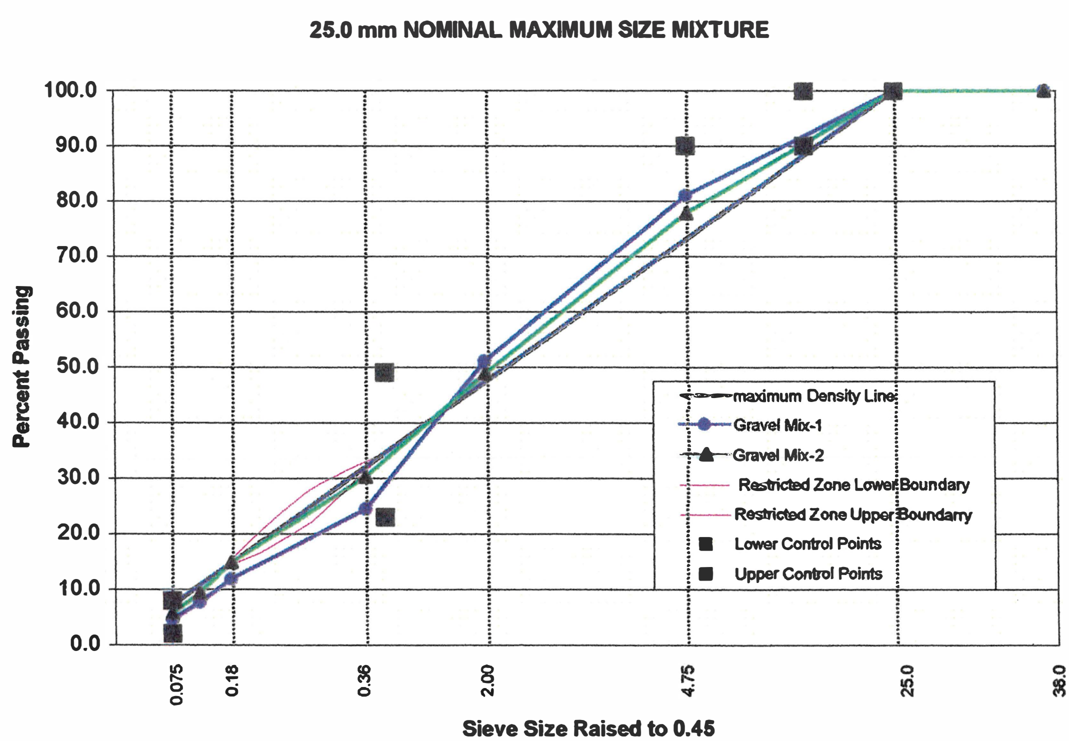


Figure 6.2 Gradation Curves for Gravel Mixes

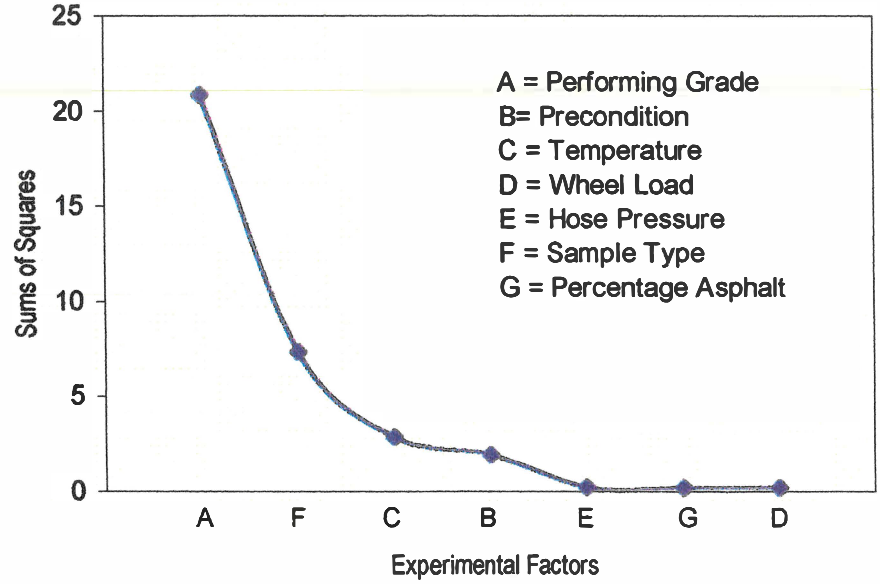


Figure 6.3 Significance Plot

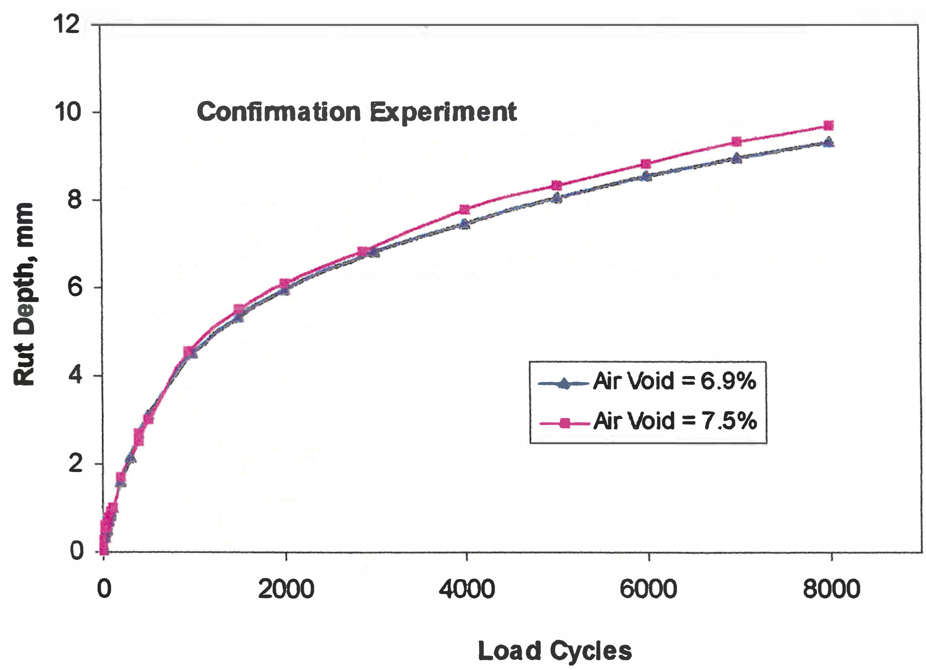


Figure 6.4 Typical Rut Depths versus Load Cycles in Confirmed Experiment

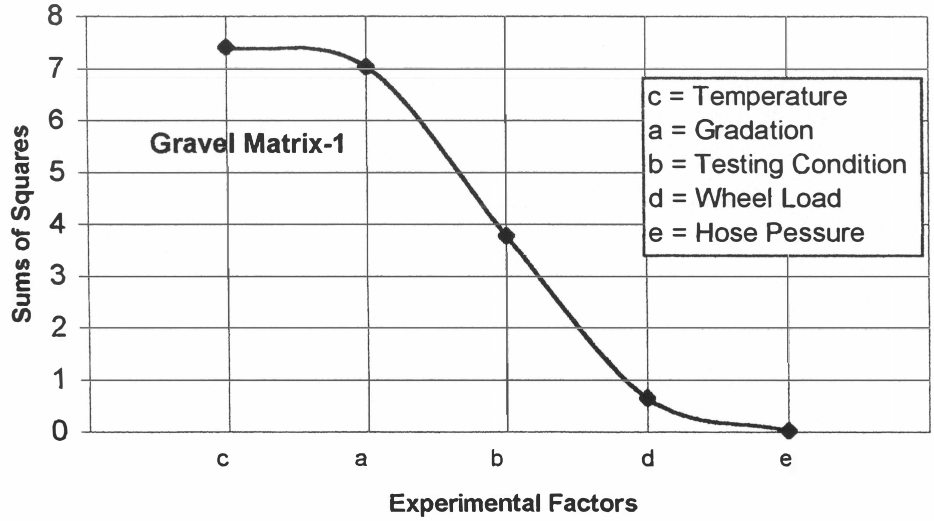


Figure 6.5 Significance Plot for Gravel in Matrix-1

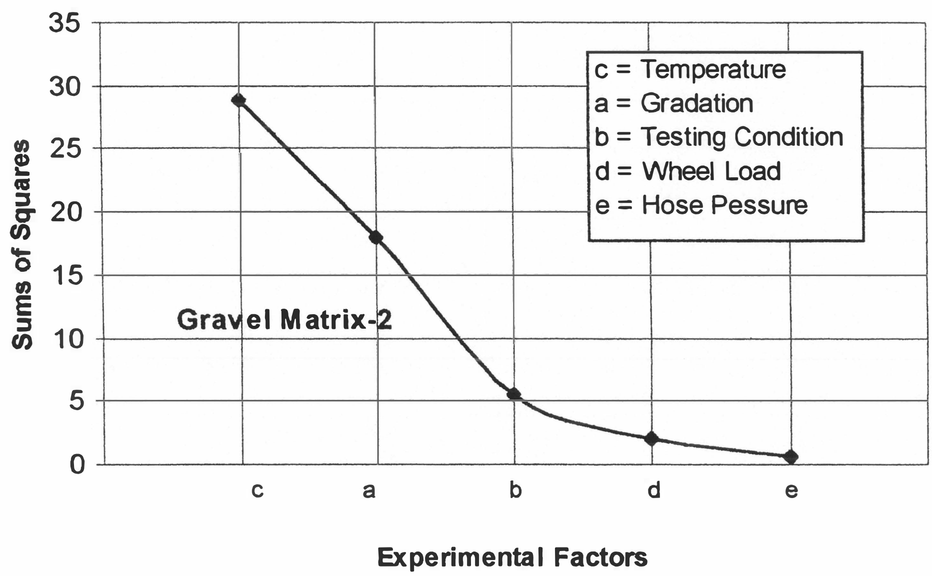


Figure 6.6 Significance Plot for Gravel in Matrix-2

Table 6.1a Factors Affecting Rutting

Traffic	Material	Environment
