Joint Transportation Research Program

JTRP

FHWA/IN/JTRP-97/13

Final Report

CONDITIONS FOR STRIPPING USING ACCELERATED TESTING

Changlin Pan
Thomas D. White

February 1999

Indiana Department of Transportation

Purdue University

Conditions for Stripping Using Accelerated Testing

Introduction

The objective of this study was to determine factors influencing asphalt mixture stripping/rutting potential. Two major variables were selected for the research, aggregate type and antistripping additive. These variables were used in the design of experiment to characterize the bituminous mixture performance relative to environmental factors such as moisture and temperature. Both AASHTO T-283 and the PURWheel laboratory wheel tracking device were incorporated into the study. Currently, mixture stripping potential in the Superpave system is evaluated with AASHTO T-283. The PURWheel device was developed specifically for the study.

Findings

Results from AASHTO T-283 tests indicate that moisture conditioning has a significant effect on the stripping potential of the seven mixes tested. That is, the tensile strength of the mixtures was reduced after the environmental procedures in AASHTO T-283 tests.

Comparison of the results for the two antistripping agents based on TSR indicates that hydrated lime is more effective than the liquid chemical anti-stripping agent. Hydrated lime produces a slightly higher tensile strength for the mixtures before and after moisture conditioning. The liquid chemical anti-stripping agent increased the tensile strength for the mixtures after moisture conditioning. In some instances, it also reduced the tensile strength for the mixture before moisture conditioning. Currently mixture stripping potential in the Superpave system is evaluated with AASHTO T-283 and adopts a minimum TSR of 80% as a design criteria. The reduction of the dry indirect tensile strength by the antistripping agent should be considered as a negative modifier effect.

Aggregate type has a significant effect on the wheel rack test results. Limestone and slag generally provided better performance than other types of aggregate in this study. Examination of the PURWheel performance of Indiana #11 surface mixture shows that a higher percentage of natural sand causes progressively poorer performance. This is not true for binder mixtures for the amount of natural sand utilized.

The antistripping agents did not affect the rutting resistance of mixtures significantly. However, a comparison of hot/wet and hot/dry test results indicates the moisture damage is associated with excessive deformation. Maximum aggregate size and mixture gradation both have significant effect on rutting resistance

A finite element program ABAQUS (ABAQUS, 1995) was used in this study to model the permanent deformation of mixtures in the PURWheel. The rutting phenomenon in the PURWheel was modeled through a reasonable approximation of loading and material properties. Results of model verification studies show that the creep model utilized can successfully characterize the pavement material behavior. Based on deformation data from the PURWheel tests, material parameters in the creep model were backcalculated. Good agreement was obtained between predicted and

measured deformation in APT tests of the same material.

FEM analysis shows that the effect of temperature can be modeled by a time dependent material model. Test results show the potential of the PURWheel as a performance test apparatus to evaluate the rutting resistance of asphalt mixtures. Through appropriate level of loading and a reasonable range of temperatures, the asphalt mixture permanent deformation can be predicted within a short period of time of testing. This test can be utilized as an evaluation tool for the Superpave mix design system.

Comparison of the TSR results for the 102 mm and 150 mm specimens indicates that 102 mm specimens are more sensitive to the current moisture conditioning procedures. Application of the 150 mm SGC specimen for AASHTO T-283 test still needs further evaluation before modification of the current test standard.

In this study, an Indiana #11 dolomite surface mix performed poorly in both wet and dry conditions. There is no question that the combination and gradation of the aggregates caused instability of the mixture. In a review of this mixtures in-place performance on Interstate highway I-64, the pavement exhibits similar distresses as the WTD test samples. Additional investigation is needed to complete the correlations of laboratory test results to actual field performance.

Implementation

Several implementable results were obtained from HPR-2086, Conditions for Stripping Using Accelerated Testing. The implementation results include recommendations to adopt the Purdue University laboratory wheel (PURWheel) tracking device, discontinue use of 150 mm diameter Superpave gyratory compacted cores for AASHTO T-283 tests until an effective conditioning protocol is identified, conduct additional research to identify an acceptable level of tensile strength in lieu of the tensile strength ratio in AASHTO T-283, and additional research on effectiveness of anti-stripping agents.

The PURWheel was developed with a primary goal of evaluating mixtures over a range of temperature in both wet and dry environments. Rutting results in wet conditions or a ratio of wet and dry results were projected as a means of evaluating mixture stripping potential.

For ease of use, a maximum wheel path rut depth of 10mm at 20,000 passes is recommended for hot/wet test conditions. For these test conditions, the sample is submerged in water. Recommended test temperatures were 60°C for surface mixtures (9.5mm) and 57.5°C for intermediate mixtures (12.5mm and 19mm).

The study also included a significant number of PURWheel tests of hot mix asphalt (HMA) mixtures in hot/dry conditions. These results indicated that the dry rutting performance reflected the effects of a number of HMA mixture factors. The PURWheel proved to be an effective tool for evaluating HMA mixture stripping potential in a hot/wet environment. As well as exhibiting potential for evaluating HMA mixture hot/dry rutting potential. Consequently, it is recommended that the Indiana Department of Transportation (INDOT) fund development of a PURWheel device for use in the Division of Materials and Tests laboratory.

The study also addressed AASHTO T-283 *"Resistance of Compacted Bituminous Mixtures to Moisture Induced Damage"*. Tests were conducted to compare stripping characteristics of 102mm cores compacted with the Marshall effort to 150mm SGC compacted cores. Results indicated that the current conditioning is not effective for the 150mm cores. Comparison of tensile strength ratio (TSR) from AASHTO T-283 and PURWheel results indicate that the TSR does not reflect a mixture stripping/rutting potential as well as the PURWheel. As a result, recommendations were made to discontinue use of the 150mm SGC cores until effective conditioning is identified. In such future research a pass/fail test criteria is desired. Or, alternatively, it may be feasible to use 102mm diameter cores prepared with the SGC. An NCHRP study is currently underway to address this issue. If the NCHRP study is not successful in developing conditioning then additional research is recommended for that purpose.

In application of AASHTO T-283, a tensile strength ratio is produced. Mixtures not

sensitive to moisture are supposed to have a ratio higher than a certain value. Data from the study indicates that anti-stripping agents may be achieving an increase of this ratio by lowering the "dry" strength more than the "wet" strength. Use of the ratio masks this effect which is not desirable. It is recommended that a minimum 600kPa "wet" tensile strength can be utilized.

A limited number of anti-stripping agents were incorporated in the study. Indications are that hydrated lime is a reasonably effective anti-stripping agent.

However, it is recommended that a greater number of liquid anti-stripping agents along with hydrated lime should be tested. An additional study is recommended that would utilize both AASHTO T-283 and PURWheel tests can be conducted to develop/verify minimum tensile strength as well as the allowable rutting criteria. There is also a need for research on long term performance of anti-stripping materials.

Contact

For more information:

Prof. Thomas D. White
Principal Investigator
School of Civil Engineering
Purdue University
West Lafayette IN 47907
Phone: (765) 494-2215
Fax: (765) 496-1364

Final Report

FHWA/IN/JTRP-97/13

CONDITIONS FOR STRIPPING USING ACCELERATED TESTING

by

Changlin Pan
and
Thomas D. White

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

School of Civil Engineering
Purdue University
West Lafayette, Indiana 47907

February 1999

1. Report No. FHWA/IN/JTRP/97-13	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Conditions for Stripping Using Accelerated Testing		5. Report Date February 1999	
		6. Performing Organization Code	
7. Author(s) Changlin Pan and Thomas D. White		8. Performing Organization Report No. FHWA/IN/JTRP-97/13	
9. Performing Organization Name and Address Joint Transportation Research Program 1284 Civil Engineering Building Purdue University West Lafayette, Indiana 47907-1284		10. Work Univ No.	
		11. Contract or Grant No. HPR-2086	
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	

15. Supplementary Notes

Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.

16. Abstract

A laboratory study was conducted to determine water sensitivity and rutting potential of asphalt mixtures. Two major tests were included in the study: AASHTO T-283 and a laboratory wheel tracking device (PURWheel). AASHTO T-283 has been adopted in the Superpave system for evaluating mixture stripping potential. The PURWheel device and test method was developed with the concept creating conditions associated with stripping, i.e. moisture, high temperature, and a moving wheel load. The laboratory wheel track tests can be conducted with hot/wet or hot/dry environments. The objective of the study is to determine the factors that most influence bituminous mixture stripping potential. The laboratory wheel tests can simulate mixture stripping conditions as well pavement loadings. Rutting potential with and without stripping, hot/wet and hot/dry environments, respectively, can be determined independently. The difference in rutting for the two environmental conditions indicates the magnitude of rutting associated with stripping.

PURWheel tests show the abilities of the machine to evaluate the rutting/stripping of asphalt mixtures under various temperature/moisture conditions. In a comparison of two Indiana #11 surface mixtures, limestone and dolomite, the limestone mix has a lower susceptibility to rutting than that of the dolomite mix at 50 and 60°C. Moisture damage was shown to occur over a range of temperatures from 60°C to room temperature.

Results of FEM studies show that the creep model can successfully characterize the pavement material behavior through a reasonable approximation of loading and material properties. Based on deformation data from the PURWheel tests, material parameters in the creep model were backcalculated. Good agreement was obtained between predicted and measured deformation in APT tests.

17. Key Words asphalt, mixtures, Superpave, stripping, AASHTO T283, wheel testing		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161	
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages 190	22. Price

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

IMPLEMENTATION REPORT

Several implementable results were obtained from HPR-2086, Conditions for Stripping Using Accelerated Testing. The implementation results include recommendations to adopt the Purdue University laboratory wheel (PURWheel) tracking device, discontinue use of 150 mm diameter Superpave gyratory compacted cores for AASHTO T-283 tests until an effective conditioning protocol is identified, conduct additional research to identify an acceptable level of tensile strength in lieu of the tensile strength ratio in AASHTO T-283, and additional research on effectiveness of anti-stripping agents.

The PURWheel was developed with a primary goal of evaluating mixtures over a range of temperature in both wet and dry environments. Rutting results in wet conditions or a ratio of wet and dry results were projected as a means of evaluating mixture stripping potential.

For ease of use, a maximum wheel path rut depth of 10mm at 20,000 passes is recommended for hot/wet test conditions. For these test conditions, the sample is submerged in water. Recommended test temperatures were 60°C for surface mixtures (9.5mm) and 57.5°C for intermediate mixtures (12.5mm and 19mm).

The study also included a significant number of PURWheel tests of hot mix asphalt (HMA) mixtures in hot/dry conditions. These results indicated that the dry rutting performance reflected the effects of a number of HMA mixture factors. The PURWheel proved to be an effective tool for evaluating HMA mixture stripping potential in a hot/wet environment. As well as exhibiting potential for evaluating HMA mixture hot/dry rutting potential. Consequently, it is recommended that the Indiana Department of Transportation (INDOT) fund development of a PURWheel device for use in the Division of Materials and Tests laboratory.

The study also addressed AASHTO T-283 *"Resistance of Compacted Bituminous Mixtures to Moisture Induced Damage"*. Tests were conducted to compare stripping characteristics of 102mm cores compacted with the Marshall effort to 150mm SGC compacted cores. Results indicated that the current conditioning is not effective for the 150mm cores. Comparison of tensile strength ratio (TSR) from AASHTO T-283 and PURWheel results indicate that the TSR does not reflect a mixture stripping/rutting potential as well as the PURWheel. As a result, recommendations were made to discontinue use of the 150mm SGC cores until effective conditioning is identified. In such future research a pass/fail test criteria is desired. Or, alternatively, it may be feasible to use 102mm diameter cores prepared with the SGC. An NCHRP study is currently underway to address this issue. If the NCHRP study is not successful in developing conditioning then additional research is recommended for that purpose.

In application of AASHTO T-283, a tensile strength ratio is produced. Mixtures not sensitive to moisture are supposed to have a ratio higher than a certain value. Data from the study indicates that anti-stripping agents may be achieving an increase of this ratio by lowering the "dry" strength more than the "wet" strength. Use of the ratio masks this effect which is not desirable. It is recommended that a minimum 600kPa "wet" tensile strength can be utilized.

A limited number of anti-stripping agents were incorporated in the study. Indications are that hydrated lime is a reasonably effective anti-stripping agent. However, it is recommended that a greater number of liquid anti-stripping agents along with hydrated lime should be tested. An additional study is recommended that would utilize both AASHTO T-283 and PURWheel tests can be conducted to develop/verify minimum tensile strength as well as the allowable rutting criteria. There is also a need for research on long term performance of anti-stripping materials.

CHAPTER 1 INTRODUCTION

Asphalt pavement permanent deformation is a significant distress relative to performance. The reason for excessive permanent deformation can be due to an increase in traffic volume, loads and tire pressure as well as environmental conditions, such as moisture and temperature.

Over the last few years state highway agencies have been increasingly concerned about bituminous mixture stripping. Stripping was suggested as a fourth distress type to be considered in the Superpave system. However, the position taken was that stripping distress could not be identified from the surface. In fact, stripping in the field can be identified by an experienced pavement engineer. Manifestation of traffic induced stripping is the appearance of rutting where the uplift and flow from shear failure centered on the wheel path has an irregular width. The distress may also appear as a localized shear failure. Stripping distress can be severe and develop quickly.

1.1 Problem statement

Stripping, according to Roberts, et al. (1991), is the result of the weakening or eventual loss of the adhesive bond of the asphalt from aggregate in the presence of moisture in a hot mix asphalt (HMA) pavement. This may occur from separation of the

asphalt film from the aggregate surface or from emulsification of the asphalt. In addition, loss of cohesion is another form of stripping. Loss of cohesion is the failure of the bond within the asphalt. Parker and Gharaybeh (1987) state that cohesive failure can increase a chance of adhesive failure.

Causes of stripping are related to moisture. A number of tests are used to determine the moisture susceptibility of an asphalt mixture. However, some of the test results are subjective, also, some of the tests have tenuous correlation with actual field performance. There is increasing interest in using a small-scale wheel tracking device to evaluate the performance of asphalt mixtures. With adequate control of temperature, moisture and wheel load, both rutting performance and moisture susceptibility of asphalt concrete can be examined using such a device.

This research work involves simulating the conditions for stripping of asphalt mixtures. Conditions include heat, moisture, and moving pneumatic wheel load. The Purdue Wheel Tracking Device (PURWheel) has shown potential for evaluating asphalt mixture stripping and rutting. Tests can be conducted on laboratory compacted specimens as well as specimens taken from in-service pavements. Several preliminary test results demonstrate that stripping can be created in laboratory controlled environments. Test data also show that stripping can be examined without subjective judgment.

1.2 Objectives and Scope

The goal of this study is to determine factors that influence asphalt mixture stripping/rutting potential. Two major variables were selected for the research, aggregate type and antistripping additive. These variables are used in the experimental designs to characterize the bituminous mixture performance relative to environmental factors such as moisture and temperature.

A laboratory study was undertaken to determine the moisture sensitivity and rutting potential of asphalt mixtures. Rutting, fatigue and thermal cracking are distresses usually considered in characterizing asphalt pavement performance. In fact, those are the distresses used in setting the Superpave mix design criteria. Currently, mixture stripping potential in the Superpave system is evaluated with AASHTO T-283 (AASHTO, 1995). Both AASHTO T-283 and the PURWheel laboratory wheel tracking device were incorporated into the research plan. The latter equipment was developed specifically for the study.

The report contains seven chapters. A review of literature on stripping of bituminous mixtures and accelerated wheel track testing devices is included in Chapter Two. Chapter Three presents discussion of materials and the experimental design. Chapter Four presents the laboratory testing procedures for AASHTO T-283 tests. Chapter Five presents the tests performed with the laboratory wheel tracking device. Chapter Six presents the finite element prediction model and the influence of testing temperature and moisture on the PURWheel test results. Conclusions and recommendations are presented in Chapter Seven.

CHAPTER 2 LITERATURE REVIEW

This chapter reviews the literature regarding causes of stripping and rutting, as well as the current literature used in moisture susceptibility tests. These tests usually involve subjective judgment or the ratio of physical properties (such as strength) to predict moisture susceptibility of the bituminous mixture.

2.1 Causes of Rutting

Rutting is the result of a permanent deformation in the pavement layers because of traffic loads. It can be divided into two stages. The first rutting stage is called the postcompaction stage. During this stage, void contents of hot mix asphalt (HMA) surfaces are reduced because of densification. After the initial stage, further rutting is caused by plastic flow of the asphalt mixture(Roberts, et al., 1991). According to Kruger et al. (1985), the rutting problem primarily falls into three categories:

1. Excessive traffic consolidation in the upper portion of the pavement,

2. Plastic deformation due to insufficient mixture stability, and

3. Instability caused by stripping of asphalt below the riding surface.

2.1.1 Effect of Load and Tire Pressure on Rutting Potential

In recent years, the effect of increased truck tire pressure has become an important issue in the performance of bituminous concrete pavements. A study by Roberts et al. (1985) showed that actual tire pressures are much higher than 90 psi (621 kPa) which are used in design procedures. He reported that the average tire inflation pressures were between 95 and 100 psi (655 to 690 kPa). Table 2.1 illustrated a nationwide survey of five-axle tractor semi-trailer truck tire inflation pressures (Okamoto and Packard, 1989). In this study, approximately 83% of the maximum rated tire pressures were between 95 to 110 psi (655 to 758 kPa). One reason for increasing tire inflation pressures is to reduce rolling resistance. Test data suggested that increasing tire inflation pressure by 10 psi (69 kPa) would result in a 2-1/2% decrease in rolling resistance and theoretically decrease fuel consumption 1%.

Increased tire pressure is related to increased asphalt pavement rutting and accelerated loss of serviceability. Bonaquist et al. (1988) concluded that the effect of increasing tire pressure from 76 to 140 psi (524 to 965.3 kPa) is equivalent to a 2,000 lb. (8.9 kN) axle load increase. This equivalency is for the fatigue damage of the pavement.

2.1.2 Effect of Temperature on Rutting Potential

Many bituminous pavements are experiencing premature and significant rutting even though the paving materials passed every current mix design criteria. Many

researchers associate this problem with properties of the binder. In bituminous concrete pavements, the binder (bitumen) is a temperature susceptible material because of its viscoelastic material characteristics. That is, the stiffness of bitumen can vary with respect to the change of temperature. The change in bitumen stiffness results in a stiffness change of the bituminous mixture. Huekelom and Klomp (1964) introduced the following equation to obtain the mixture stiffness if the bitumen is known.

$$S_m = S_b \left[1 + \left(\frac{2.5}{n} \right) \left(\frac{C_v}{1 - C_v} \right) \right]^n \tag{2.1}$$

where S_m = mix stiffness (kg/cm^2)

S_b = Bitumen stiffness (kg/cm^2)

$n = 0.83 \log_{10} [(4 \times 10^5)/S_b]$

C_v = Volume of aggregate/($V_{aggregate} + V_{asphalt}$)

Equation 2.1 is applicable for a bituminous mixture with air voids of about 3 percent and a C_v value between 0.7 and 0.9. Van Draat and Sommer (1965) recommended a modification to C_v such that,

$$C_v' = \frac{C_v}{1 - H} \tag{2.2}$$

and $\quad C_B \geq \dfrac{2}{3}(1 - C_v')$ $\hfill$ (2.3)

where H = Actual air voids -0.03

$\quad C_B = V_{asphalt}/(V_{aggregate} + V_{asphalt})$ $\hfill$ (2.4)

Decker and Goodrich (1989) indicated that a high viscosity bitumen resulted in a stiffer mix at a given temperature and loading rate. At high ambient temperature, bitumen viscosity is less important than its elastic modulus. Bituminous cement with high elastic modulus increases rutting resistance of the mix.

2.2 Causes of Stripping

In 1938, Hubbard wrote, "Stripping of asphalt from mineral aggregate surfaces in the presence of water is no new phenomenon in the field of highway engineering. It has been observed at times ever since asphalt paving came into existence." Stripping is the loss of the adhesive bond between the bitumen and the aggregate surface. The water accumulates between the asphalt film and the aggregate surface because of the hydrophilic characteristics of the aggregate. A Canadian publication (Pavement Management Systems Limited, 1983) included a specific list of factors causing stripping and they are as follows:

1. mineral and chemical composition of aggregates;

2. exposure history of aggregates (e.g. freshly crushed versus days of exposure to environmental weathering after crushing);

3. original properties of asphalt cement (physical and chemical);

4. modifications in bitumen cement during storage and handling;

5. interactions between individual aggregates, bitumen cements, and additives (if included);

6. water content in the mixes;

7. curing variables (e.g. time, temperature);

8. nature of water to which mix is exposed (salt content, pH);

9. bitumen content; and

10. special field variables (e.g. climate, construction quality, etc.).

Scherocman, et al. (1986) indicated that the coarse and fine aggregate characteristics are important factors related to moisture damage. There is some evidence that moisture damage can be minimal if stripping is restricted only to the coarse aggregate (Kennedy, et al., 1982). If the fine aggregate strips, severe damage can occur because the fine aggregate constitutes the basic matrix of the mixture.