• Wheel load • Axel load • No of load repetitions • Tire pressure • Speed of vehicle • Lateral and lane distribution of load • Wheel configuration	• Aggregate angularity, fractured face, gradation, type, specific gravity • Asphalt Cement grade, Type • Mix air void, asphalt content, dust content, VMA, VFA, compaction	• Temperature • Moisture • Frost • Water table

TABLE 6.1 Limestone Mixture's Aggregate Information

Material	Source	Type	% Used
5/8" Chips	Western Rock at Davis, Oklahoma	Rhyolite	35
Screening	Western Rock at Davis, Oklahoma	Rhyolite	35
Shot	Dolese Co. at Davis, Oklahoma	Limestone	20
Sand	Dolese Co. at Oklahoma City, Oklahoma	Quartz	10

TABLE 6.2 Blended Aggregate Properties (Limestone Mixture)

Properties	Measured	Required
L.A. Abrasion, % wear	23	40 Max.
Durability Index	74	40 Min.
Insoluble Residue (%)	68.7	40 Min.
Fractured Faces (%)	100	95/90 Min.
Sand Equivalent (%)	52	45 Min.
Fine Aggregate Angularity (%)	46	45 Min.
Specific Gravity (SSD)	2.639	
Absorption (%)	0.189	

TABLE 6.3 Volumetric Properties for Optimum Asphalt Content

Binder	Optimum AC	% air @ N_d	% VMA @ N_d	% VFA @ N_d	% G_{mm} @ N_i	% G_{mm} @ N_d
PG 70-28	5.4	4.0	14.2	72.0	88.8	96.0
PG 64-22	5.1	4.0	14.0	70.9	88.2	96.0
Superpave Requirement		4.0	14 min	65-76	Less than 89	96.0

TABLE 6.4 Factor and Levels

Factor Number	Factors	Level 1	Level 2
1	Binder's PG	PG 64-22	PG 70-28
2	Sample Conditioning	Dry	Wet
3	Temperature	60^0 C	64^0 C
4	Wheel Load	100 lb	110 lb
5	Hose Pressure	100 lb	110 lb
6	Specimen Type	SGC cylinder	AVC beam
7	Percentage Asphalt	5.1	5.4

TABLE 6.5 Test Matrixes

Trial Number	Grade	Conditioning	Temperature (^{0} C)	Wheel Load (lb)	Hose Pressure (psi)	Sample	% Asphalt	% Air
1	PG 64-22	Dry	60	110	110	Cylinder	5.1	7.5
2	PG 64-22	Dry	60	100	100	Beam	5.4	7.3
3	PG 64-22	Wet	64	110	110	Beam	5.4	7.2
4	PG 64-22	Wet	64	100	110	Cylinder	5.1	7.0
5	PG 70-28OK	Dry	64	110	100	Cylinder	5.4	6.3
6	PG 70-28OK	Dry	64	100	110	Beam	5.1	8.0
7	PG 70-28OK	Wet	60	110	100	Beam	5.1	7.5
8	PG 70-28OK	Wet	60	100	110	Cylinder	5.4	6.3

TABLE 6.6 Experimental Total and Average Rut Depth

Trial Number	Grade	Conditioning	Temperature	Wheel Load	Hose Pressure	Sample Type	% Asphalt	Average Rut Depth (mm)
Factors	A	B	C	D	E	F	G	
1	1	1	1	1	1	1	1	4.952
2	1	1	1	2	2	2	2	6.823
3	1	2	2	1	1	2	2	9.426
4	1	2	2	2	2	1	1	6.960
5	2	1	2	1	2	1	2	2.677
6	2	1	2	2	1	2	1	5.177
7	2	2	1	1	2	2	1	4.235
8	2	2	1	2	1	1	2	3.174
								Total = 43.4

Note: 1, 2 are factor levels (Table 4)

TABLE 6.7 Trial Combinations for Calculating the Level Sums for Each Factor in an L_8 Array

Factor	Level 1	Level 2
A	1,2,3,4	5, 6, 7, 8
B	1,2, 5, 6	3,4,7,8
C	1,2,7,8	3,4,5,6
D	1,3,5,7	2,4,6,8
E	1,3,6,8	2,4,5,7
F	1,4,5,8	2,3,6,7
G	1,4,6,7	2,3,5,8

TABLE 6.8 Level Sums Calculation for Factor F at Level 1

Trial Number	Grade	Conditioning	Temperature (64^0 C)	Wheel Load (Lb)	Hose Pressure (psi)	Sample Type	% Asphalt	Average Rut Depth (mm)
	A	B	C	D	E	F	G	
1	1	1	1	1	1	**1**	1	4.952
2	1	1	1	2	2	2	2	
3	1	2	2	1	1	2	2	
4	1	2	2	2	2	**1**	1	6.960
5	2	1	2	1	2	**1**	2	2.677
6	2	1	2	2	1	2	1	
7	2	2	1	1	2	2	1	
8	2	2	1	2	1	**1**	2	3.174
								Total = 17.8

TABLE 6.9 Level Sums Table

Factor	Level 1	Level 2	Total (level1+level2)
Performing Grade (A)	28.2	15.2	43.40
Pre-conditioning (B)	19.6	23.8	43.40
Temperature (C)	19.2	24.2	43.40
Wheel Load (D)	21.3	22.1	43.40
Hose Pressure (E)	22.7	20.7	43.40
Sample Type (F)	17.8	25.6	43.40
Percent Asphalt (G)	21.3	22.1	43.40

TABLE 6.10 Sums of the Squares Calculations

Factor	SS	Significance
Grade	20.86	Significant
Sample Type	7.34	
Temperature	2.86	
Conditioning	1.94	
Hose Pressure	0.23	Insignificant
Percentage Asphalt	0.19	
Wheel Load	0.19	
SS_{Total}	34.64	
Error	0.61	