Scherocman (1986) also stated that the air void content of the mixture can be another important factor related to stripping. At air void content greater than 6 percent, a given mixture can be severely damaged when subjected to moisture and traffic. As the air void content in the mix decreases down to 2-3 percent, the amount of moisture damage sustained by the same mix is also reduced since very little moisture can move through the mix at that air void ratio.

2.2.1 Mechanisms of Stripping

There are several ways that moisture can affect bituminous mixtures. Once moisture accesses the mix, the mix structure is weakened. The mix losses stiffness, and it fails under repeated traffic loading.

Taylor and Khosla (1983) listed five mechanisms for the asphalt film to be stripped from an aggregate surface. These mechanisms may act individually or together.

1. Detachment,

2. Displacement,

3. Spontaneous emulsification,

4. Pore pressure, and

5. Hydraulic scouring.

The last two mechanisms result from the moving traffic loads and usually happen underneath the pavement surface. It has been suggested by Gzemski, et al. (1968) that the role of traffic includes a mechanical separation of the asphalt film from the aggregate. They also suggested that traffic is directly related to the hydraulic scouring mechanism. According to Fromm (1974), high pore pressure can develop with densification of the paving mixture as a result of traffic loading. The high pore pressure in the mixture is associated with stripping.

An aggregate-asphalt interface thermodynamic stripping model has been presented by Gzemski, et al. (1968). It contains a three phase interface relation and is illustrated in Fig. 2.1. The binder can be spontaneously removed from the aggregate surface by one of two ways, illustrated in Fig. 2.2 and 2.3. The condition illustrated in Figure 2.2 is called the "roll-back" case and in Figure 2.3 the "lift-off" case. Expressions for the free energy change can be written as follows. For the "roll-back" case

$$\Delta F_1 = \gamma_{AW} - \gamma_{AB} - c_1 * \gamma_{BW} \qquad (2.5)$$

where ΔF_1 = free surface energy changes,

$\gamma's$ = the interfacial tensions for appropriate interfaces

c_1 = per unit change of destroyed bitumen-water interface/ per unit change of the other two destroyed interfaces and $c_1 < 1$.

For the "lift-off" case, the free energy change is

$$\Delta F_2 = \gamma_{AW} - \gamma_{AB} + \gamma_{BW} \qquad (2.6)$$

If the free energy changes given in Eq. (2.5) and (2.6) are negative, the process can occur spontaneously. These two equations also shows that when the interfacial

tensions are equal, the "roll-back" case of stripping is more likely than the "lift-off" case.

2.2.2 Influence of Aggregate on Stripping Potential

Aggregates mineralogical and chemical composition are important factors in the moisture susceptibility of a bituminous mixture (Roberts, et al., 1991). Aggregates are usually classified as being either hydrophilic (water loving) or hydrophobic (water hating). Hydrophilic aggregates, such as quartz and siliceous gravel, appear to have a greater affinity for water than for bitumen cement, and they tend to be acid in nature. On the other hand, hydrophobic aggregates, such as limestone and other carbonate rocks, are considered to be chemically basic and have a low silica content.

Aggregates surface physical characteristics such as texture and particle shapes have been shown to be related to the occurrence of stripping in bituminous pavements. Graf (1986) indicated that limestone aggregates have much longer Texas Freeze-Thaw Pedestal Test lives than dolomite aggregates. He mentioned that the dolomite appears as thin flakes of fairly uniform size, but the limestone includes a wide range of particle shapes and sizes with much less symmetry. Those factors promote more aggregate interlock resulting in an inherently stronger lattice.

2.2.3 Influence of Anti-Stripping Agents on Stripping Potential

Additives have been used for a number of years to reduce or eliminate bituminous mixture stripping problems. Tunniciff and Root (1984) define antistripping additives as "substances designed to convert the aggregate surface to one that is more easily wetted by asphalt than water".

Historically, hydrated lime has been incorporated in bituminous mixtures as an antistripping agent. The hydrated lime is added in amounts of 0.5 to 3 percent, replacing an equal amount of the mineral filler(minus No. 200 material). Calcium in the lime reacts with silicates in the aggregate (Kennedy, 1984). Two methods have been used to incorporate hydrated lime in bituminous mixtures. One method is to proportion the dry hydrated lime into the heated aggregate. A second method is to prepare a slurry with the lime. The slurry is mixed with the stockpile aggregates and left to condition. After a period of conditioning the stockpile is reworked and then proportioned into the bituminous plant.

Liquid chemical antistripping agents have also been used in bituminous mixtures. Their function is to improve adhesion between the asphalt film and aggregate. A number of such products are available. The liquid chemical antistripping agents are proportioned into the liquid bitumen. Results presented by Tunnicliff and Root (1984) indicated that chemical antistripping additives improved antistripping performance when added in amounts of 0.5 to 1.0 percent. No correction is made in the bitumen content for the amount of agent. A field performance evaluation of antistripping additives has been conducted by Tunnicliff (1997) including laboratory

tests and field condition surveys. Eight of nine additives successfully reduced the potential for stripping.

2.3 Laboratory Moisture Susceptibility Tests

A number of tests are used to evaluate moisture susceptibility of bituminous mixtures (White, 1987). In addition to AASHTO T-283 these tests are detailed in the following:

- NCHRP Report 192 (Lottman).

- NCHRP Report 274 (Modified Lottman).

- ASTM D 1075-81 (AASHTO T 165-82), "Effect of Water on Cohesion of Compacted Bituminous Mixtures".

- ASTM D 1664-80 (AASHTO T 182-82), "Coating and Stripping of Bituminous-Aggregate Mixtures".

- MIL-STD-620, Immersion-Compression Test.

Some of these tests are based on subjective evaluation of results. In general, the tests have a tenuous correlation with actual field performance. These tests are designed to capture the effects that cause stripping by addressing different modes of failure. Because of their low reliability, up to now, none of the tests have been adopted nationwide. It is important to have an effective test to objectively evaluate the stripping potential of bituminous mixtures and ensure they can resist various performance factors, i.e. heat, moisture, and moving load.

2.3.1 Immersion - Compression Test

In the Immersion-Compression Test (ASTM D 1075) the strength of compacted bituminous mixes is measured before and after moisture conditioning. The test involves applying a compressive load to the flat surfaces of the core (i.e. parallel to the axis of the core as a right cylinder). Six specimens are prepared and are separated into two groups of three specimens so that the average bulk specific gravity of both groups are approximately equal. One set of specimens is conditioned in a 50^0 C (120^0 F) water bath for four days and tested in compression at 25^0 C (77^0 F). The unconditioned group is tested dry at 25^0 C. The average compressive strength of each group and an Index of Retained Strength (IRS) are calculated. The asphalt Institute (1981) recommends that an IRS of 75 percent of greater be used as the acceptance/rejection criterion for the test.

Scheroman, et al. (1986) found that some antistripping agents can significantly increase the dry/unconditioned compressive strength of the samples. This results in a lower IRS ratio even though the wet/conditioned compressive strengths are satisfactory. Any test based on a relative wet/dry ratio can produce similar results.

2.3.2 Indirect Tension Test

The Indirect Tension Test involves determining the tensile strength of cylindrical specimens by using a diametrical compression test at a specified loading rate and temperature (Lottman, 1978). Like the immersion-compression test, the result is

based on a relative wet/dry retained tensile strength ratio (TSR). The moisture conditioning includes a vacuum saturation and a single freeze-plus-soak cycle (-18 to 60^0 C). Lottman recommends a TSR of 70 percent or larger to distinguish between moisture susceptible mixtures and moisture resistant mixtures.

This test method has been criticized as being too severe with regard to moisture conditioning (Tunnicliff and Root, 1982). This appears to be a procedural matter rather than a problem inherent in the test method. Tunnicliff and Root also recommend that moisture conditioning could be modified to match the actual climatic conditions.

McDaniel (1990), conducted a preliminary study to determine if the Root-Tunnicliff (Modified Lottman) test (1984) would be effective in evaluating stripping potential of mixes. The TSR results were highly variable. One aggregate in the study varied widely having the highest as well as the lowest values. According to McDaniel (1990), with further refinement, the test recommended by Lottman may provide quantitative correlation of moisture damage to the field performance of bituminous mixes.

2.3.3 Texas Freeze-Thaw Pedestal Test

This test method evaluates the moisture susceptibility of an bituminous mixture by determining the number of freeze-thaw cycles that a specimen can survive before cracking (Kennedy, et al., 1982). It uses a compacted cylindrical specimen, composed of a uniformly-sized fraction of aggregate, usually passing the 850 μm (No. 20) sieve

and retained on the 500 μm (No. 35) or 425 μm (No. 40), and 2 percent more asphalt than proposed for the job mix. The compacted specimen is sealed in a jar and subjected to freeze-thaw cycles (-23.3^{0}C to 60^0 C) until cracks can be observed on the surface of the specimen. Kennedy, et al. (1982) concluded that the dividing line between stripping-prone and stripping-resistant mixtures lies between 10 and 20 cycles to failure.

Scheroman, et al. (1986) indicated that the Texas Freeze-Thaw Pedestal Test primarily measures the cohesion or strength of the asphalt cement film itself rather than the adhesion of the asphalt cement to the surface of the aggregate. Bolzan (1989) suggested that it is necessary to modify the Freeze-Thaw Pedestal Test with a mechanical based procedure to simulate the traffic effects on the asphalt-aggregate bond.

2.4 Laboratory Accelerated Wheel Tracking Tests

There is increasing interest in using a small-scale wheel tracking device to evaluate the performance of bituminous mixtures. Some of the wheel tracking devices have already been used to evaluate pavement performance (Williams, 1996). Those include:

- Laboratoire Central des Ponts et Chaussees (LCPC) French Rutting Tester

- Georgia Loaded Wheel Tester (GLWT)

- Hamburg Steel Wheel Tracking Device (HSWT)

Their features and test conditions are shown in Table 2.2 to 2.4. These equipments provide a test method to evaluate the performance of bituminous mixtures. This is a very different approach than those currently used by most state highway agencies.

Aschenbrener, et al. (1992), indicated that wheel track testing requires 20 to 30 minutes to compact and approximately 6 to 9 hours to test one sample. They also describe laboratory wheel tracking tests as "torture tests".

According to Aschenbrener, et al. (1992), different criteria are used with each device to evaluate mixture performance. A successful test for the French Rut Tester is one with a rut depth that is less than 10% of the slab thickness after 30,000 cycles. The test criteria for the GLWT is a rut depth of 7.6 mm after 8,000 cycles. And, the criteria for the HSWT is a 4 mm rut depth after 20,000 cycles. Up to date, no comparisons of equivalency between the different test apparatus have been report (Williams, 1996).

Aschenbrener and Currier (1993) recommended that the test temperature for the Hamburg Wheel Tracking Device should relate to the temperature the pavement will experience. Table 2.5. lists recommended testing temperature as well as corresponding performance grade (PG) asphalt recommended by SHRP. They also recommended the air void contents on testing samples should be about $6 \pm 1\%$ air voids because the stripping inflection point is not significantly influenced by the air void content in this range. Or, no control is maintained on air void content of the specimen, replicate samples should be tested.

Table 2.1 Tire Pressure Survey Summary (Okamoto and Packard, 1989)

State (Year)	No.of Vehicles	Percent Radial Tires	Radials Average Psi[6]	Radials S.D.[7], Psi[6]	Bias Ply Average Psi[6]	Bias ply S.D.[7], Psi[6]	Overall Average Psi[6]	Overall S.D.[7], Psi[6]
Illinois [1] (1984)	36	-	-	-	-	-	96	11
Montana (1984)	-	-	105	-	84	-	-	-
Florida [2] (1985)	-	-	103	11	88	12	96	11
Kentucky[3] (1985)	59	74	105	11	90	10	103	13
Texas [4] (1986)	1033	71	98	14	85	15	94	15
Arizona (1986)	350	91	103	11	88	11	102	12
Oregon (1986)	-	-	102	-	82	-	-	-
Nationwide [5] (1987)	1008	-	-	-	-	-	97	14

1. Rear trailer axle only.
2. Average of steering and non-steering axle statistics for three sites.
3. Standard deviation estimated from grouped data.
4. AASHTO truck classification 3-S2.
5. Statistics estimated from grouped data.
6. 1 psi = 6.895 kPa.
7. S.D. = Standard Deviation

Table 2.2 Test Parameters of the LCPC French Rut Tester (Williams, 1996)

Parameter	Condition
No. of specimens tested simultaneously	Two.
Range of test temperature	35 - 60° C.
Environmental condition	Dry cycle testing only.
Maximum specimen size	Up to 100 x 160 x 500 mm.
Wheel types	Pneumatic only (up to 690 kPa tire pressure).
Wheel size	400 mm diameter, 90 mm wide.
Load	Up to 5000 N.
Frequency of measurement	User designated by setting a mechanical counter after every rut depth measurements.
Rut depth measurement location	Three locations centered ±90 mm about center of specimens.
Method of rut depth measurement	Manually placing "fingers" at new place of measurement.
Acquisition of data	Automatic.
Wheel speed	1.6 m/s.
Wheel wander	Wheel wander is not an option.

Table 2.3 Test Parameters of the Georgia Loaded Wheel Tester (Williams, 1996)

Parameter	Condition
No. of specimens tested simultaneously	Three.
Range of test temperature	40 - 60° C.
Environmental condition	Dry cycle testing only.
Maximum specimen size	Up to 17 x 125 x 300 mm.
Wheel types	Aluminum wheel on a pressurized hose (700 kPa hose pressure)
Wheel size	Not available
Load	Up to 445 N.
Frequency of measurement	User designated by setting a mechanical counter after every rut depth measurements.
Rut depth measurement location	Three locations centered ±50 mm about center of specimens.
Method of rut depth measurement	Manually adjusting a sliding table at place of measurement.
Acquisition of data	Automatic.
Wheel speed	0.6 m/s.
Wheel wander	Wheel wander is not an option.

Table 2.4. Test Parameters of the Hamburg Steel Wheel Tracking Device (Williams, 1996)

Parameter	Condition
No. of specimens tested simultaneously	Two.
Range of test temperature	Room Temperature - 60^{0}C.
Environmental condition	Wet cycle testing only.
Maximum specimen size	Up to 175 x 305 x 305 mm.
Wheel types	Steel wheel, 47 mm wide.
Wheel size	203.5 mm.
Load	Up to 697 N.
Frequency of measurement	Every 250 wheel passes.
Rut depth measurement location	Center of specimen.
Method of rut depth measurement	Automatic by linear voltage displacement transducers.
Acquisition of data	Automatic.
Wheel speed	Sinusoidal with a maximum of 0.33 m/s at the center of sample.
Wheel wander	Wheel wander is not an option.

Table 2.5 Recommended Testing Temperature for the Hamburg Wheel Tracking

Device, (Aschenbrener and Currier, 1993)

High Temperature. Category	Appro. Highest Average 7-Day Air Temperature	High Temp. Performance Grade (PG) ^{0}C	Asphalt Cement Grade Meeting the High Temp. PG	Recommended Test Temp. for the Hamburg Device
Very Cool	$< 27^0$ C	46	N/A	35^0 C
Cool	27 to 31^0 C	52	AC-5	40^0 C
Moderate	32 to 36^0 C	58	AC-10	45^0 C
Hot	$> 36^0$ C	64	AC-20	50^0 C
Very Hot	*	76	AC-20P	55^0 C

* No pavements in Colorado are at this temperature.
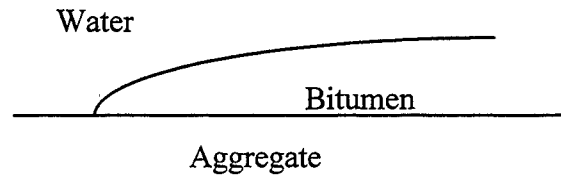
Figure 2.1 Schematic representation of Aggregate-asphalt interface model (Gzemski, et al., 1968)
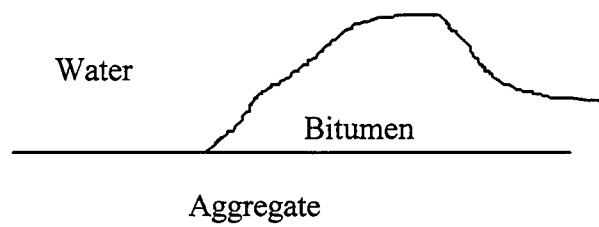
Figure 2.2 Schematic representation of "roll-back" interface model (Gzemski, et al., 1968)
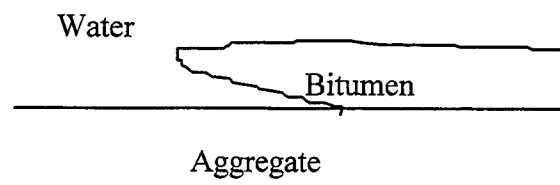
Figure 2.3 Schematic representation of "lift-off" interface model (Gzemski, et al., 1968)

CHAPTER 3 MATERIALS AND EXPERIMENTAL DESIGNS

3.1 Introduction

This chapter described materials, mix design results and experimental designs of the study. Different mixture types (i.e. surface, binder, and base) and aggregates commonly utilized in Indiana were included. Those mixes were also treated with hydrated lime and a liquid antistripping agent.

3.2 Materials

3.2.1 Asphalt and Aggregate

The asphalt cement incorporated in this study was an AC-20 (PG 64-22) from AMOCO, Whiting, Indiana. Table 3.1. lists test results for the asphalt and the INDOT (INDOT, 1995) asphalt specifications. The aggregate selection is based on resource availability in Indiana and represent a wide range of aggregate types. Aggregate characteristics and sources are listed in Tables 3.2. and 3.3, respectively.

3.2.2 Asphalt Mixtures

Seven asphalt mixtures were chosen for the study. They included three #11 surface mixes, three #8 binder mixes, and one #5C coarse gradation base mix. The difference between these mixtures is their nominal maximum aggregate size and gradation requirements. Fig. 3.1 through Fig. 3.3 show the gradations for the surface, binder, and base mixtures, respectively.

Mix designs were conducted using a seventy-five blow Marshall hand-hammer compaction effort. According to INDOT's criteria, optimum asphalt contents were selected solely on six percent air voids and to be within a range of acceptable asphalt content for different types of mixtures (INDOT, 1995). Otherwise, the mix design followed the procedure described in the Asphalt Institute Manual, MS-2 (Asphalt Institute, 1995). INDOT mix design criteria also includes a minimum stability of 545 Kg, and a maximum flow of 4 mm (0.16 in.). Voids in the mineral aggregate (VMA) requirements are a minimum of 15%, 13%, and 12% for the surface, binder, and base mixes, respectively. Summaries of mix design results are listed in Table 3.4. and Table 3.5. Each mix included 2 % mineral filler to represent fines expected to be generated in the mixture production.

3.2.3 Additive/Modifiers

Two anti-stripping additives were evaluated to examine their effects on moisture susceptibility of the mixes. A liquid anti-stripping additive, Pave-Bond Special, was used

as supplied by Morton International. The liquid antistripping agent was proportioned into the liquid asphalt (AC-20) at a 0.5 % dosage rate. No correction was made in the bitumen content for the amount of agent. Hydrated lime, obtained from a local hardware store, was also utilized. Two percent of hydrated lime was incorporated into the bituminous mixtures, replacing an equal amount of the mineral filler(minus No. 200 sieve).

3.3 Experimental Designs

From the literature review and preliminary research, the following factors were identified as significant for determining stripping/rutting potential of bituminous mixtures.

1. Mixture gradation and maximum aggregate size

2. Coarse crushed aggregate

3. Fine aggregate angularity

4. Aggregate type

5. Anti-stripping agent

In this study, the experimental design was focused on different types of aggregate and mix gradations. Most of the mixtures included an uncrushed natural sand as the fine aggregate source to emphasized rutting/stripping potential. The effect of anti-stripping agents can be easily examined if the mix is susceptible to stripping. As noted above, asphalt content for each mix was based on the Indiana mix design criteria and no

adjustment was made for the anti-stripping additive. Variation of asphalt binder was not included in this study.

Three levels of maximum aggregate sizes were included in this study, surface, binder, and open graded base course. These three levels were selected based on gradation requirements for HMA in the INDOT Specifications (INDOT, 1995). Each level contained three different types of coarse aggregate, except the open graded base course. Only limestone aggregate was utilized in the open graded base mixture because of limited availability of large aggregate.

Since AASHTO T-283 (AASHTO, 1995) has been recognized as a standard laboratory test, material variations and anti-stripping agents were the variables considered in the experimental designs. The matrix of tests in this experiment is shown in Table 3.6.

Table 3.7. and Table 3.8 show the matrix of tests for the laboratory wheel track tests. Seven different asphalt mixtures were tested to evaluate their rutting/stripping potential. Three of the mixes were also utilized to evaluate the effects of anti-stripping agents. Triplicate samples were prepared and tested to include the effect of sample variation. Two surface mixtures (dolomite and limestone) were tested over a range of temperature from room (25^0 C) to 60^0 C. These tests were conducted to determine the effect of temperature on the asphalt concrete mixture rutting/stripping potential. These two mixtures were selected because the aggregates are widely used in Indiana.