TABLE 6.11 Calculations of Variance, F Statistic and Percent Contribution

Factor	df_x (n_x-1)	SS_x	V_x	F (V_x/V_{err}) (Statistics)	F $(1,3)_{0.05}$ (Table)	SS'_x	P
Grade	1	20.86	20.86	417.20	10.1	20.71	59.79
Sample type	1	7.34	7.34	146.80	10.1	7.19	20.76
Temperature	1	2.86	2.86	57.20	10.1	2.71	7.82
Conditioning	1	1.94	1.94	38.80	10.1	1.79	5.17
Error (err)	3	0.15	0.05			Sum =	93.53
SS_{Total}	7	34.64	4.95				

TABLE 6.12 Parameters for Calculation of Predicted Results

Factor	Significance Level	Level Sum	Level Sum response
Grade	1	28.20	7.05
Sample Type	2	25.60	6.4
Temperature	2	24.20	6.05
Sample Conditioning	2	23.80	5.95
Total			43.4

Estimated Mean Response = 9.18

TABLE 6.13 Test Matrix-1 for Gravel Mixes

Trial Number	AC	BRZ/TRZ	Condition	Temperature	Load	Hose	Air	8000
1	4.5	BRZ	Dry	60	100	100	6.2	6.0
2	4.5	BRZ	Dry	64	110	110	8.7	7.1
3	5.5	BRZ	Wet	60	100	110	5.5	7.6
4	5.5	BRZ	Wet	64	110	100	5.5	11.4
5	4.3	TRZ	Wet	60	110	100	7.4	8.3
6	4.3	TRZ	Wet	64	100	110	7.1	11.3
7	5.3	TRZ	Dry	60	110	110	6.1	10.1
8	5.3	TRZ	Dry	64	100	100	7.0	9.9

TABLE 6.14 Test Matrix-2 for Gravel Mixes

Trial Number	AC	TRZ/ARZ	Condition	Temperature	Load	Hose	Air	8000
1	4.9	BRZ	Dry	62	100	100	6.1	4.8
2	4.9	BRZ	Dry	66	110	110	7.7	10.6
3	5	BRZ	Wet	62	100	110	7.9	5.3
4	5	BRZ	Wet	66	110	100	6.7	9.1
5	4.5	TRZ	Wet	62	110	100	7.6	7.6
6	4.5	TRZ	Wet	66	100	110	7.9	10.5
7	4.8	TRZ	Dry	62	110	110	6.3	10.5
8	4.8	TRZ	Dry	66	100	100	6.3	13.2

TABLE 6.15 Significant Parameters in Gravel Mixes for both Matrices

Factor	Significance
Gradation	Significant
Temperature	
Conditioning	
Hose Pressure	Insignificant
Wheel Load	

VII. REPEATABILITY AND REPRODUCIBILITY

7.1 General

It is not likely that an identical result will be obtained from the tests performed under presumably identical circumstances. The difference in results is due to unavoidable random errors inherent to every test procedure. In other words, the factors that influence the outcome of a test cannot all be completely controlled. For practical interpretation of test results, this inherent variability must be accounted for. Several factors may contribute to variability associated with the application of a test method. They include, the operator, the equipment, equipment calibration; and the environment.

An interlaboratory study was undertaken to determine whether the data collected are adequately consistent, to investigate data considered to be inconsistent and also to verify precision statistics. In the case of APA test procedure, the primary factor of concern is the sample preparation at a target level of air void. Other factors such as temperature, wheel load, and tire pressure can be controlled by proper calibration. A measure of the greatest difference between two test results would be considered acceptable when properly conducted repetitive determination are made on the same material by a competent operator. This is defined as "repeatability" or within laboratory precision (ASTM 670). It is the square root of the pooled average of within laboratory variances.