The goal of the experiments was to identify the influence of test variables on the results from the existing laboratory stripping test (AASHTO T-283) as well as the

laboratory wheel track test. It is important to evaluate how those variables change the performance of the asphalt mixture and to develop a standard laboratory procedure for the wheel track test.

Table 3.1 Binder Properties

Binder Properties	Test Result	INDOT Specifications, 902.01(g)-95
Specific Gravity @ 25^0 C	1.036	N/A
Flash Point (Cleveland), ^{0} C	288	232 minimum
Kinematic Viscosity @ 135^0 C, cSt	393	300 minimum
Absolute Viscosity @ 60^0 C (300 mm Hg vacuum), P	2165	1600 - 2500
Penetration @ 25^0 C, 100g, 5 sec	65	50 - 110
Solubility, %	99.9	99.0 minimum
Viscosity @ 60^0 C, P	5293	8000 maximum
Ductility @ 25^0 C, 5 cm/min, cm	110	40 minimum
Lost on Heat (T. F. O. T.)	0.25	N/A

Table 3.2 Coarse Aggregate Stockpiles

Agg. Size	12.5 mm			9.5 mm	25.0 mm			37.5 mm
Agg. Type	Limestone	Dolomite	Slag	Dolomite	Slag	Limestone	Gravel	Limestone
Agg. Source	Rogers, Kentland, IN	Charlestown IN	Gary, IN	Lockport, IL	Gary, IN	Rogers, Kentland, IN	W. Lafayette IN	Delphi IN
Sp. Gravity	2.655	2.614	2.350	2.680	2.339	2.653	2.615	2.650
Sieve Size	Percent Passing by Weight							
37.5 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
25.0 mm	100.0	100.0	100.0	100.0	100.0	100.0	100.0	91.4
19.0 mm	100.0	100.0	100.0	100.0	91.0	88.0	89.0	70.8
12.5 mm	100.0	100.0	100.0	100.0	55.0	48.0	53.0	38.4
9.5 mm	79.8	91.7	85.0	100.0	33.0	29.0	29.0	21.3
4.75 mm	17.0	15.7	20.0	23.0	8.0	6.0	2.0	3.3
2.36 mm	1.5	6.7	3.0	6.0	5.0	1.0	1.5	1.0
1.18 mm	0.0	6.0	1.9	5.5	4.5	1.0	1.0	1.0
0.6 mm	0.0	5.8	1.5	5.0	4.0	1.0	1.0	1.0
0.3 mm	0.0	5.6	1.3	4.0	3.6	1.0	0.7	1.0
0.15 mm	0.0	5.2	1.1	3.0	3.1	1.0	0.6	1.0
0.075 mm	0.0	3.9	1.0	2.0	2.6	0.5	0.3	1.0

Table 3.3 Fine Aggregate Stockpiles

Agg. Size	4.75 mm					Mineral Filler
Agg. Type	Man. Sand	Natural Sand				
Agg. Source	Rogers, Kentland, IN	Lafayette, IN	Lafayette, IN	Evansville, IN	Hunt Lake, IN	Swayzee, IN
Bulk Sp. Gravity	2.640	2.609	2.603	2.582	2.564	2.700
Sieve Size, mm	Percent Passing					
12.5	100.0	100.0	100.0	100.0	100.0	100.0
9.5	100.0	100.0	100.0	100.0	100.0	100.0
4.75	100.0	100.0	100.0	99.4	96.0	100.0
2.36	77.0	90.0	86.1	83.5	86.4	100.0
1.18	47.3	65.0	67.6	67	76.3	100.0
0.6	30.7	43.0	41.6	50.2	63	100.0
0.3	19.7	17.0	12.1	8.4	20	96.6
0.15	9,7	2.0	4.1	1.1	1.8	71.3
0.075	4.3	0.7	1.5	0.2	0.7	21.9

Table 3.4 Percentage of Stockpiles

Mixtures	Types of Agg. (Source)	% in the Mix	% of Mineral Filler
#11 Limestone	Limestone (Rogers)	47	2
	Natural Sand (W. Lafayette)	51	
#11 Dolomite	Dolomite (Charlestown)	45	2
	Natural Sand (Evansville)	53	
#11 Slag	Slag (Gary)	25	2
	Dolomite (Lockport)	25	
	Natural Sand (Hunt Lake)	48	
#8 Gravel	Gravel (W.Lafayette)	74	2.5
	Man. Sand (Rogers)	23.5	
#8 Limestone	Limestone (Rogers)	75.9	1.1
	Natural Sand (Lafayette)	23	
#8 Slag	Slag(Gary)	70	2
	Natural Sand(Hunt Lake)	28	
#5C Limestone	Limestone (Delphi)	83	2
	Natural (Lafayette)	15	

Table 3.5 Summary of Marshall Mix Design Results

	Rice Spec. Gravity	Stability (Kg)	Flow (mm)	VMA %	Optimum Asphalt Content, %
#11 DCM[1]	2.426	726	2.2	17.5	6.3
#11 LCM[2]	2.498	859	2.3	16.3	5.2
#11 SCM[3]	2.420	1453	2.3	16.5	6.2
#8 GCM[4]	2.521	1308	2.6	14.5	4.1
#8 LCM[5]	2.584	953	2.9	14.5	4.8
#8 SCM[6]	2.343	1875	2.3	13.2	4.3
#5C LCM[7]	2.568	1410	3.1	12.4	4.0

(1) #11 DCM :#11 dolomite surface mixture
(2) #11 LCM :#11 limestone surface mixture
(3) #11 SCM :#11 slag surface mixture
(4) #8 GCM   :#8 gravel binder mixture
(5) #8 LCM   :#8 limestone binder mixture
(6) #8 SCM   :#8 slag binder mixture
(7) #5C LCM :#5C limestone base mixture

Table 3.6 Experimental Matrix for AASHTO T283 Tests

Mixture Type	Aggregate Type	Additives/Modifier		
		Control	Hydrated Lime	Liquid agent
Surface Mixtures	Dolomite	X	X	X
	Slag	X	X	X
	Limestone	X	X	X
Binder Mixtures	Dolomite	X	X	X
	Slag	X	X	X
	Limestone	X	X	X
Base Mixture	Limestone	X	X	X

Table 3.7 Experimental Matrix for Laboratory Wheel Tests to Determine the Influence of Aggregate and Additives/Modifier

Mixture Type	Aggregate Type	Additives/Modifier					
		Control		Hydrated Lime		Liquid agent	
		Wet	Dry	Wet	Dry	Wet	Dry
Surface Mixtures	Dolomite	XXX	XXX	XXX	XXX	XXX	XXX
	Slag	XXX	XXX				
	Limestone	XXX	XXX				
Binder Mixtures	Gravel	XXX	XXX	XXX	XXX	XXX	XXX
	Slag	XXX	XXX				
	Limestone	XXX	XXX				
Base Mixture	Limestone	XXX	XXX	XXX	XXX	XXX	XXX

Table 3.8 Experimental Matrix for Laboratory Wheel Tests to Determine the Influence of Temperature

Aggregate Type	Test Temperature (^{0}C)									
	60		50		40		30		25	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Dolomite	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Limestone	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX

Figure 3.1 #11 Surface Mixture Gradations contains a chart titled with axes "Percent Passing" (y-axis, 0.0 to 100.0) and "Sieve Opening in mm (0.45 power)" (x-axis: 0.6, 1.18, 2.36, 4.75, 9.5, 12.5). The legend shows: Spec., Dolomite, Slag, Limestone, Spec.

* Spec.: Indiana Gradation Specifications (INDOT, 1995)

Figure 3.1 #11 Surface Mixture Gradations
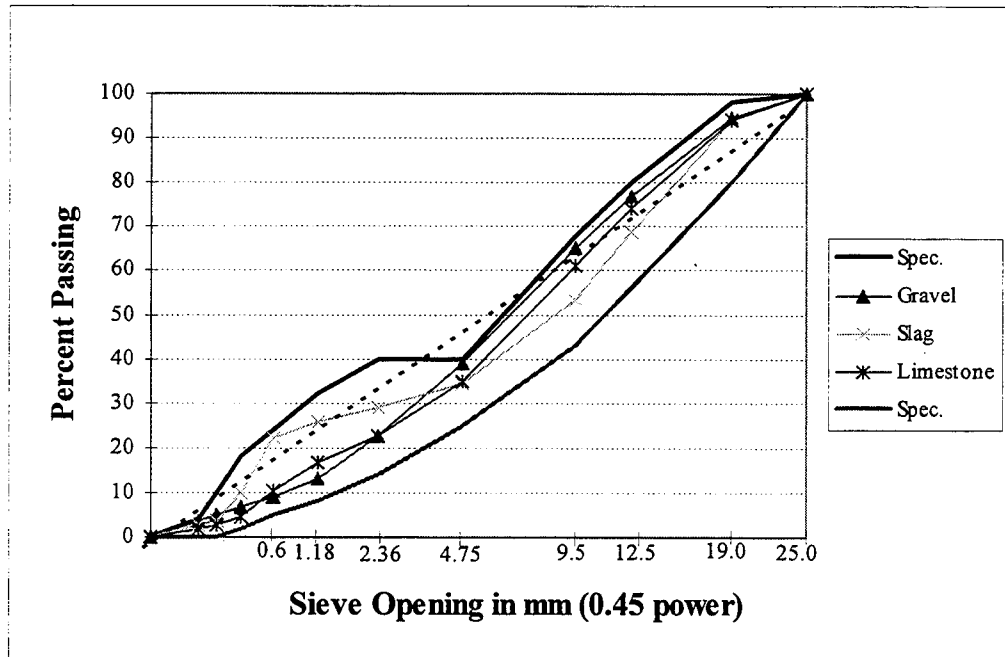
Figure 3.2 #8 Binder Mixture Gradations

* Spec.: Indiana Gradation Specifications (INDOT, 1995)
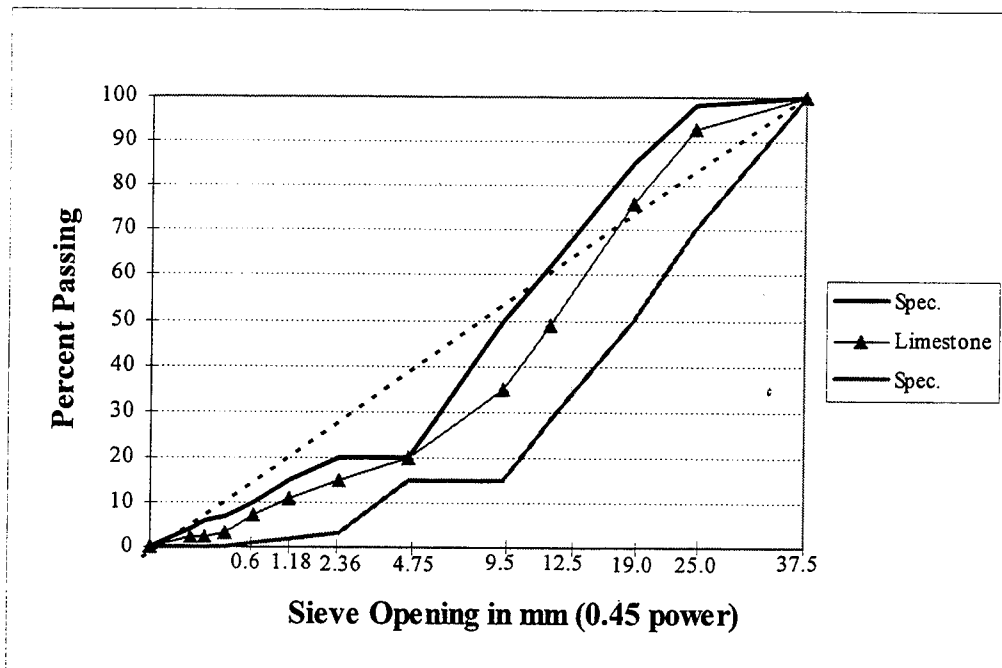
* Spec.: Indiana Gradation Specifications (INDOT, 1995)

Figure 3.3 #5C Open Gradation Base Mixture Gradations

CHAPTER 4 LABORATORY MOISTURE SENSITIVITY TESTS

There are several laboratory tests that have been used for evaluating moisture sensitivity of asphalt mixtures. Currently mixture stripping potential in the Superpave system is evaluated with AASHTO T-283 (AASHTO, 1995). AASHTO T-283, *"Standard Method of Test for Resistance of Compacted Bituminous Mixtures to Moisture Induced Damage,"* was conducted in this study not only to determine its applicability but also as a benchmark test method. The general procedures and results of the tests are discussed in the following sections.

4.1 Specimen Preparations for AASHTO T-283 Tests

Currently sample preparation in AASHTO T-283 are prepared using Marshall impact compaction. In order to determine the compaction effort to achieve the required 7 ± 1 % air voids specimens were compacted at the design asphalt content. Selection of the design asphalt content was described in Chapter Three. Two specimens were subjected to 40 and 60 blow compactive efforts, respectively. Bulk specific gravity (BSG) was determined (ASTM D2726) after an overnight room temperature curing. An air voids vs.

No. of blows relationship was utilized to establish to estimate the compactive effort to achieve the target (7 ± 1 %) air void content.

After the compactive effort was determined, six 1200g batches were prepared. Subsequently, the asphalt and aggregates were mixed in individual batches and the loose mixtures were put into a 60^0 C oven for 16 hours. The mixes were then heated to 135^0 C for 2 ± 0.5 hours. The six batches were compacted with a Marshall manual hand-hammer (Figure 4.1) with the required number of blows to achieve an air voids of 7 ± 1%. The compacted specimens were store at room temperature for 3 to 4 days before testing. In general, two additional specimens were prepared to insure there would be at least six specimens to satisfy the air voids requirement. The extra samples were used to determine the required time for vacuum saturation.

4.2 Testing Procedures

A set of six samples for a mix were separated into two groups of three so that the average air voids of the two groups were equal. One set of three is subjected to cycles of wetting, freezing, thawing and hot water curing. These conditions are utilized to accelerated environmental effects on the asphalt mixture. The wetting involves a 55 to 80 percent saturation by applying 10 to 26 inches Hg vacuum, followed by at least 16 hours of freezing in air at 0 ± 5^0C, soaking in water for 24 ± 1 hours at 60 ± 1^0C, and conditioning in water for two hours at 25 ± 0.5^0C before testing.

The indirect tensile test is conducted on the conditioned and unconditioned set of specimens. Figure 4.2 shows the indirect tensile test apparatus used in this study. The steel loading strips were used to apply a load along the diameter of the specimen. Loading rate was controlled to a vertical deformation of 50.8 mm per minute. The maximum force was recorded and converted to the tensile strength of the specimen as follows:

$$S_t = \frac{2\,P}{\pi\, t\, D} \tag{4.1}$$

where:

S_t = tensile strength,

P   = maximum load,

t   = specimen thickness (average of three measurements), and

D   = specimen diameter (102 mm).

The tensile strength ratio (TSR) is calculated as follows:

$$TSR = \frac{S_1}{S_2} \times 100 \tag{4.2}$$

where:

S_1 = average tensile strength of conditioned subset, and

S_2 = average tensile strength of dry subset.

4.3 Results for AASHTO T-283 Tests

4.3.1 Results for Surface Mixtures

Results from AASHTO T-283 tests for the #11 Limestone, Slag and Dolomite mixtures are summarized in Table 4.1. to 4.3. The tensile strength ratios (TSR) of the three control mixtures are all below 80 percent (Minimum Superpave TSR). Test results also show that the moisture susceptibility of the three mixtures can be improved to meet the Superpave mix design criteria (TSR greater than 80 percent) after addition of antistripping agents.

Comparison of the TSR results for the two antistripping agents indicates that hydrated lime is more effective than the liquid chemical antistripping agent in improving the moisture susceptibly of mixtures. Figure 4.3 to Figure 4.5 show the indirect tensile strength for #11 dolomite, limestone, and slag mix, respectively. Although the TSR is controlled by both dry and wet conditioning tensile strength, hydrated lime can still produce a slightly higher tensile strength for the mixtures after moisture conditioning.

4.3.2 Results for Binder Mixtures

Results from AASHTO T-283 tests are summarized in Table 4.4 to Table 4.6. The tensile strength ratio (TSR) of three control mixtures are all below 80 percent (Minimum Superpave TSR). In general, test results show that the TSR of the three

control mixtures can be increased to meet the Superpave mix design criteria (TSR greater than 80 percent) with addition of hydrated lime. The exception is gravel mixtures.

Comparison of the results for the #8 gravel binder mixtures indicates that the two anti-stripping agents (chemical and hydrated lime) had no effect on the ITS values with the control mix had the highest TSR value among three #8 binder mixtures. Figure 4.6 to Figure 4.8 show the indirect tensile strengths for #8 gravel, limestone, and slag mix, respectively. The #8 gravel mixtures used in this study were the only mixtures containing 100% crushed sand. Test results revealed that fine aggregates could be an major factor in the loss of adhesion of asphalt film. A proper portion of crushed sand in the mixture may by itself help reduce moisture damage.

4.3.3 Results for Base Mixtures

Results from AASHTO T-283 tests on the limestone base mixture are summarized in Table 4.7. The tensile strength ratios (TSR) of the control mixtures are below 80 percent (Minimum Superpave TSR). Test results also show that TSR of the mixtures can be increased by the antistripping agents. However, the TSRs are still below the minimum Superpave mix design criteria (TSR greater than 80 percent).

The ITS results for the #5C Limestone base mix are also shown in Table 4.7. Figure 4.9 shows the indirect tensile strength for #5C Limestone mix. These results indicate that the strengths of specimens with the chemical antistripping additive were lower without than with moisture conditioning.

4.4 Analysis for AASHTO T-283 Test Results

4.4.1 Analysis for Surface Mixtures

A statistical analysis was conducted of asphalt mixture tensile strength relative to the effects of wet/dry conditions, anti-stripping treatment, and mixture properties. Test results were analyzed using the Personal Computer (PC) version of the Statistical Analysis System (SAS) software (SAS Institute, Inc. 1991). An analysis of variance (ANOVA) was performed to determine the significance of the effects of certain factors and/or interactions of factors. The class level information is illustrated in Table 4.8. Table 4.9 provides a summary of the General Linear Models (GLM) analysis. Independent variables in the analysis were type of aggregate (AGG), type of treatment (TREAT), moisture condition (MOISTURE), and air void content (AIRVOID). There were 3, 3, and 2 levels, respectively of the independent variables. The dependent variable was indirect tensile strength (STRENG).

The GLM analysis indicated that type of aggregate and treatment both had significant effect on specimen tensile strength. The analysis also showed that moisture conditioning was significant. This means the environmental conditioning procedures in AASHTO T-283 tests reduced the tensile strength of Indiana #11 surface mixtures.

A Tukey's Studentized Range (HSD) Test was also performed to examine the variability among types of aggregate as well as the effect of treatment on the indirect tensile strength (ITS). Table 4.10 and Table 4.11 show a summary of the statistical

analysis. It indicates that ITS values for dolomite mixtures are lower than those for limestone and slag mixtures. Also, only hydrated lime significantly increased ITS values for #11 surface mixtures. A Tukey's Studentized Range (HSD) Test was also performed to examine the variability among the interaction effects on the indirect tensile strength (ITS) and is listed in Table 4.12 and Table 4.13. The effects of interaction are illustrated in Figure 4.10 and Figure 4.11. The effect of aggregate-treatment interaction is significant. Hydrated lime increased the tensile strength of the slag mix. Both hydrated lime and chemical treatment also increased the indirect tensile strength of the #11 dolomite and limestone mixes. The interaction effect of moisture-treatment is significant. The antistripping agents can have higher ITS value than the control mix after moisture conditioning.

4.4.2 Analysis for Binder Mixtures

For #8 binder mixtures, independent variables in the statistical analysis were type of aggregate (AGG), type of treatment (TREAT), moisture condition (MOISTURE), and air void content (AIRVOID). There were 3, 3, and 2 levels, respectively of the independent variables. An analysis of variance (ANOVA) was performed to determine the significance of the effects of certain factors and/or interactions of factors. The class level information is illustrated in Table 4.14. The dependent variable was indirect tensile strength (STRENG). Table 4.15 presents a summary of the General Linear Models (GLM) analysis. The GLM analysis indicates that type of aggregate had a significant

effect on the tensile strength of the specimens. The analysis also showed that moisture conditioning was significant in the GLM model. This means the environmental conditioning procedures in AASHTO T-283 test reduced the tensile strength of Indiana #8 binder mixtures. This is also shown in Figure 4.12.

A Tukey's Studentized Range (HSD) Test was also performed to examine variability among types of aggregate on the indirect tensile strength (ITS). Table 4.16 shows a summary of the analysis. ITS values for slag mixtures are lower than those for limestone and gravel mixtures. A Tukey's Studentized Range (HSD) Test was also performed to examine the variability among the aggregate-moisture interaction effects on the indirect tensile strength (ITS) and is listed in Table 4.17. This means after moisture conditioning, the slag mix has lower ITS than other two types of aggregate. Figure 4.12 also illustrates this result. The statistical analysis is clear about the effect of aggregate type. However, the plotted data does not highlight the effect.