While "reproducibility" is a measure of the greatest difference that would be considered acceptable when properly conducted determinations are made by two different operators in different laboratories on portions of a material that are intended to be identical, or at least a nearly identical as possible. The reproducibility is the square root of the pooled average of between laboratory variances. The fundamental statistics underlying repeatability and reproducibility is the standard deviation (one sigma limit, 1s or difference two-sigma limit, d2s) of the population of measurements. In some cases it is appropriate to use the coefficient of variation in place of the standard deviation as the fundamental statistic. The results of two properly conducted tests from two different laboratories on samples of same material should not differ the value obtained from multiplying 1s or d2s by 2.828 (ASTM C 670).

7.2 Outlier

Outlier can be defined as discarding individual test results that appear to differ by suspiciously large amounts from the others. However, discarding of suspicious test results should be avoided unless there is clear reason that there was some physical reason to consider the result faulty. There is no purely statistical criterion be used for the purpose. In particular, laboratories should be asked to report all results in their proper place and include notes describing the conditions surrounding those results that are suspected of being faulty. Sometimes if a test really went wrong, a laboratory should discard the results and repeat the test. Tests should not be repeated, however, just because the results don't look good. The consistency statistics generated through the method may assist in the detection of outlying data (ASTM E691). For a single APA rut test, there are

3 sets of rut results from six samples. An outlier was imposed to these 3 sets according to OHD L-43 method. If the difference between any set and average of the set divided by the standard deviation of that set exceeds 1.155 then the result of that particular set is rejected.

7.3 Test Results

One of the limes stone aggregate (T.J.Campbell materials) was used for variability study. It was decided produced to batch aggregate from OU laboratory. The designed optimum asphalt content 5.1% was from the laboratory design. Batching was not performed from both laboratories because it might to many variables into a limited number of mixes. However, mixing was performed in both OU laboratory as well as ODOT laboratory. Total 24 samples were prepared; half of them were prepared in OU laboratory and half of them were in ODOT laboratory. Four combination of samples were tested namely, OU-ODOT, OU-OU, ODOT-OU, ODOT-ODOT for packing purpose. Half of the samples prepared at OU were tested at ODOT (OU-ODOT) and another half was tested at OU (OU-OU). Similarly, half of the samples prepared at ODOT were tested at OU (ODOT-OU) and another half was tested at ODOT (ODOT-ODOT). The test results are plotted in **Figure 7.1**. It can be seen that one result (average of two samples) for the case of (OU-OU) with air void of 6.9 % showed rut higher depth. Similarly, one result (average of two samples) for the case of (ODOT-ODOT) with air void of 7.5 % showed rut higher depth. A sample calculation for outlier is shown in Table 7.1. The critical value for student test (T-statistic) was taken as 1.155, If the calculated T-statistic value is greater or equal to this value then only one chance in one hundred that the value is from the same population as in the other (OHD L-43, 2001). It is to mention that there was no set to be rejected for all combination of tests by the outlier.

7.4 Data Analysis

Table 7.2 shows that the results of between and within analysis for the various sample tested. The table shows average and standard deviation for each combination of testing. It is evident that the results of sample prepared at OU and tested at ODOT (combination, OU-ODOT) differ radically compared to the other combinations. The combination OU-ODOT has 10 times higher than the second highest variance. Therefore, the data obtained from this combination is excluded. Therefore, outlier applied in OHD 43 has to reinvestigate. **Table 7.2** also shows one sigma limit (1s) or coefficient of variation, which is an indication of variability.

The within laboratory or repeatability (1s%) is 2.6 to 5.5. Therefore, results of two properly conducted tests by the same operator on the same material should not differ by more than 7% to 15% (second last column of **Table 7.2**). The multilaboratory coefficient of variation has been found to be 15% to 45%. Therefore, results of two different laboratories on differ from each other by more than 45% of the average.