4.4.3 Analysis for Base Mixtures

Independent variables in the statistical analysis of the #5C base mixture were , type of treatment (TREAT), and moisture condition (MOISTURE). There were 3 and 2 levels, respectively of each independent variables. Air void content (AIRVOID) is also one of the independent variables. The class level information is illustrated in Table 4.18. The dependent variable was indirect tensile strength (STRENG). An analysis of variance (ANOVA) was performed to determine the significance of the effects of certain factors

and/or interactions of factors. Table 4.19 presents a summary of the General Linear Model (GLM) analysis. The GLM analysis indicates that treatment had a significant effect on the tensile strength of the specimen. The analysis also showed that moisture conditioning was significant to the GLM model. The environmental conditioning procedures in AASHTO T-283 tests reduced the tensile strength of #5C base mixtures.

A Tukey's Studentized Range (HSD) Test was also performed to examine the effect of type of treatment as well as the treatment-moisture interaction on the indirect tensile strength (ITS). These results are shown in Table 4.20 and Table 4.21. The results indicate that ITS values for chemical treated samples are lower than hydrated lime treated and control samples.. The chemical anti-stripping agent reduced the ITS in the dry condition. Figure 4.13 also illustrates this result.

4.5 Summary

The AASHTO T-283 test results for the seven mixtures tested indicate that moisture conditioning has a significant effect on the stripping potential of the mixes. This means the environmental conditioning procedures in AASHTO T-283 reduced the tensile strength of the mixtures.

Figure 4.14 shows TSR values for all seven mixtures tested. Clearly, the two anti-stripping agents increased TSR values except for the #8 gravel binder mixes. The #8 gravel mixture used in this study was the only mixture containing 100% crushed sand.

The test results based on TSR indicates that a proper portion of crushed sand in the mixture may help to reduce moisture damage and usage of anti-stripping agents.

Comparison of the results for the two antistripping agents based on TSR values indicates that hydrated lime is more effective than the liquid chemical anti-stripping agent. Hydrated lime produces a slightly higher tensile strength for the mixtures before and after moisture conditioning. The liquid chemical anti-stripping agent increased the tensile strength for the mixtures after moisture conditioning. It also can reduce the tensile strength for the mixture before moisture conditioning.

Table 4.1 AASHTO T-283 Test Results for #11 Dolomite Mixtures

	Dry			Wet				TSR, %
	Air Voids, %	ITS (kPa)	ITS(Average) (kPa)	Air Voids, %	Saturation, %	ITS, (kPa)	ITS(Average) %	
Control	6.49	1103	1089	6.59	71.1	747	738	68
	6.48	1077		6.74	73.3	717		
	6.80	1087		6.44	70.2	750		
Pave Bond	6.87	1076	1053	6.76	74.5	821	842	80
	6.89	1048		6.84	69.1	854		
	6.73	1036		6.91	73.7	850		
Hydrated Lime	6.35	1010	1001	6.51	65.6	856	869	87
	6.94	951		6.54	63.8	891		
	6.28	1041		6.49	65.3	860		

Note: ITS: Indirect Tensile Strength
TSR: Tensile Strength Ratio

Table 4.2 AASHTO T-283 Test Results for #11 Limestone Mixtures

	Dry			Wet				TSR, %
	Air Voids, %	ITS (kPa)	ITS(Average) (kPa)	Air Voids, %	Saturation, %	ITS, (kPa)	ITS(Average) %	TSR, %
Control	7.01	1378		7.25	71.0	896		
	7.21	1349	1345	7.05	70.4	885	913	68
	6.92	1309		6.81	71.0	958		
Pave Bond	6.46	1262		6.65	71.0	985		
	6.71	1206	1254	6.70	68.1	1040	1022	82
	6.72	1295		6.65	69.7	1043		
Hydrated Lime	6.78	1320		6.68	64.5	1032		
	6.64	1298	1320	6.82	67.1	1060	1081	82
	6.60	1341		6.53	64.2	1150		

Note: ITS: Indirect Tensile Strength
TSR: Tensile Strength Ratio

Table 4.3 AASHTO T-283 Test Results for #11 Slag Mixtures

	Dry			Wet				TSR, %
	Air Voids, %	ITS (kPa)	ITS(Average) (kPa)	Air Voids, %	Saturation, %	ITS, (kPa)	ITS(Average) %	TSR, %
Control	6.98	1333	1329	7.08	71.8	853	882	66
	7.03	1331		6.91	70.2	877		
	7.23	1322		7.21	73.3	915		
Pave Bond	6.79	1160	1162	6.55	69.6	973	940	81
	6.93	1176		6.99	65.7	914		
	6.68	1149		6.88	68.2	933		
Hydrated Lime	6.61	1357	1334	6.56	63.8	1171	1109	83
	6.73	1321		6.74	69.1	1102		
	6.84	1323		6.92	65.4	1055		

Note: ITS: Indirect Tensile Strength
TSR: Tensile Strength Ratio

Table 4.4 AASHTO T-283 Test Results for #8 Gravel Mixtures

	Dry			Wet				TSR, %
	Air Voids, %	ITS (kPa)	ITS(Average) (kPa)	Air Voids, %	Saturation, %	ITS, (kPa)	ITS(Average) %	
Control	7.16	1028		6.49	74.4	925		
	6.54	1159	1133	7.07	65.8	849	890	79
	6.72	1213		6.89	69.2	897		
Pave Bond	6.52	1045		6.84	73.6	821		
	6.53	1231	1150	6.81	69.9	791	855	74
	7.52	1175		6.82	67.5	953		
Hydrated Lime	6.76	1080		6.27	79.4	867		
	6.37	1131	1097	6.48	75.1	881	859	78
	6.26	1078		6.51	69.4	828		

Note: ITS: Indirect Tensile Strength
        TSR: Tensile Strength Ratio

Table 4.5 AASHTO T-283 Test Results for #8 Limestone Mixtures

	Dry			Wet				TSR, %
	Air Voids, %	ITS (kPa)	ITS$_{(Average)}$ (kPa)	Air Voids, %	Saturation, %	ITS, (kPa)	ITS$_{(Average)}$ %	
Control	7.39	1055	1082	7.72	67.9	801	839	78
	7.48	1069		7.74	66.4	827		
	7.76	1123		7.35	62.3	889		
Pave Bond	6.70	1098	1158	6.50	62.5	1085	985	85
	6.90	1139		6.84	60.9	1055		
	6.99	1236		7.31	65.9	815		
Hydrated Lime	7.34	1077	1134	7.57	62.0	836	947	84
	6.75	1184		6.83	62.6	1018		
	7.32	1141		6.81	59.4	987		

Note: ITS: Indirect Tensile Strength
         TSR: Tensile Strength Ratio

Table 4.6 AASHTO T-283 Test Results for #8 Slag Mixtures

	Dry			Wet				TSR, %
	Air Voids, %	ITS (kPa)	ITS(Average) (kPa)	Air Voids, %	Saturation, %	ITS, (kPa)	ITS(Average) %	
Control	7.41	1293		6.98	78.1	807		
	7.06	1229	1226	7.24	75.2	703	738	60
	6.77	1156		6.96	75.0	702		
Pave Bond	7.26	989		6.80	88.2	·676		
	6.37	1074	1010	7.12	65.4	736	696	69
	7.37	966		7.03	74.6	676		
Hydrated Lime	6.17	1105		6.29	79.7	916		
	6.40	993	1027	7.05	74.6	843	911	89
	7.49	985		6.62	77.1	974		

Note: ITS: Indirect Tensile Strength
        TSR: Tensile Strength Ratio

Table 4.7 AASHTO T-283 Test Results for #5C Limestone Mixtures

	Dry			Wet				TSR, %
	Air Voids, %	ITS (kPa)	ITS$_{(Average)}$ (kPa)	Air Voids, %	Saturation, %	ITS, (kPa)	ITS$_{(Average)}$ %	
Control	7.65	1036	1101	7.59	58.5	693	692	63
	7.28	1059		7.16	58.9	713		
	7.35	1209		7.56	58.7	671		
Pave Bond	7.94	905	926	7.79	57.6	672	703	76
	7.88	976		8.03	56.3	701		
	7.73	897		8.01	60..5	735		
Hydrated Lime	7.63	1154	1116	7.69	58.8	812	804	72
	7.83	1082		7.65	62.9	755		
	7.88	1112		7.92	55.1	845		

Note: ITS: Indirect Tensile Strength
       TSR: Tensile Strength Ratio

Table 4.8 Class Level Information-#11 Surface Mix

Class	Levels	Values		
AGG	3	DOLOMITE	LIMESTONE	SLAG
TREAT	3	CONTROL	CHEMICAL	LIME
MOISTURE	2	DRY	WET	
Number of observations in data set = 54				

Table 4.9 Summary of Statistical Analysis for #11 Surface Mixtures

Dependent Variable: STRENG					
Source	df	SS	MS	F stat	Prob. > F
Model	35	1840832.45	52595.21	56.43	0.0001
Error	18	16777.42	932.08		
Total	53	1857609.87			
		R-Square	Adj. R-Sq.	Root MSE	Mean
		0.99	0.97	30.53	1071.24
Source	df	Type 1 SS	MS	F stat	Prob. > F
AGG	2	528427.90	264213.95	283.47	0.0001
TREAT	2	49202.43	24601.21	26.39	0.0001
MOISTURE	1	1043850.93	1043850.93	1119.92	0.0001
AIRVOID	1	6047.78	6047.78	6.49	0.0202
AIRVOID*MOISTURE	1	54855.03	54855.03	58.85	0.0001
AIRVOID*AGG	2	3505.56	1752.78	1.88	0.1813
AIRVOID*TREAT	2	4959.32	2479.66	2.66	0.0972
MOISTURE*AGG	2	3286.13	1643.06	1.76	0.1999
MOISTURE*TREAT	2	86743.69	43371.84	46.53	0.0001
AGG*TREAT	4	48020.41	12005.10	12.88	0.0001
AIRVOID*MOISTURE *AGG	2	207.45	103.73	0.11	0.8953
AIRVOID*MOISTURE *TREAT	2	609.81	304.91	0.33	0.7252
AIRVOID*AGG *TREAT	4	2050.34	512.58	0.55	0.7015
MOISTURE*AGG *TREAT	4	5568.43	1392.11	1.49	0.2458
AIRVOID*MOISTURE *AGG*TREAT	4	3497.26	874.31	0.94	0.4644

Table 4.10 Mean Comparison of ITS for Different Types of Aggregate (#11 Surface)

Aggregate	Mean (kPa)	N	Tukey Grouping
Limestone	1155.94	18	A
Slag	1125.83	18	A
Dolomite	931.94	18	B
Alpha=0.05, df=45, MSE=2396.403			
Critical Value of Studentized Range=3.428			
Min. Significant Difference=39.548			

Table 4.11 Mean Comparison of ITS for Different Treatments (#11 Surface)

Treatment	Mean (kPa)	N	Tukey Grouping
Hydrated Lime	1118.83	18	A
Control	1049.28	18	B
Liquid Additive	1045.61	18	B
Alpha=0.05, df=45, MSE=2396.403			
Critical Value of Studentized Range=3.428			
Min. Significant Difference=39.548			

Table 4.12 Mean Comparison of ITS for Aggregate&Treatment interactions (#11 Surface)

Aggregate	Treatment	Mean (kPa)	N	Tukey Grouping
Slag	Hydrated Lime	1221.5	6	A
Limestone	Hydrated Lime	1200.2	6	A B
Limestone	Liquid Additive	1138.5	6	B C
Limestone	Control	1129.2	6	C
Slag	Control	1105.2	6	C D
Slag	Liquid Additive	1050.8	6	D
Dolomite	Liquid Additive	947.5	6	E
Dolomite	Hydrated Lime	934.8	6	E
Dolomite	Control	913.5	6	E
Alpha = 0.05, df = 18, MSE = 932.08 Critical Value of Studentized Range = 4.96 Min. Significant Difference = 61.76				

Table 4.13 Mean Comparison of ITS for Moisture&Treatment interactions (#11 Surface)

Treatment	Moisture	Mean (kPa)	N	Tukey Grouping
Control	Dry	1254.3	9	A
Hydrated Lime	Dry	1218.0	9	A
Liquid Additive	Dry	1156.4	9	B
Hydrated Lime	Wet	1019.7	9	C
Liquid Additive	Wet	934.8	9	D
Control	Wet	844.2	9	E
Alpha = 0.05, df = 18, MSE = 932.08 Critical Value of Studentized Range = 4.49 Min. Significant Difference = 45.74				

Table 4.14 Class Level Information-#8 Binder Mix

Class	Levels	Values		
AGG	3	GRAVEL	LIMESTONE	SLAG
TREAT	3	CONTROL	CHEMICAL	LIME
MOISTURE	2	DRY	WET	
Number of observations in data set = 54				

Table 4.15 Summary of Statistical Analysis for #8 Binder Mixtures

Dependent Variable: STRENG					
Source	df	SS	MS	F stat	Prob. > F
Model	35	1310495.31	37442.72	9.52	0.0001
Error	18	70825.53	3934.75		
Total	53	1381320.83			
		R-Square	Adj. R-Sq.	Root MSE	Mean
		0.95	0.85	62.73	985.39
Source	df	Type 1 SS	MS	F stat	Prob. > F
AGG	2	101762.40	50881.20	12.93	0.0003
TREAT	2	9572.05	4786.03	1.22	0.3159
MOISTURE	1	871575.03	871575.03	221.51	0.0001
AIRVOID	1	27886.35	27886.35	7.09	0.0159
AIRVOID*MOISTURE	1	23885.43	23885.43	6.07	0.0240
AIRVOID*AGG	2	26889.26	13444.63	3.42	0.0552
AIRVOID*TREAT	2	3619.08	1809.54	0.46	0.6386
MOISTURE*AGG	2	68268.33	34134.17	8.68	0.0023
MOISTURE*TREAT	2	25276.58	12638.29	3.21	0.0641
AGG*TREAT	4	38325.16	9581.29	2.44	0.0848
AIRVOID*MOISTURE*AGG	2	8565.54	4282.77	1.09	0.3579
AIRVOID*MOISTURE*TREAT	2	2058.60	1029.30	0.26	0.7727
AIRVOID*AGG*TREAT	4	34633.56	8658.39	2.20	0.1099
MOISTURE*AGG*TREAT	4	46108.08	11527.02	2.93	0.0499
AIRVOID*MOISTURE*AGG*TREAT	4	22069.85	5517.46	1.40	0.2732

Table 4.16 Mean Comparison of ITS for Different Types of Aggregate (#8 Binder)

Aggregate	Mean (kPa)	N	Tukey Grouping
Limestone	1024.17	18	A
Gravel	997.33	18	A
Slag	934.67	18	B
Alpha=0.05, df=35, MSE=4467.584			
Critical Value of Studentized Range=3.461			
Min. Significant Difference=54.525			

Table 4.17 Mean Comparison of ITS for Aggregate & Moisture interactions (#8 Binder)

Aggregate	Moisture	Mean (kPa)	N	Tukey Grouping
Gravel	Dry	1126.7	9	A
Limestone	Dry	1124.7	9	A
Slag	Dry	1087.8	9	A
Limestone	Wet	923.7	9	B
Gravel	Wet	868.0	9	B C
Slag	Wet	781.6	9	C
Alpha = 0.05, df = 18, MSE = 3934.75				
Critical Value of Studentized Range = 4.49				
Min. Significant Difference = 93.98				

Table 4.18 Class Level Information-#5C Base Mix

Class	Levels	Values		
TREAT	3	CONTROL	CHEMICAL	LIME
MOISTURE	2	DRY	WET	
Number of observations in data set = 18				

Table 4.19 Summary of Statistical Analysis for #5C Base Mixtures

Dependent Variable: STRENG					
Source	df	SS	MS	F stat	Prob. > F
Model	9	544703.75	60522.64	21.86	0.0001
Error	8	22148.53	2768.57		
Total	17	566852.28			
		R-Square	Adj. R-Sq.	Root MSE	Mean
		0.96	0.92	52.62	890.39
Source	df	Type 1 SS	MS	F stat	Prob. > F
TREAT	2	64030.11	32015.06	11.56	0.0044
MOISTURE	1	445882.72	445882.72	161.05	0.0001
AIRVOID	2	5.11	5.11	0.00	0.9668
TREAT*MOISTURE	2	26218.38	13109.19	4.74	0.0440
AIRVOID*TREAT	2	4803.46	2401.73	0.87	0.4561
AIRVOID*MOISTURE	1	3763.97	3763.97	1.36	0.2772

Table 4.20 Mean Comparison of ITS for Different Treatments (#5C Base)

Treatment	Mean (kPa)	N	Tukey Grouping
Hydrated Lime	960.00	6	A
Control	896.83	6	A
Liquid Additive	814.33	6	B
Alpha=0.05, df=12, MSE=2589 Critical Value of Studentized Range=3.773 Min. Significant Difference=78.37			

Table 4.21 Mean Comparison of ITS for Moisture&Treatment interactions (#5C Base)

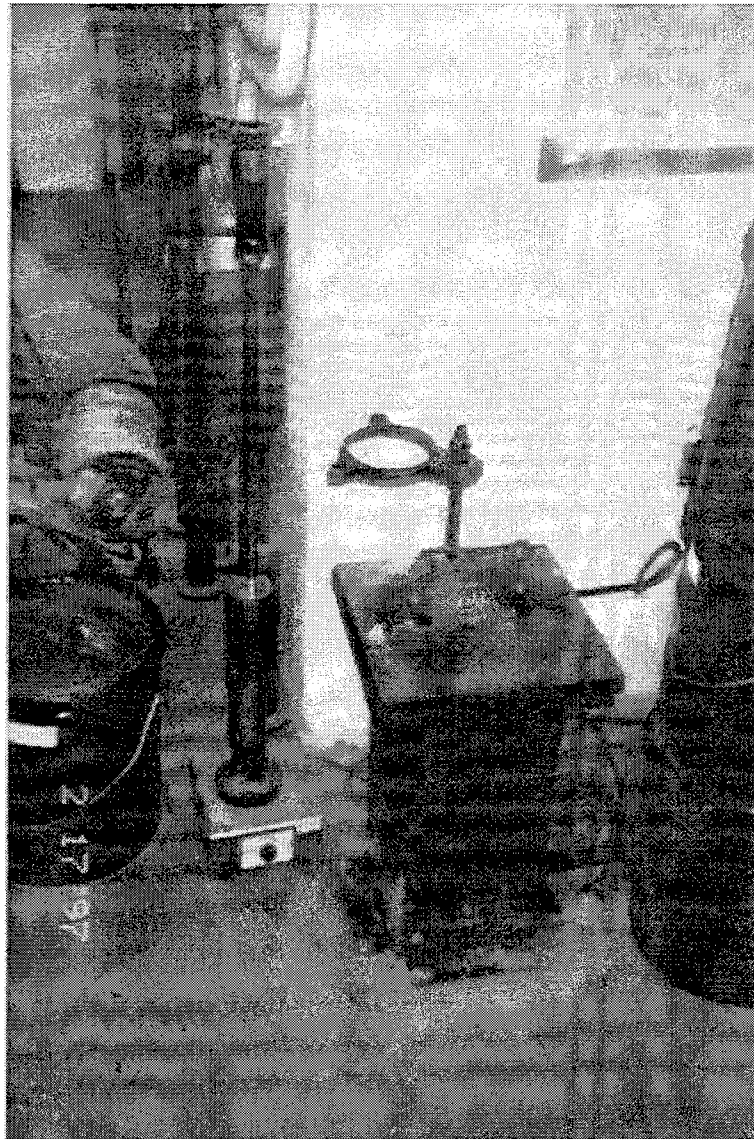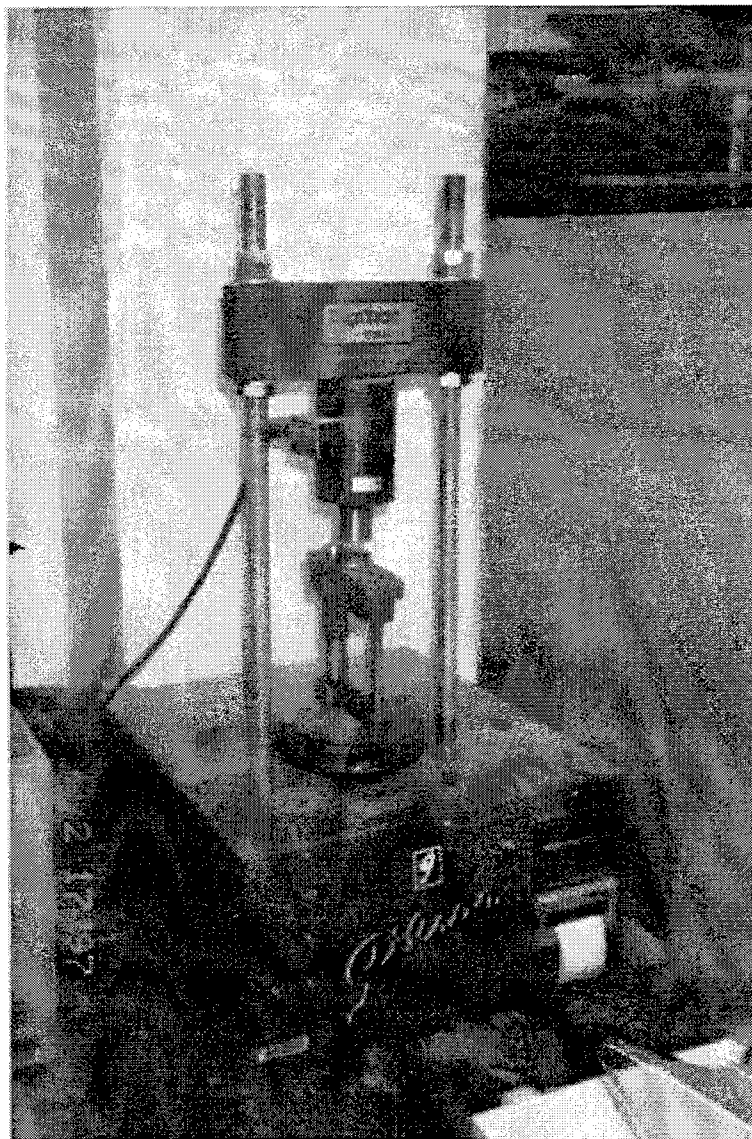| Treatment	Moisture	Mean (kPa)	N	Tukey Grouping
Hydrated Lime	Dry	1116.0	3	A
Control	Dry	1101.3	3	A
Liquid Additive	Dry	926.0	3	B
Hydrated Lime	Wet	804.0	3	B C
Liquid Additive	Wet	702.7	3	C
Control	Wet	692.3	3	C
Alpha = 0.05, df = 8, MSE = 2768.57 Critical Value of Studentized Range = 5.17 Min. Significant Difference = 156.97				

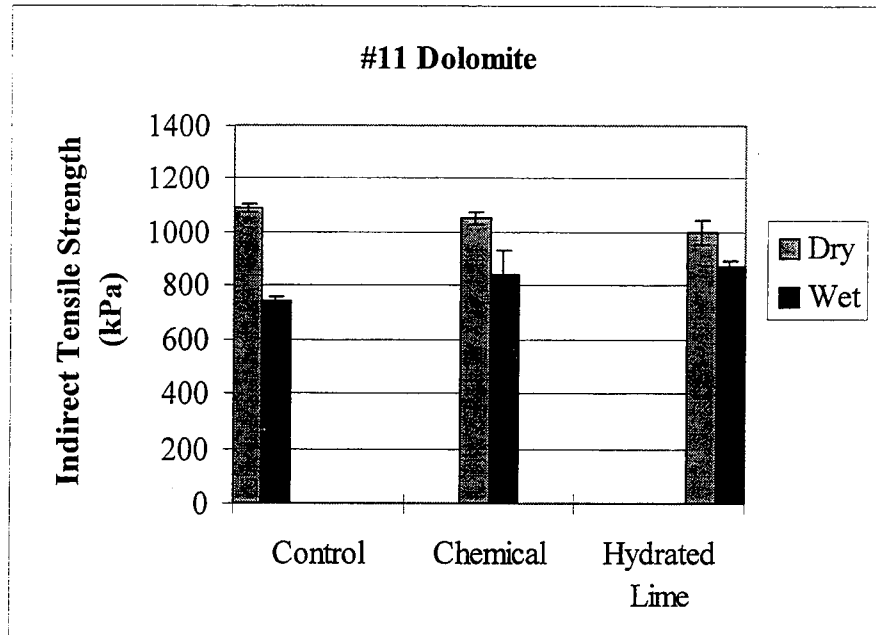Figure 4.1 Manual Marshall Hand Hammer

Figure 4.2 Indirect Tensile Test Apparatus

* Each bar represents the average value of 3 samples

Figure 4.3 Indirect Tensile Strength for #11 Dolomite Mix

* Each bar represents the average value of 3 samples

Figure 4.4 Indirect Tensile Strength for #11 Limestone Mix

* Each bar represents the average value of 3 samples

Figure 4.5 Indirect Tensile Strength for #11 Slag Mix

* Each bar represents the average value of 3 samples

Figure 4.6 Indirect Tensile Strength for #8 Gravel Mix
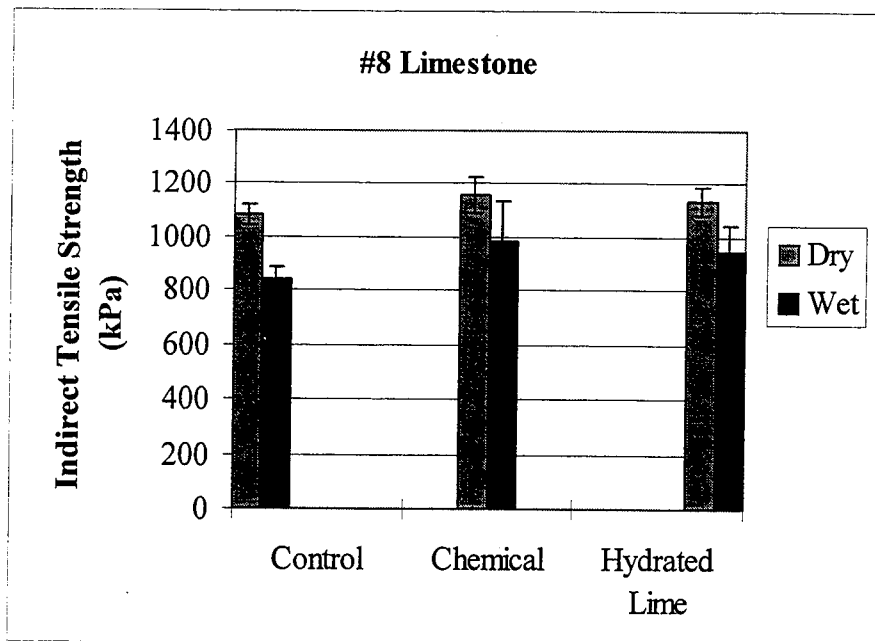
* Each bar represents the average value of 3 samples

Figure 4.7 Indirect Tensile Strength for #8 Limestone Mix
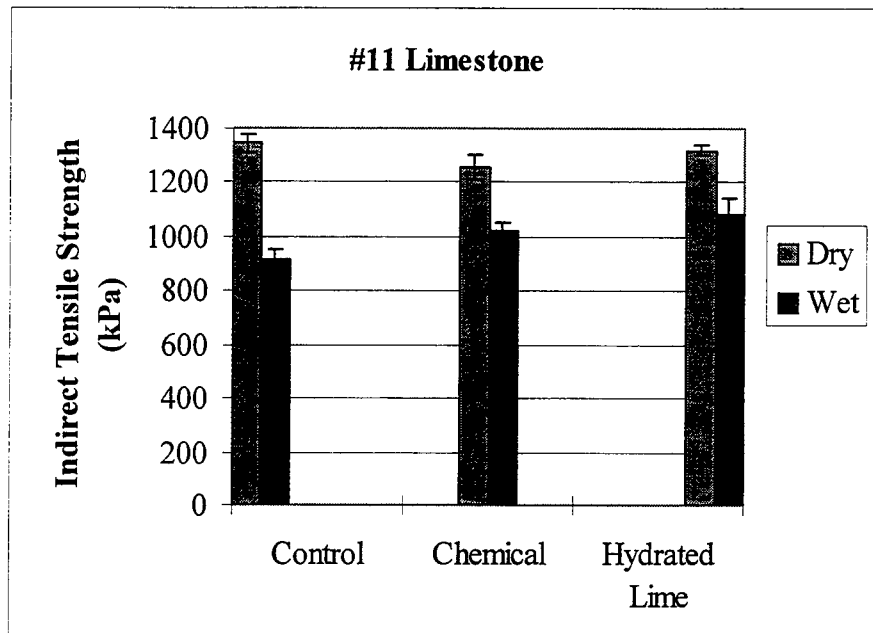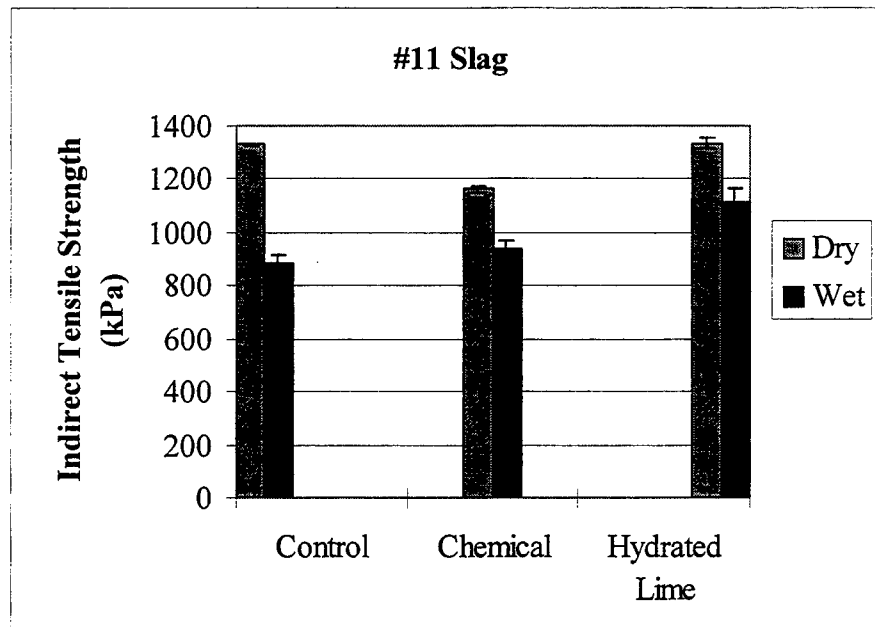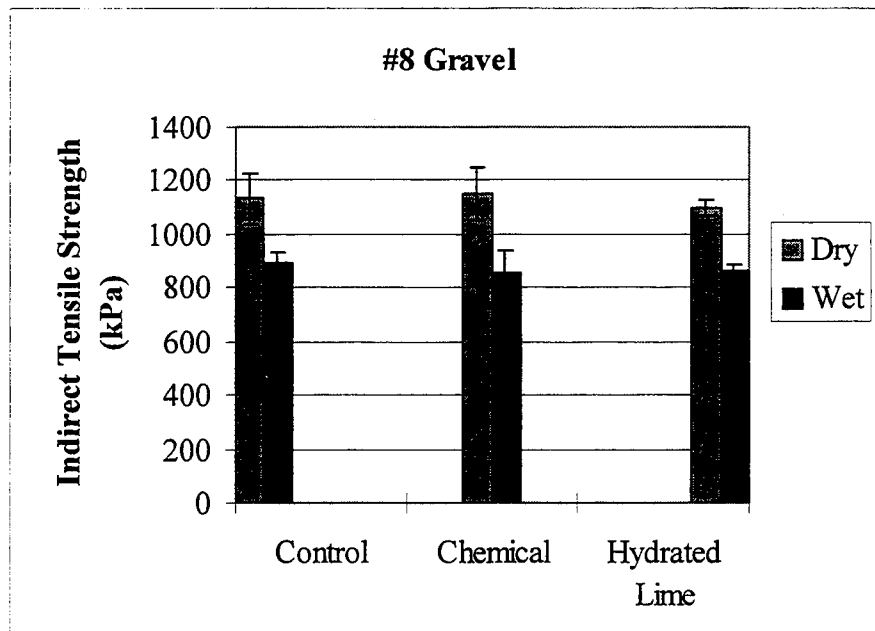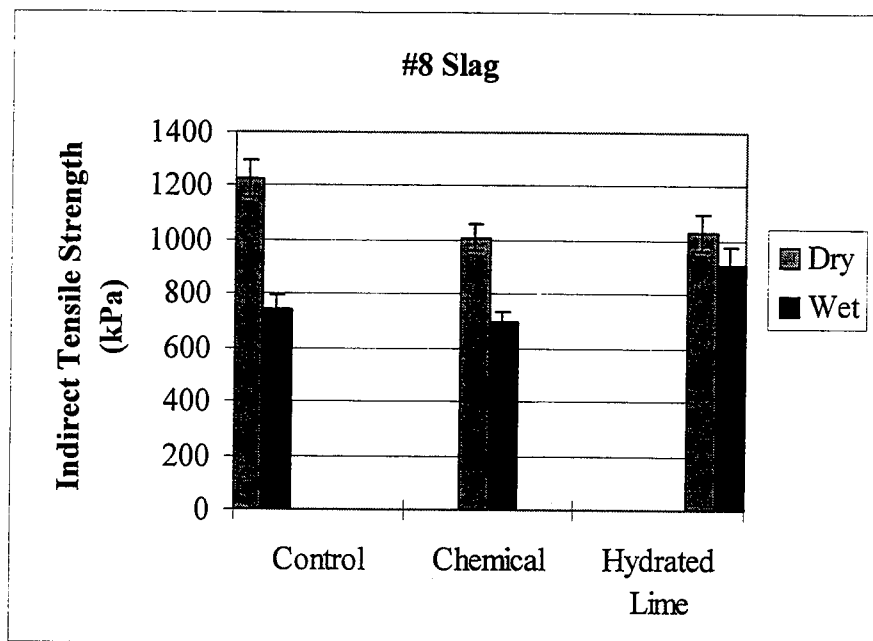

* Each bar represents the average value of 3 samples

Figure 4.8 Indirect Tensile Strength for #8 Slag Mix
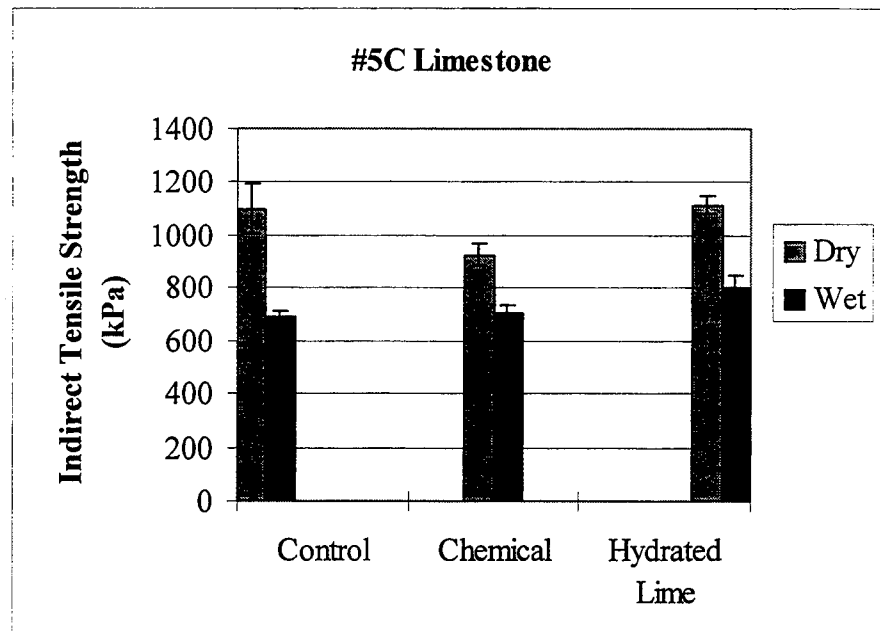
* Each bar represents the average value of 3 samples

Figure 4.9 Indirect Tensile Strength for #5C Limestone Mix
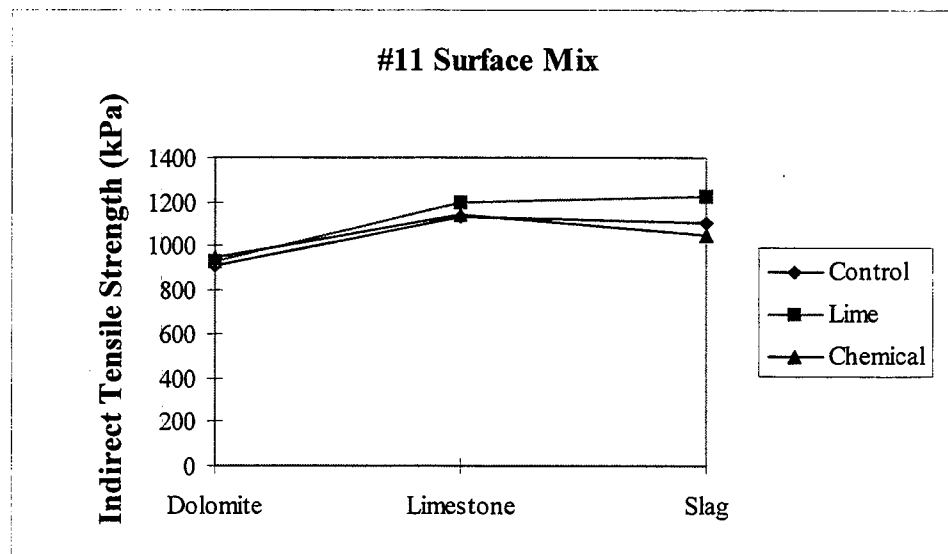
Figure 4.10 Plot of Mean Indirect Tensile Strength by Aggregate and Treatment (#11 Surface Mix)
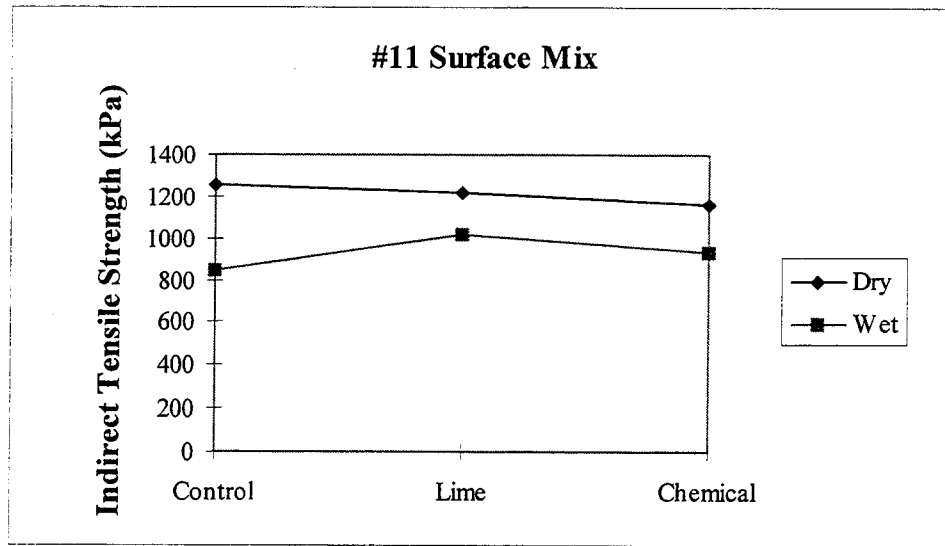
Figure 4.11 Plot of Mean Indirect Tensile Strength by Moisture and Treatment (#11 Surface Mix)
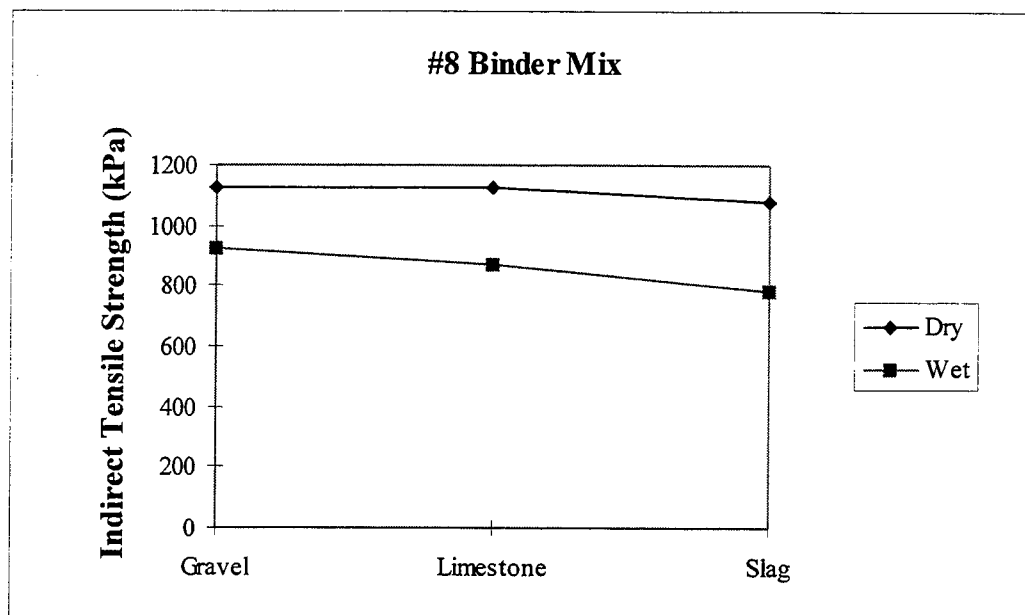
Figure 4.12 Plot of Mean Indirect Tensile Strength by Aggregate and Moisture (#8 Binder Mix)
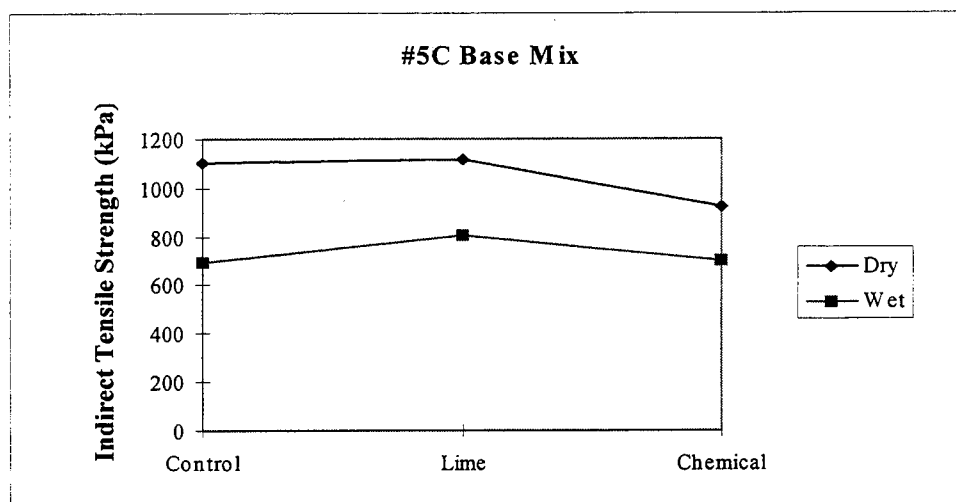
Figure 4.13 Plot of Mean Indirect Tensile Strength by Moisture and Treatment (#5C Base Mix)
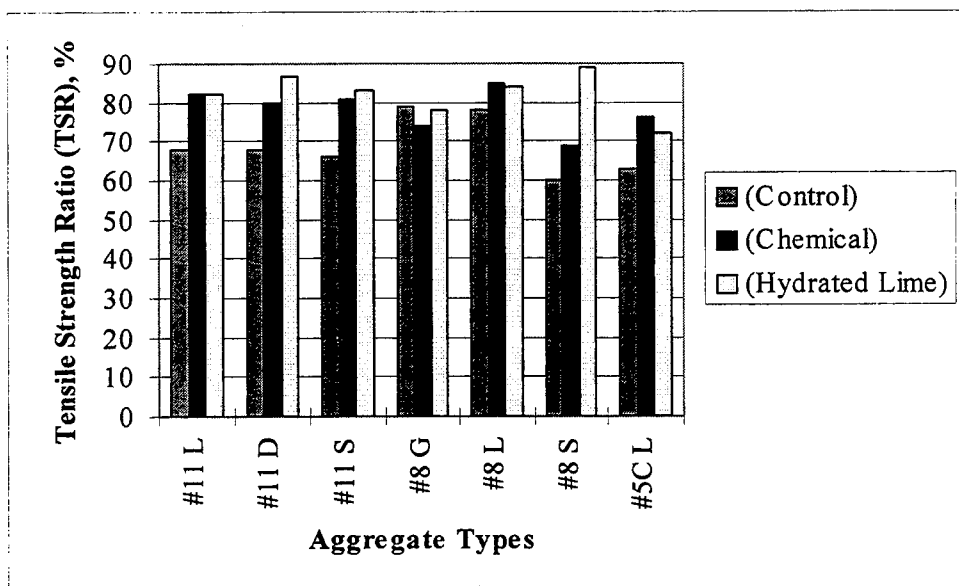
#11L:	:#11 dolomite surface mixture
#11D:	:#11 limestone surface mixture
#11S:	:#11 slag surface mixture
#8G:	#8 gravel binder mixture
#8L:	:#8 limestone binder mixture
#8S:	:#8 slag binder mixture
#5CL:	:#5C limestone base mixture