7.5 Conclusion

APA-induced rutting at OU was compared to APA induced rutting at ODOT in SGC samples representing common HMA designs. It is evident that the actual variability in measured rutting seemed to moreover be a function of variability in air voids for the sample set. Results generated with the APA were actually more consistent when test specimens comprising the sample set were compacted to more uniform air voids. Essentially, there were no significant difference in final rut depths obtained from Ou and ODOT laboratory. It was found that the test results repeatable and reproducible.

Acknowledgement

The author would like to express his deepest sense of gratitude and sincere appreciation to Kenneth Hobson, Reynolds Toney, Eric Robert and Jerry for their assistance, which enabled the completion of the task.

Reference

ASTM C 670, (1999) “Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials”, vol. 03.03, 1998.

OHD L 43, (2001). “Method of Test for Determining Rutting Susceptibility Using the Asphalt Pavement Analyzer”, Oklahoma Highway Department Laboratory Test No. 43. ODOT, OKC, Oklahoma.

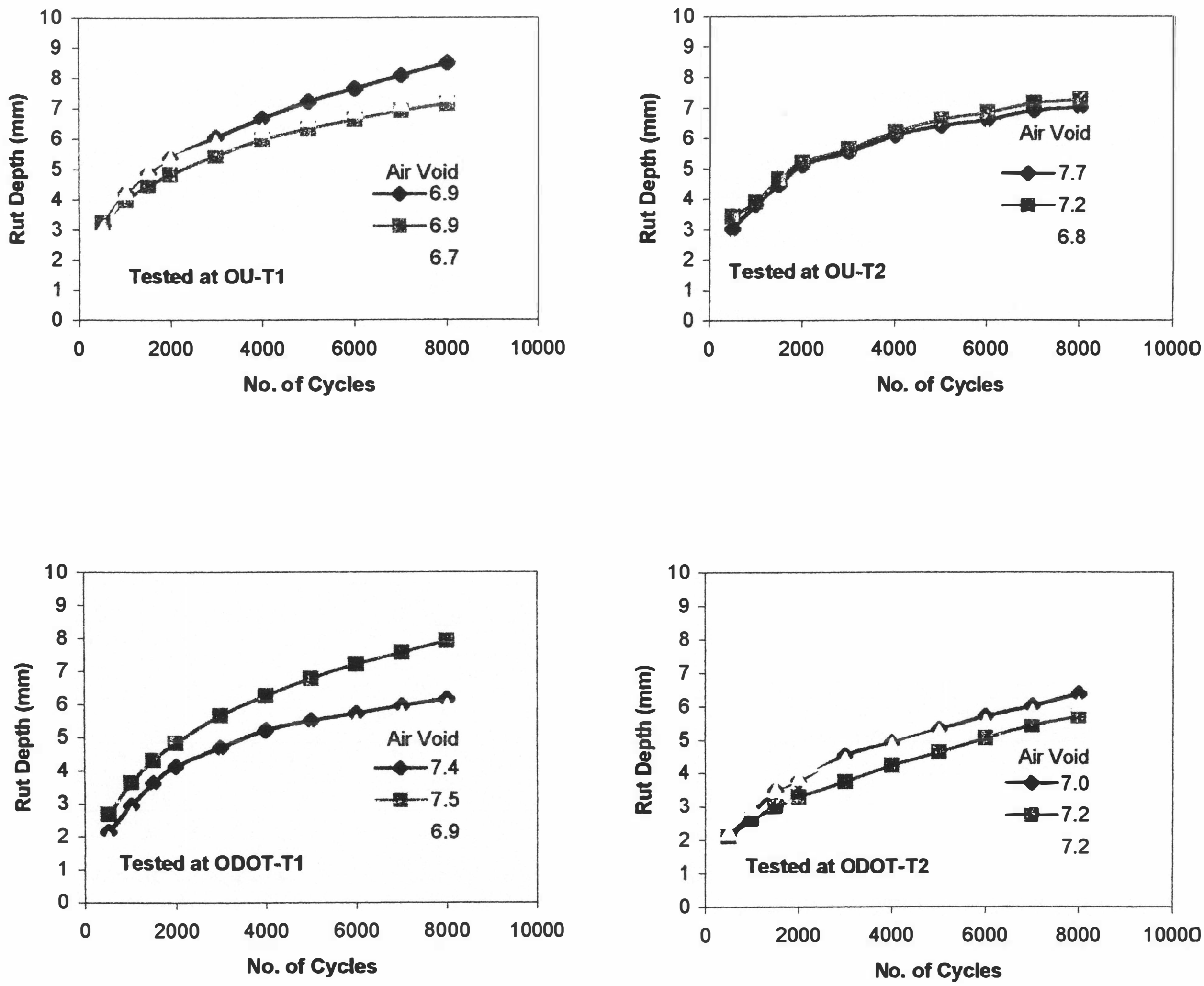


Figure 7.1 Rut Depths Versus Number of Cycles

Table 7.1 Outlier for Rut Depth Calculation

Sample	Rut	m	Outlier	Average
1	8.5033	1.124	8.5033	
2	7.1522	0.791	7.152	**7.71**
3	7.4755	0.333	7.4755	
Average	7.710	Note: m= (x-average)/stdev		
Std.	0.705	If m> 1.155 then throw		

Table 7.2 Between and Within Analysis for Rut Tests

Within Laboratory	**Specimen 1**	**Specimen 2**	**Specimen 3**	**Average**	**Stdev**	**Variance**	**Stdev* 2.83**	**1s%**
OU-OU	7.503	7.152	7.475	7.377	0.195	0.038	7.484	2.644
ODOT-ODOT	6.371	5.699	6.074	6.048	0.337	0.113	15.757	5.568
Between Laboratory	**Specimen 1**	**Specimen 2**	**Specimen 3**	**Average**	**Stdev**	**Variance**	**Stdev* 2.83**	**1s%**
ODOT-OU	7.012	7.265	6.596	6.958	0.338	0.114	13.740	4.855
OU-ODOT	6.162	7.92	5.961	6.681	1.078	1.161	45.650	16.131

Note: OU-OU means sample prepared at OU and tested at OU

Note: OU-ODOT means sample prepared at OU but tested at ODOT

Average = sum of n tests results for a particular combination divided by the specimen no.

Variance = sum of the squares of n test results for a particular combination minus n times the square of the average for that combination, divided by one less than the number of replicate test results.