Figure 4.14 TSR Results for AASHTO T-283 Tests

CHAPTER 5 LABORATORY WHEEL TRACKING TESTING

This chapter describes and presents results of laboratory work conducted using the Purdue wheel (PURWheel) testing device. Tests were conducted on mixtures described in Chapter Three. Development of the testing equipment and techniques are also discussed.

5.1 Introductions

The Purdue wheel testing Device (PURWheel), a laboratory wheel tracking device, was developed specifically for this study. Design of the PURWheel was predicated on creating conditions associated with both rutting and stripping. These conditions include high moisture, high temperature and moving wheel load. Tests can be conducted on laboratory compacted specimens as well as specimens taken from in-service pavements. A recent proposal was made to package the unit for testing field test sections.

The PURWheel laboratory wheel test device (shown in Figure 5.1) was designed and fabricated to evaluate the stripping/rutting performance of bituminous mixtures. Two specimens can be tested simultaneously. The test environment can be either hot/wet or hot/dry. Typical test temperature ranges from 55^0 C to 60^0 C, although the test

temperature can vary from room temperature to 65^0 C. In application specimens are compacted to 6 ~ 8% air voids with the Purdue linear compactor (see Figure 5.2). Specimen dimensions are typically 29.0 cm wide and 31.0 cm long. Specimen depth varies depending on the type of mixture being tested. For example, surface, binder and base mixtures are 3.8 cm, 5.1 cm, 7.6 cm, respectively. A pneumatic tire is loaded to achieve a gross contact pressure of about 620 kPa with a 793 kPa tire pressure. The wheel velocity selected for these tests was 33 ± 2 cm/sec (1.1 ft/sec or 1 mph). In this study, each specimen was subjected to 20,000 wheel passes or until 20.0 mm of deformation developed. Figure 5.3 illustrates a typical PURWheel test result. The test data includes creep slope, number of wheel passes and rut depth for the stripping inflection point, and stripping slope (if available). Design characteristics of the test apparatus, sample preparation, test results and analysis are included in subsequent sections.

5.2 Laboratory Wheel Test Apparatus Development

Two major pieces of equipment for the laboratory wheel track testing were developed in this study. They are: (1) Laboratory linear compactor, and (2) Purdue wheel testing device (PURWheel). The linear compactor was designed and fabricated to produce samples for PURWheel testing, bending fatigue tests and Nuclear density and moisture (asphalt) content testing. Both devices are described in the following sections.

5.2.1 Laboratory Linear Compactor

The linear laboratory compactor was designed and fabricated as a multi-purpose compactor. Its design concept is based on a similar device developed for Koch asphalt in preparing samples for the Hamburg Steel Wheel Tester (HSWT) (Habermann, 1994). The modifications included facility for compacting larger slabs. Maximum length and width of slabs that can be prepared are 62.2 cm by 30.5 cm. These dimension were selected as part of the design parameters for the PURWheel Testing device to minimize end and side boundary effects. Maximum slab thickness that can be prepared is 10.2 cm. This thickness was selected to minimize bottom boundary effects in nuclear density and moisture (asphalt) content measurements. A 10.2 cm thickness also allows 7.6 cm by 38.1 cm beams for bending fatigue tests to be sawn. The Purdue linear compactor is shown in Figure 5.4. Essential features of the linear compactor include a 304.8 mm (12 in.) X 622.3 mm (24.5 in.) rectangular steel mold attached to an air cylinder, a set of steel plates, a loading frame with a steel roller, and a hydraulic ram to apply a compaction force. The Koch linear compactor and the initial Purdue design had a threaded, vertical steel rod (Figure 5.5) to apply the compaction force. Compactive load was applied to the loading frame through the attached roller to the steel plates by turning the rod. In operation the rod is turned, applying load on the plates until the sample in the steel mold is at the desired thickness. The threaded rod failed a number of times and contributed to sample density variations because load varied as the sample compacted. A modification involved replacing the threaded rod with a hydraulic ram (Figure 5.6). Hydraulic pressure is supplied by an electric powered hydraulic pump. With the hydraulic loading the force

is constant. The result was that compaction for most mixtures was reduced from thirty to five minutes. Target density can be achieve by compacting the material into a certain volume. A slab sample can also be used for other tests as noted above. In addition, cored sample can obtain for indirect tensile as well as creep tests. The linear compactor has proven to be an effective, flexible laboratory compaction device.

5.2.2 Development of The Wheel Track Testing Device

There are several laboratory wheel testing devices being utilized in the U.S. The devices include Laboratoire Central des Ponts et Chaussees (LCPC) French Rutting Tester, Georgia Loaded Wheel Tester (GLWT), and Hamburg Steel Wheel Tracking (HSWT) Device. A survey is currently being conducted by an American Society for Testing Materials Subcommittee on features of such devices. The purpose of the survey is to evaluate the need for a standard. There is increasing interest in the potential of predicting stripping/rutting performance of asphalt mixtures. Conceptionally, wheel tracking tests simulates the effect of moving wheel loads. After reviewing the features of available wheel testing devices, the Hamburg Wheel Tracking Device which tests compacted slabs immersed in hot water was considered a more effective device. This was based on the history of its application and the goal of the current study.

Since a new device was to be fabricated, a number of features were added to the basic Hamburg Steel Wheel Testing concept. The added features included:

1. Use of two air cylinders to drive the wheels independently as well as achieve a constant speed throughout the stroke,

2. A wheel mounting assembly for different types of wheels (steel, rubber coated, or pneumatic),

3. A transverse mechanism to incorporate wheel wander (Figure 5.7).

4. A larger sample box to minimize boundary effects (Figure 5.8).

5. Ability to measure rut depth for entire length of specimen using movable transducers (Figure 5.9).

Additionally, the testing chamber was modified so that tests can be conducted in hot/dry as well as in hot/wet conditions. The heating system for the hot/dry condition included circulating hot water through conduits in plate under the specimen. Figure 5.10 shows features of the heating system. An additional air heating device was added to minimize sample/air temperature differential and ensure uniform temperature through the specimen. The air heating system uses electric resistance heating elements and a blower as shown in Figure 5.11. Thermocouples embedded in dummy samples were used to determine time of heating.

Initial tests were conducted with samples 304.8 mm (12 in.) wide by 622.3 mm (24.5 in.) long. In these tests the rutting appeared to be uniform. As a result, a decision was made to reduce the length of the sample to one-half of its original length. Concrete blocks with the same thickness of the sample were used to fill in on both ends. Figure 5.12 illustrates rutting.

<u>5.3 Test Parameters</u>

The PURWheel design proved to be flexible, allowing numerous test configurations. However, the intent of this study was to evaluate the performance of the asphalt mixtures under simulated service conditions. Simulation involved matching actual ambient factors, such as load, geometry, and temperature. In service pavement thickness varies depending on type of mixture. Target test slab thickness were selected based on the usual thickness for the various mixtures, i.e. surface, binder and base. They are 1.5 in. (38 mm), 2 in. (51 mm), and 3 in. (76 mm) for the surface, binder, and base mixtures respectively.

5.3.1 Tire Contact Pressure

The majority of tests conducted with the APT were with a tire pressure of 620 kPa (90 psi). Gross tire contact pressure of the APT tire based on applied load and tire print area was also 620 kpa (90 psi). In order to achieve this level of contact pressure, a 175 kg load was applied to each wheel at a tire inflation pressure was 793 kpa (115 psi). The contact pressure is equal to the following:

$$\sigma = \frac{P}{A} \tag{5.1}$$

where:

σ = Gross wheel contact pressure,

P = Wheel load, and

A = Gross contact area between tire and sample surface.

Typical thicknesses for surface and binder layers in Indiana are 38.1 mm and 50.8 mm, respectively. In order to estimate the stress at the top of the binder and base layers, an analysis was made using Bitumen Structures Analysis in Roads (BISAR) software which was developed by Shell (De Jong, et al., 1973). It is a linear-elastic, multilayered system program for computing stresses, strains and deflections resulting from one or more uniform circular loads at a surface. Figure 5.13 shows the stress distribution using BISAR. These results are for 620 kPa surface loading. Since the reduction in stress for the 38.1 mm surface layer is minimal and traffic is allowed on binder surfaces, the same stress was assumed for both the surface and the binder mixtures. The BISAR results also indicates a stress of 517 kPa at a depth of 89 mm (3.5 in.) which is typically the top of the base mixture.

5.3.2 Test Temperature

Performance of asphalt mixture is influenced significantly by temperature. The elastic modulus decreases with increasing temperature and as a result stresses on underlying materials will increase as a result of the larger stresses, the asphalt mixture will deform viscously resulting in permanent deformation.

To estimate pavement temperature profiles in Indiana, a finite difference heat transfer model developed by Gupta (1987) was utilized. The model input includes ambient air temperature and solar radiations. Figure 5.15 illustrates the highest hourly pavement surface temperatures in Indiana which is from the heat transfer model output results. As a worst case condition, a temperature of 60^0 C (140^0 F) was assumed for surface mixture tests. As noted above surface mixtures in Indiana average 38.1 mm (1.5 inches) thick. The finite difference analysis predicted a temperature gradient of 2.5^0 C (4.5^0 F) for the 38.1 mm surface course thickness. As a result, a test temperature of 57.5^0 C (135^0 F) was adapted for binder mixtures. Binder thickness average 50.8 mm (2 in.). A temperature gradient of 6.0^0 C would be expected for the pavement at 89 mm in depth. Consequently, a test temperature of 54.0^0 C was adopted for base mixtures.

5.4 Sample Preparation and Test Procedures

Plan dimensions of slabs prepared for this study averaged 304.8 mm wide and 622.3 mm long. Surface and binder course slab thickness were 38 mm and 76 mm respectively. The aggregate was batched out in steel pans, each holding about 10 to 11 kg of dry aggregate for every 25.4 mm (1 in.) thickness for the binder and base mixtures. For surface mixtures, two pans of aggregate were batched out, each holding about 7 to 8 kg of dry aggregate for every 19 mm (0.75 in.) thickness. The pans of aggregate were placed in a forced draft oven and heated to the mixing temperature. When the mixing temperature was achieved, the aggregate and required amount of asphalt were combined

and mixed using a mechanical drum mixer shown in Figure 5.16. After mixing, the mixture was placed in a pan and cured at 145^0 C for 30 to 60 minutes in the forced draft oven prior to compaction process.

The linear compactor, as previously shown (Figure 5.2) was fabricated for sample preparation in this study. Procedures for using the linear compactor are as follows:

1. preheat the mold to about 145^0 C by using an infrared heater,

2. place a filter paper at the bottom of the mold and then load the batches of mixture, carefully leveling the mix,

3. place in consecutive order on the leveled mixture another piece of filter paper, a galvanized sheet metal plate, and the set of kneading plates,

4. lower the loading frame and connect the hydraulic ram,

5. lower the side cage panels and start compaction,

6. compact the specimen to the desired thickness,

7. allow the specimen to cool for about 2 to 3 hours,

8. remove the specimen from the mold and cut the specimen in half, resulting in two test specimens,

9. dry the specimens at room temperature, weigh and measure the length, width and thickness at eight locations (two on each edge), and

10. compute the volumetric density and voids relations.

Each half of the slab is placed in the wheel tracking device and grouted in place with plaster-of-Paris. After the plaster cures for about 30 minutes, the hood is closed and

the control program is initiated. The following information is entered in the program for regular test conditions:

1. Type of test (wet or dry),

2. Test temperature (60^0 C for surface, 57.5^0 C for binder, and 54^0 C for base mixtures),

3. Pneumatic tire pressure (793 kpa inflation pressure),

4. Wheel path (Fixed for these tests),

5. Total mass in load box (85 kg for surface and binder mixtures, 56 kg for base mixtures)

6. Deformation measurements (average of 9 points near the center of the sample, 10 mm between each measure point),

7. Data recording frequency (every 250 wheel passes),

8. Test criteria (20,000 wheel passes or 20 mm deformation, or soonest), and

9. Conditioning time (20 minutes for wet testing and 60 minutes for dry testing after reaching target test temperature) after the specimens reaching the target temperature.

During the test, data are displayed on the monitor including number of wheel passes, deformation for each sample and elapsed test time. The control program ends the test based on the above test criteria. The data file can be transferred to any spreadsheet software for analysis and graphical presentation.

5.5 Results and Analysis

5.5.1 Wheel Track Testing Evaluation

Permanent deformation on the pavement surface usually includes two different modes. According to Huang (1995), these two modes are compactive deformation and plastic deformation. The first mode (compactive) is identified where the deformed surface is lower than the initial pavement surface. This type of deformation occurs in the wheel path. The second mode (plastic) is where the deformed surface that is higher than the original surface. It is often referred to as "heave" and occurs between and outside the wheel path. Rutting data recorded during PURWheel tests included only the compactive deformation. Total or "stringline" rutting is measured manually after completion of each test. Difference in the total rut and compactive rutting is the plastic or "heave" rutting component. A relationship was developed between the wheel track "rutting" (compactive deformation) and total rutting (rut depth). This relation has a goodness of fit of 0.96. The relationship is:

$$\text{Rut Depth} = 0.0153(\text{Deformation})^2 + 1.3144(\text{Deformation}) \qquad (5.2)$$

where:

Deformation = Rut depth recorded by the transducer, mm

Rut Depth = Total rut depth measurement under the straight-edge, mm

Figure 5.16 illustrates the relationship between PURWheel deformation data and measured rut depth. A rut depth level of 12.7 mm was adopted for evaluating the rutting potential of the mix. It is equal to an 8.9 mm wheel track rut depth using equation 5.2. The 8.9 mm wheel track rut depth allows for the relative performance evaluation of mixtures tested at the same temperature. This number was selected because it is possible to retain water on a highway surface creating hydroplaning potential (Shahin and Kohn, 1979). Experience also shows that once the rut depth exceed 15 mm wheel path cracking is likely. This creates an access for water and accelerates failure (Croney, 1991)

5.5.2 Results and Analysis for The Surface Mixtures

Results from laboratory wheel tests are shown in Figure 5.17 to Figure 5.21. Triplicate samples were prepared and tested to included the effect of sample variation. The summary of deformation rates is shown in Table 5.1. These rates were calculated by determining the number of wheel passes resulting in a 12.7 mm rut depth. From test results, it is obvious that damage occurs much faster with wet conditions. Also, temperature is an important factor in rutting. None of those surface mixtures finished 20,000 wheel passes in the PURWheel tests. All three surface mixes showed almost a straight deformation curve without a creep deformation stage. This shows that the mix has already lost its structural integrity and can not resist the 620 kPa tire loading. A high amount of natural sand utilized in the #11 surface mix may cause a progressively poor performance.

An analysis of variance (ANOVA) was performed on PURWheel test results to determine the significance of certain factors and/or interactions of factors. The class level information is illustrated in Table 5.2 and Table 5.4. Table 5.3 and Table 5.5 list the summaries of the General Linear Models (GLM) analysis. Independent variables in the analysis were types of aggregate (AGG), types of treatments (TREAT), moisture conditions (MOISTURE), and air void content (AIRVOID). Each independent variables had 3, 3, and 2 levels, respectively. The dependent variable was the wheel passes to reach a 12.7 mm rut (WPASS). Due to the incomplete experimental design for all combinations of factors investigated, the statistical analyses were performed among two sub-blocks of the experimental design that were complete for some combinations of the factors.

The GLM analysis indicated that the main effects, type of aggregate and air void content, both had significant effect on the rate of rutting. The analysis also shows that moisture conditioning and antistripping agents are significant in the test.

A Tukey's Studentized Range (HSD) Test was also performed to examine variability among types of aggregate as well as the effect of treatment on the number of wheel passes. Table 5.6 and Table 5.7 shows a summary of the statistical analysis. It indicates that rate of rutting for dolomite mixtures is higher than limestone and slag mixtures. Results also indicate that only hydrated lime improved the rutting performance for the #11 dolomite surface mixtures. The interaction effects mean with higher air void content progressively poorer performance can be expected when combined with moisture. Hydrated lime treatment mitigates the poorer performance. The dolomite mix was used

in a highway pavement project (Interstate I-64) and exhibited significant rutting/stripping problems in less than three years (Figure 5.30).

5.5.3 Results and Analysis for #8 Binder Mixtures

Results from laboratory wheel tests are shown in Figure 5.22 to Figure 5.26. Triplicate samples were prepared and tested to included the effect of sample variation. Data for rate of deformation at 12.7 mm rut depth are shown in Table 5.8. Compared to #11 surface mixtures #8 binder mixtures perform better. For example, the #8 slag binder mixture all had less than 5 mm deformation after 20,000 wheel passes.

Analysis of variance (ANOVA) of #8 binder mixture results included as independent variables types of aggregate (AGG), types of treatments (TREAT), moisture conditions (MOISTURE), and air void content (AIRVOID). Each independent variable had 3, 3, and 2 levels, respectively. The class level information is illustrated in Table 5.9 and Table 5.11. The dependent variable was the wheel passes to reach a 12.7 mm rut (WPASS). Table 5.10 and Table 5.12 shows results of the General Linear Models (GLM) analysis. No effects are significant at 95 percent confidence level. However, types of aggregate were significant at 90 percent level. The analysis also showed that air void content, moisture condition, and antistripping agents were not significant. The latter confirms the AASHTO T-283 test results discussed in Chapter Four.

A Tukey's Studentized Range (HSD) Test was performed to examine variability among types of aggregate on the number of wheel passes. Table 5.13 show a summary of

the statistical analysis. It indicates that the slag mixtures were more rut resistance than the gravel and limestone mixtures.

5.5.4 Results and Analysis for Base Mixtures

Results from laboratory wheel tests of #5C base mixtures are shown in Figure 5.27 to Figure 5.29. Triplicate samples were prepared and tested to included the effect of sample variation. A lower rutting criteria of 6.35 mm was utilized to evaluate base mixtures because the overall level of rutting for these mixtures was less than surface and binder mixtures. Data for rate of deformation at the 6.35 mm rut depth are also shown in Table 5.14. The #5C base mixtures show good rutting/stripping performance with some mixtures having less than 5 mm deformation after 20,000 wheel passes.

Independent variables in the analysis of variance (ANOVA) were types of treatments (TREAT), moisture conditions (MOISTURE). There were 3 and 2 levels, respectively. Air void content (AIRVOID) is also one of the independent variables. Each independent variables had 3, 3, levels respectively. The class level information is illustrated in Table 5.15. The dependent variable was the wheel passes to reach a 6.35 mm rut (WPASS). Table 5.16 shows results of the General Linear Models (GLM) analysis. The GLM analysis indicates that moisture condition was the only significant factor in the GLM model. Other main effects and interaction effects were not significant in the GLM model. This means that moisture increases the rate of rutting.

5.6 Summary

Laboratory wheel tracking test results for all seven types of mixtures indicated that temperature and moisture conditions were significant. It is obvious that damage occurs much faster with wet conditions. Both factors are important in identifying stripping/rutting potential.

Aggregate type has a significant effect on the wheel track test results. Limestone and slag generally provided better performance than other types of aggregate in this study. Examination of the performance of Indiana #11 surface mixture shows that a higher percentage of natural sand causes progressively poorer performance. This is not true for binder mixtures for the amount of natural sand utilized.

The effect of the antistripping agents is not significant in the test. However, a comparison of hot/wet and hot/dry test results indicates the moisture damage is associated with excessive deformation.

In this study, the dolomite mix performed poorly in both wet and dry conditions. This may be due to the high asphalt content of the #11 dolomite surface mix itself. The dolomite mixture was reproduced from aggregates utilized on a distressed section of Indiana I-64 in the Vincennes district (Figure 5.30). Distresses in the laboratory wheel track tests were similar. Review of this mixture in-place on interstate highway I-64, the pavement exhibits similar distresses as the wheel track testing samples revealed. A field investigation is needed to correlate laboratory test results to the actual field performance.

Table 5.1 # 11 Surface Wheel Track Test Results Summary (Wheel Passes @12.7 mm

Rut)

Types of Agg.	Dry Test (Air Voids, %)	Passes @ 6% Air Voids	Wet Test (Air Voids, %)	Passes @ 6% Air Voids	Wet/Dry Ratio
#11 Slag	3750 (5.79)	3371	1550 (6.79)	1138	0.34
	2650 (6.53)		1070 (6.01)		
	1900 (8.12)		660 (6.92)		
#11 Limestone	2600 (4.17)	2535	1300 (4.24)	1477	0.58
	5170 (3.44)		1840 (3.64)		
	2850 (6.03)		1290 (4.55)		
#11 Dolomite	350 (4.59)	585	291 (4.03)	146	0.25
	82 (8.53)		108 (6.44)		
	70 (8.96)		133 (6.25)		
#11 Dolomite w/ Chemical	375 (4.98)	231	333 (3.55)	223	0.97
	150 (6.81)		310 (5.66)		
	107 (6.65)		128 (6.95)		
#11 Dolomite w/ Lime	1040 (3.10)	296	600 (2.83)	291	0.98
	330 (5.84)		250 (6.49)		
	130 (6.67)		200 (6.88)		

Table 5.2 Class Level Information-#11 Dolomite Surface Mix

Class	Levels	Values		
TREAT	3	CONTROL	CHEMICAL	LIME
MOISTURE	2	DRY	WET	
Number of observations in data set = 18				

Table 5.3 Summary of Statistical Analysis for #11 Dolomite Surface Mixtures

Dependent Variable: WPASS					
Source	df	SS	MS	F stat	Prob. > F
Model	11	924744.60	84067.69	52.63	0.0001
Error	6	9584.35	1597.39		
Total	17	934328.94			
		R-Square	Adj. R-Sq.	Root MSE	Mean
		0.99	0.97	39.97	277.06
Source	df	Type 1 SS	MS	F stat	Prob. > F
TREAT	2	76264.18	38132.09	23.87	0.0014
MOISTURE	1	56412.06	56412.06	35.32	0.0010
AIRVOID	1	578401.75	578401.75	362.09	0.0001
AIRVOID*TREAT	2	90413.49	45206.74	28.30	0.0009
AIRVOID*MOISTURE	1	70896.36	70896.36	44.38	0.0006
TREAT*MOISTURE	2	6536.64	3268.32	2.05	0.2101
AIRVOID*TREAT *MOISTURE	2	45820.12	22910.06	14.34	0.0052

Table 5.4 Class Level Information-#11 Surface Mix

Class	Levels	Values		
AGG	3	DOLOMITE	LIMESTONE	SLAG
MOISTURE	2	DRY	WET	
Number of observations in data set = 18				

Table 5.5 Summary of Statistical Analysis for #11 Surface Mixtures

Dependent Variable: WPASS					
Source	df	SS	MS	F stat	Prob. > F
Model	11	31877199.80	2897927.26	6.02	0.0192
Error	6	2883563.97	480593.99		
Total	17	34760763.80			
		R-Square	Adj. R-Sq.	Root MSE	Mean
		0.92	0.77	693.25	1536.89
Source	df	Type 1 SS	MS	F stat	Prob. > F
AGG	2	13056942.50	6528471.23	13.58	0.0059
MOISTURE	1	9351038.03	9351038.03	19.46	0.0045
AIRVOID	1	5311915.71	5311915.71	11.05	0.0159
AIRVOID*AGG	2	617163.60	308581.80	0.6421	0.5589
AIRVOID*MOISTURE	1	545393.91	545393.91	1.13	0.3277
AGG*MOISTURE	2	2831896.18	1415948.09	2.95	0.1284
AIRVOID*AGG *MOISTURE	2	162849.92	81424.96	0.17	0.8481

Table 5.6 Mean Comparison of wheel Passes for Different Aggregate Types(#11 Surface)

Aggregate	Mean	N	Tukey Grouping
Limestone	2508.3	6	A
Slag	1930.0	6	A
Dolomite	172.3	6	B
Alpha = 0.05, df = 6, MSE = 480594			
Critical Value of Studentized Range = 4.339			
Min. Significant Difference = 1228			

Table 5.7 Mean Comparison of Wheel Passes for Different Treatments (#11 Dolomite)

Treatment	Mean	N	Tukey Grouping
Hydrated Lime	425.0	6	A
Liquid Additive	233.8	6	B
Control	172.3	6	B
Alpha = 0.05, df = 6, MSE = 1597.391			
Critical Value of Studentized Range = 4.339			
Min. Significant Difference = 70.798			

Table 5.8 # 8 Binder Wheel Track Test Results Summary (Wheel Passes @12.7 mm Rut)

Types of Agg.	Dry Test (Air Voids, %)	Passes @ 6% air Voids	Wet Test (Air Voids, %)	Passes @ 6% air Voids	Wet/Dry Ratio
#8 Slag	582888 (6.71)	332742	63549 (6.22)	73860	0.22
	85117 (7.36)		152863 (4.40)		
	296965 (4.91)		97777 (4.15)		
#8 Limestone	12000 (4.17)	11650	14250 (5.88)	11527	0.99
	9500 (6.15)		3750 (7.12)		
	8000 (6.87)		2500 (8.99)		
#8 Gravel	8000 (6.87)	16358	9000 (9.75)	8544	0.52
	13000 (4.87)		8500 (5.64)		
	31502 (5.53)		2250 (6.63)		
#8 Gravel w/ Chemical	10750 (4.73)	7644	4500 (7.53)	7785	1.02
	4000 (4.87)		9250 (5.71)		
	8000 (6.19)		4750 (6.62)		
#8 Gravel w/ Lime	10750 (4.52)	5833	14000 (5.17)	10616	1.82
	3750 (5.67)		11000 (6.20)		
	6500 (6.43)		8500 (5.40)		

Table 5.9 Class Level Information-#8 Gravel Mix

Class	Levels	Values		
TREAT	3	CONTROL	CHEMICAL	LIME
MOISTURE	2	DRY	WET	
Number of observations in data set = 18				

Table 5.10 Summary of Statistical Analysis for #8 Gravel Mixtures

Dependent Variable: WPASS					
Source	df	SS	MS	F stat	Prob. > F
Model	11	254798511.0	23163501.0	0.7035	0.7102
Error	6	197562601.0	32927100.1		
Total	17	452361111.0			
		R-Square	Adj. R-Sq.	Root MSE	Mean
		0.5633	0	5738.21	8972.22
Source	df	Type 1 SS	MS	F stat	Prob. > F
TREAT	2	73524503.20	36762251.60	1.12	0.3871
MOISTURE	1	1212040.88	1212040.88	0.0368	0.8542
AIRVOID	1	31527207.80	31527207.80	0.96	0.3656
AIRVOID*TREAT	2	2127113.85	1063556.93	0.0323	0.9684
AIRVOID*MOISTURE	1	2291304.91	2291304.91	0.0696	0.8008
TREAT*MOISTURE	2	116471029.00	58235514.30	1.7686	0.2490
AIRVOID*TREAT *MOISTURE	2	27645311.20	13822655.60	0.4198	0.6751

Table 5.11 Class Level Information-#8 Binder Mix

Class	Levels	Values		
AGG	3	GRAVEL	LIMESTONE	SLAG
MOISTURE	2	DRY	WET	
Number of observations in data set = 18				

Table 5.12 Summary of Statistical Analysis for #8 Binder Mixtures

Dependent Variable: WPASS					
Source	df	SS	MS	F stat	Prob. > F
Model	11	2.416E+11	2.196E+10	1.0681	0.4931
Error	6	1.234E+11	2.056E+10		
Total	17	3.650E+11			
		R-Square	Adj. R-Sq.	Root MSE	Mean
		0.66	0.04	143394.28	77856.17
Source	df	Type 1 SS	MS	F stat	Prob. > F
AGG	2	1.589E+11	7.946E+10	3.8644	0.0835
MOISTURE	1	3.086E+10	3.086E+10	1.5006	0.2665
AIRVOID	1	7.410E+09	7.410E+09	0.3604	0.5703
AIRVOID*AGG	2	401801307	200900653	0.0098	0.9903
AIRVOID*MOISTURE	1	2.250E+09	2.250E+09	0.1094	0.7521
AGG*MOISTURE	2	4.169E+10	2.084E+10	1.0138	0.4176
AIRVOID*AGG *MOISTURE	2	57202428	28601214	0.9986	0.9986

Table 5.13 Mean Comparison of wheel Passes for Different Aggregate Types(#8 Binder)

Aggregate	Mean	N	Tukey Grouping
Slag	213193	6	A
Gravel	12042	6	B
Limestone	8333	6	B
Alpha = 0.10, df = 6, MSE = 1.543E10			
Critical Value of Studentized Range = 3.374			
Min. Significant Difference = 171090			

Table 5.14 # 5C Base Wheel Track Test Results Summary (Wheel Passes @6.35 mm

Rut)

Types of Agg.	Dry Test (Air Voids, %)	Est. Passes @ 6% Air Voids	Wet Test (Air Voids, %)	Est. Passes @ 6% Air Voids	Wet/Dry Ratio
#5C Limestone	18109 (6.09)	21616	7000 (4.92)	11200	0.52
	26230 (6.54)		11000 (6.76)		
	100860 (6.44)		16000 (6.44)		
#5C Limestone w/ Chemical	18250 (7.39)	30651	6500 (6.41)	5833	0.19
	31502 (5.78)		5000 (6.65)		
	29886 (7.33)		6250 (6.59)		
#5C Limestone w/ Lime	60915 (6.12)	110567	7500 (5.88)	7925	0.07
	54490 (6.80)		10500 (7.85)		
	143660 (6.14)		10750 (7.25)		

Table 5.15 Class Level Information-#5C Base Mix

Class	Levels	Values		
TREAT	3	CONTROL	CHEMICAL	LIME
MOISTURE	2	DRY	WET	
Number of observations in data set = 18				