1s% = (Standard Deviation x 100)/Average

VIII. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

This study evaluated rutting potential of Hot Mix Asphalt (HMA) concrete by laboratory predicted value of rut depth. APA in conjunction with SGC is capable of determining the rutting potential of HMA mixes. Rutting is a complex phenomenon, as evident from rutting literature. Many variables contribute to rutting and no one variable can adequately predict rutting. Much of the rutting can be attributed to improper mix design (mix gradation, binder grade and content, amount of filler material, aggregate shape and texture). Temperatures play a significant rule in rutting contribution of HMA. Each of these variables was considered in evaluating the rutting potential of HMA mixes. A series of tests was conducted considering the practical ranges of properties such as aggregate size, type, shape, texture, binder grade, mix gradation, density and temperature, etc. The tested data was analyzed using correlation analysis, linear regression analysis methods, and stepwise multiple variable analysis methods. The parameters, which have the greatest influence on rutting, were categorized. The laboratory testing suggested criterions to rank a HMA mixtures as poor, fair or good depending on the rutting magnitude. Binder's performance was evaluated by the corresponding mixture's rut performance. A linear and non-linear statistical model was developed for rut prediction. Nonlinear model showed better prediction compared to the linear model. The issue of repeatability and reproducibility was analyzed. APA test showed almost no variability between OODT and OU laboratory. The study developed a database for future model development.

8.2 Recommendations

Considering the complexity of the rutting problem, from the viewpoint of physics and mechanics involved, this study developed regression models based on laboratory test results. However, a realistic assessment of material properties, combined with computational feasibility calls for the development of a simple model that would capture all the fundamental behavior of HMA pavement with sufficient accuracy. It is recommended that neuron-based model will be an educated approach for including numerous parameters involved in rutting of HMA mixes.