Table 5.16 Summary of Statistical Analysis for #5C Base Mixtures

Dependent Variable: WPASS					
Source	df	SS	MS	F stat	Prob. > F
Model	9	1.699E+10	1.887E+09	2.2017	0.1401
Error	8	6.857E+09	857169827		
Total	17	2.384E+10			
		R-Square	Adj. R-Sq.	Root MSE	Mean
		0.7124	0.3888	29277.46	31355.67
Source	df	Type 1 SS	MS	F stat	Prob. > F
TREAT	2	2.705E+09	1.353E+09	1.5781	0.2644
MOISTURE	1	9.272E+09	9.272E+09	10.8174	0.0110
AIRVOID	1	717120510	717120510	0.8366	0.3871
AIRVOID*TREAT	2	2.178E+09	1.089E+09	1.2706	0.3317
AIRVOID*MOISTURE	1	78894311.1	78894311.1	0.0920	0.7693
MOISTURE*TREAT	2	2.033E+09	1.017E+09	1.1860	0.3539
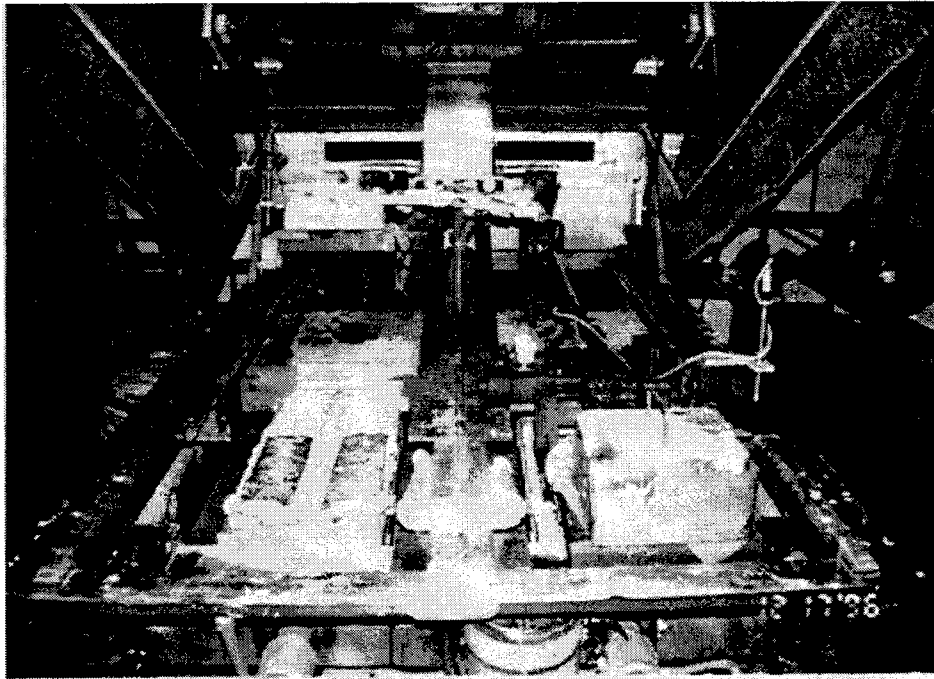
Figure 5.1 Purdue Wheel Track Testing Device
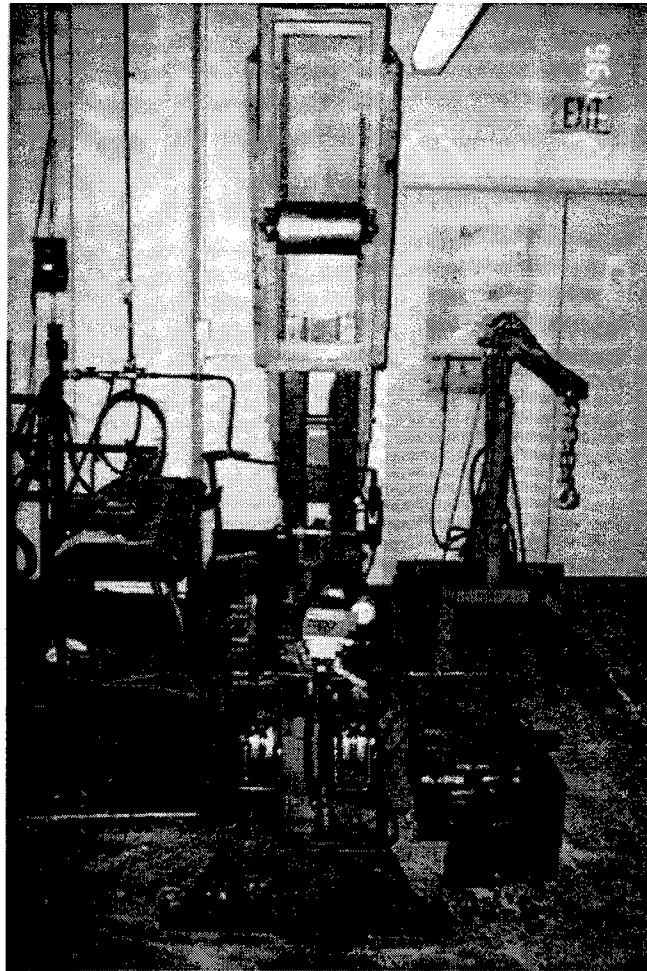
Figure 5.2 Purdue Linear Compactor
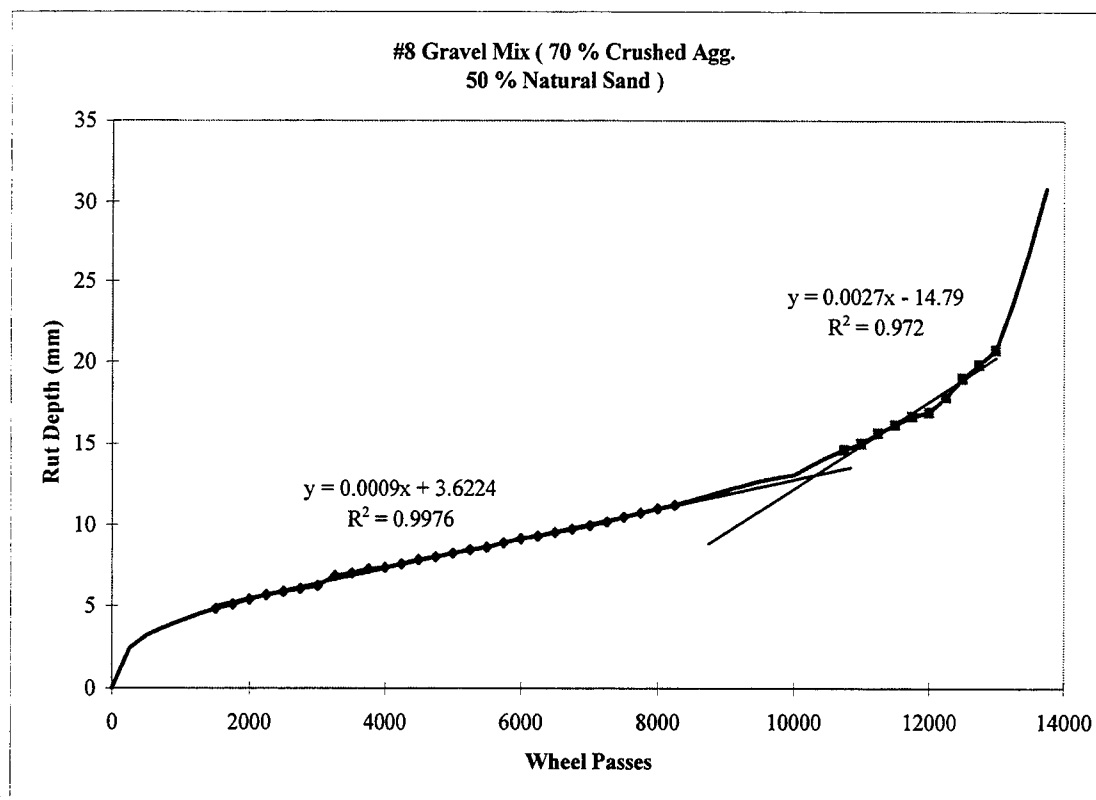
Figure 5.3 Typical PURWheel Test Results
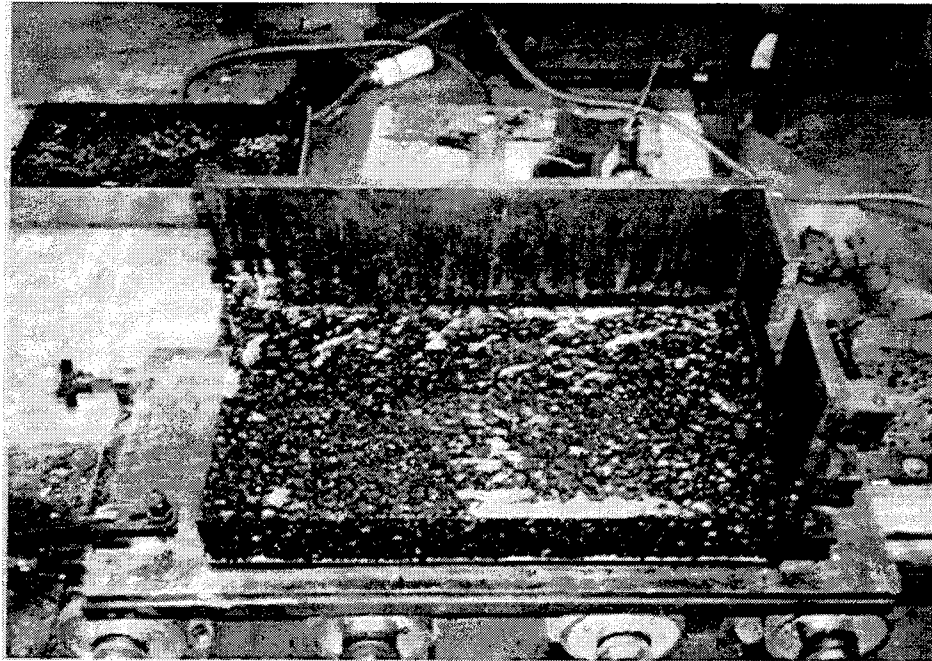
Figure 5.4 Linear Compactor Steel Mold Feature
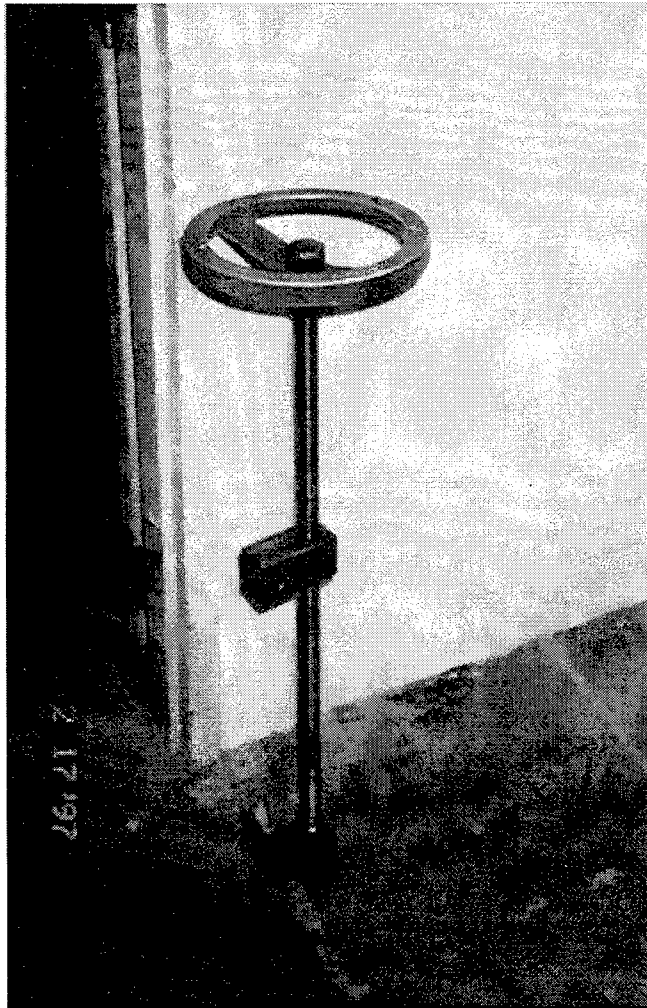
Figure 5.5 Threaded Rod
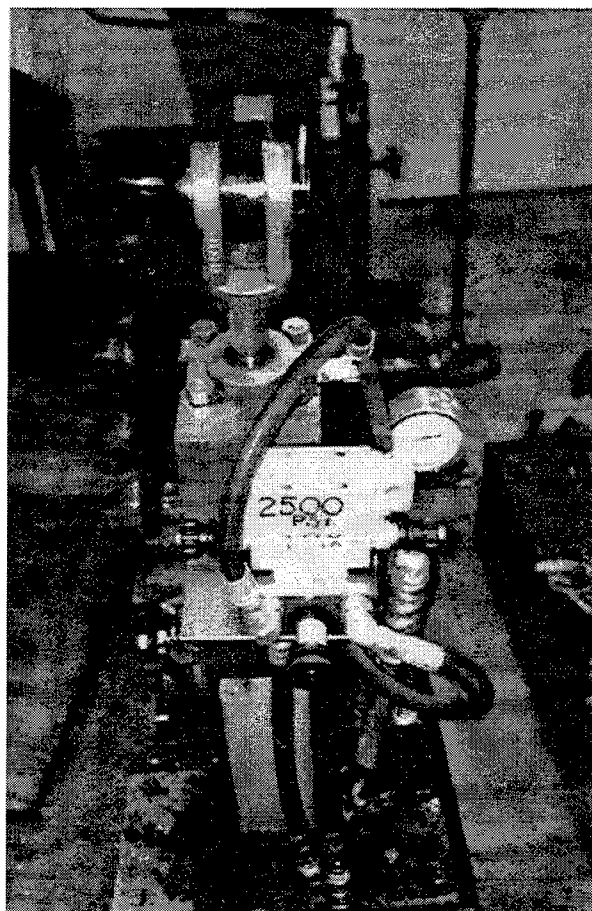
Figure 5.6 Hydraulic Loading Ram (red color)
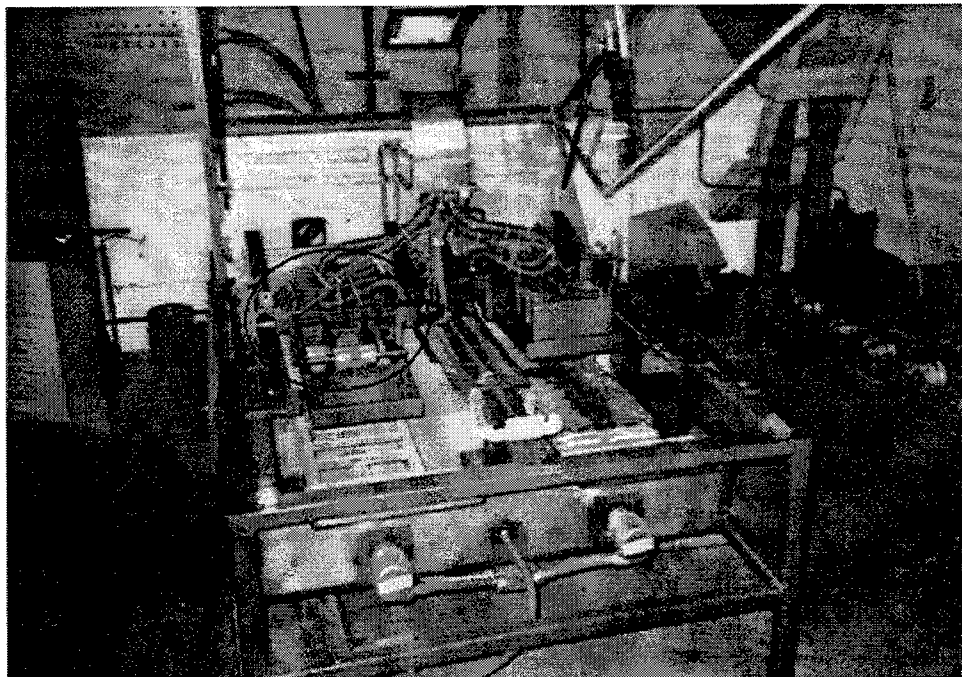
Figure 5.7 Wheel Wander Features
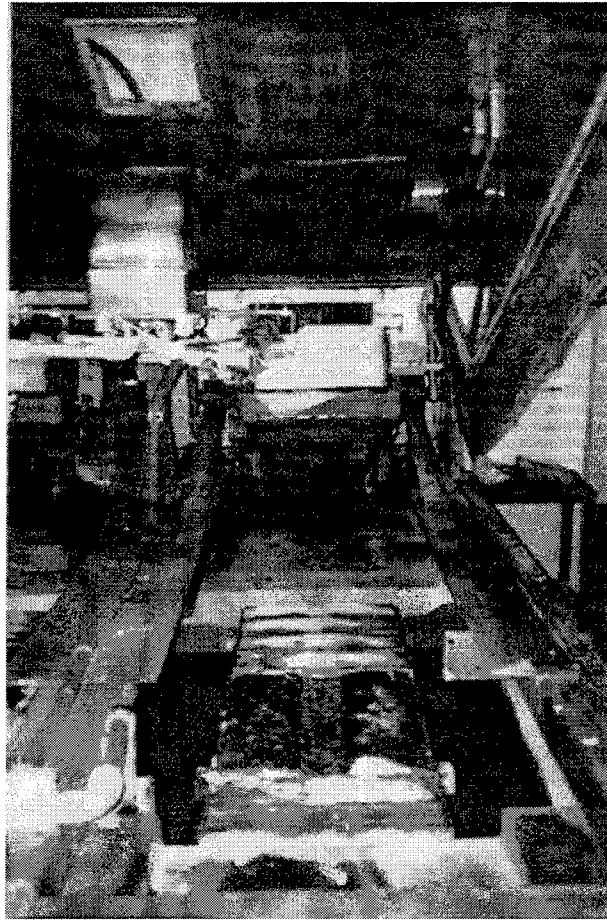
Figure 5.8 Sample Mounting Box
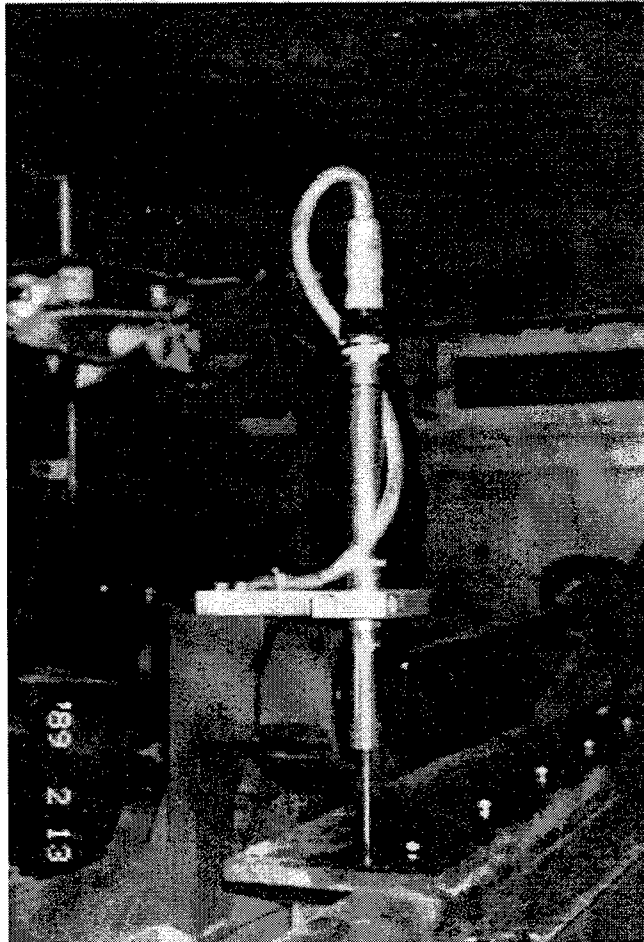
Figure 5.9 PUR Wheel Transducer
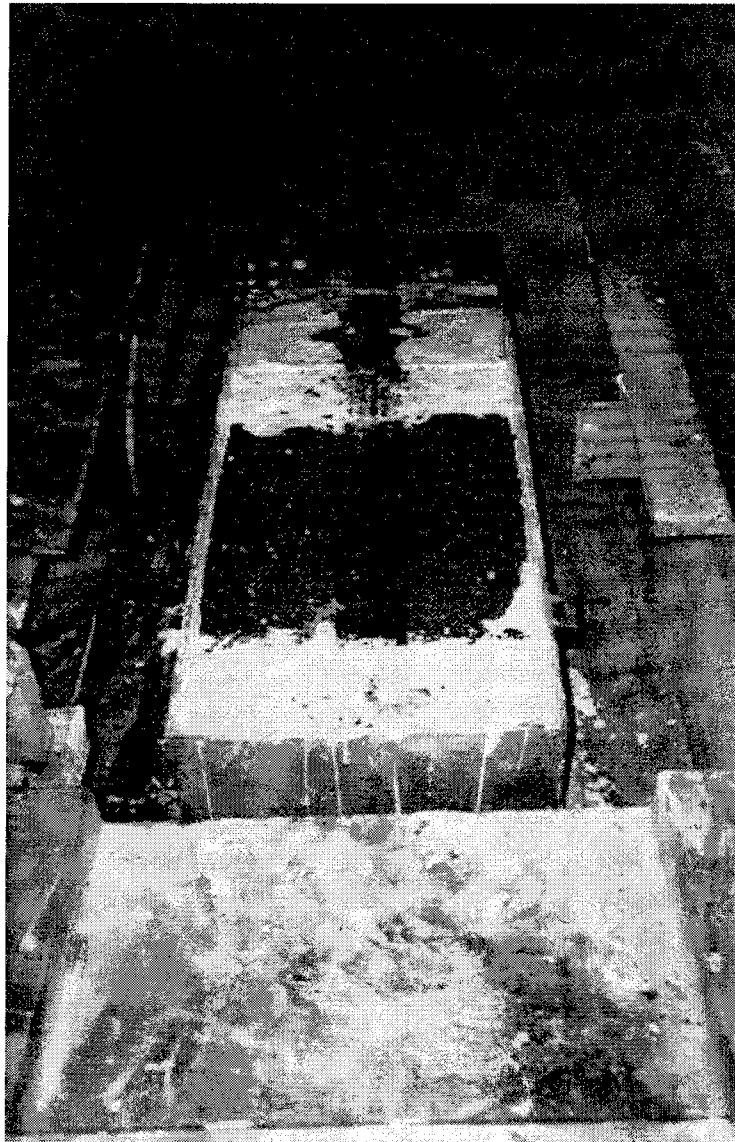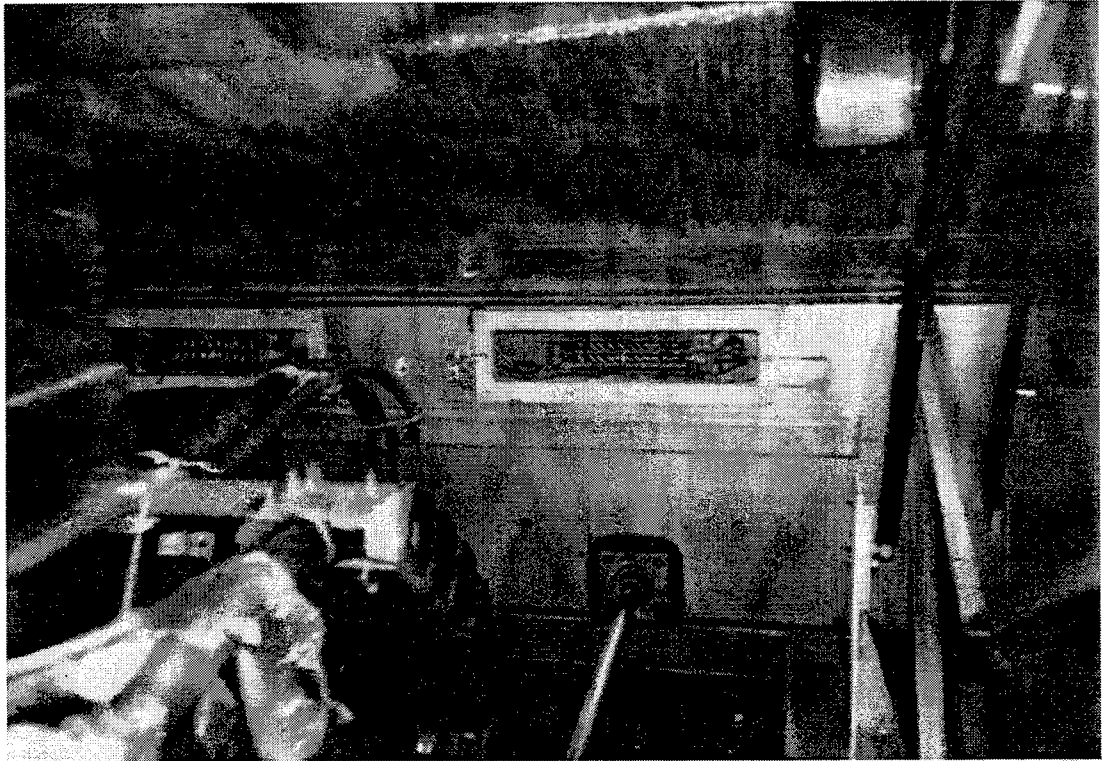
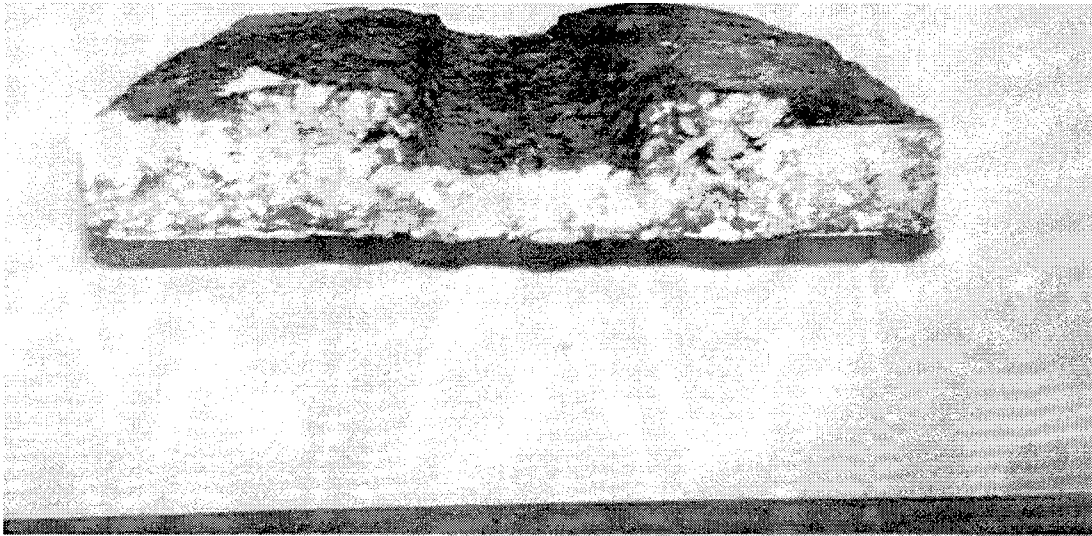Figure 5.10 Dry Cycle Heating Box

Figure 5.11 PURWheel Air Heater
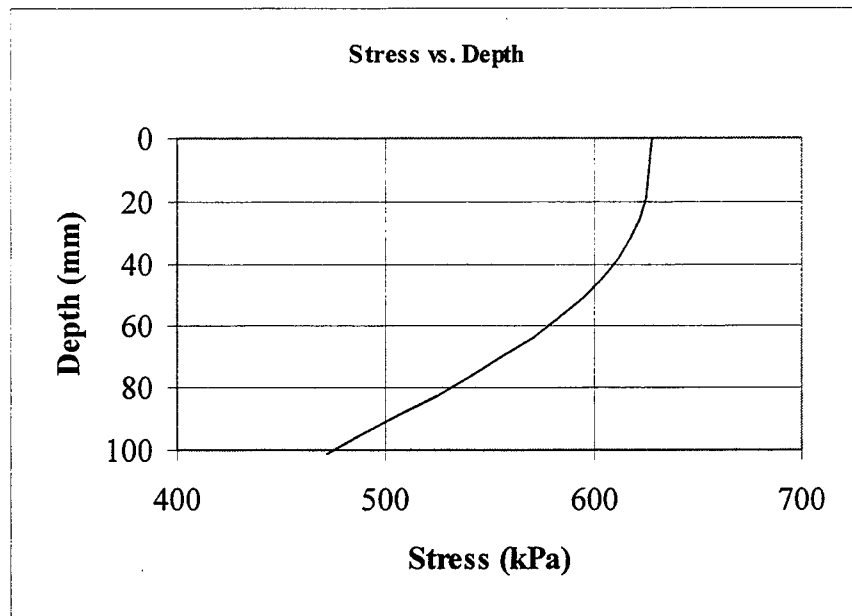
Figure 5.12 Typical Slab Section Deformation

Stress vs. Depth

Figure 5.13 Stress vs. Depth Relationship from BISAR
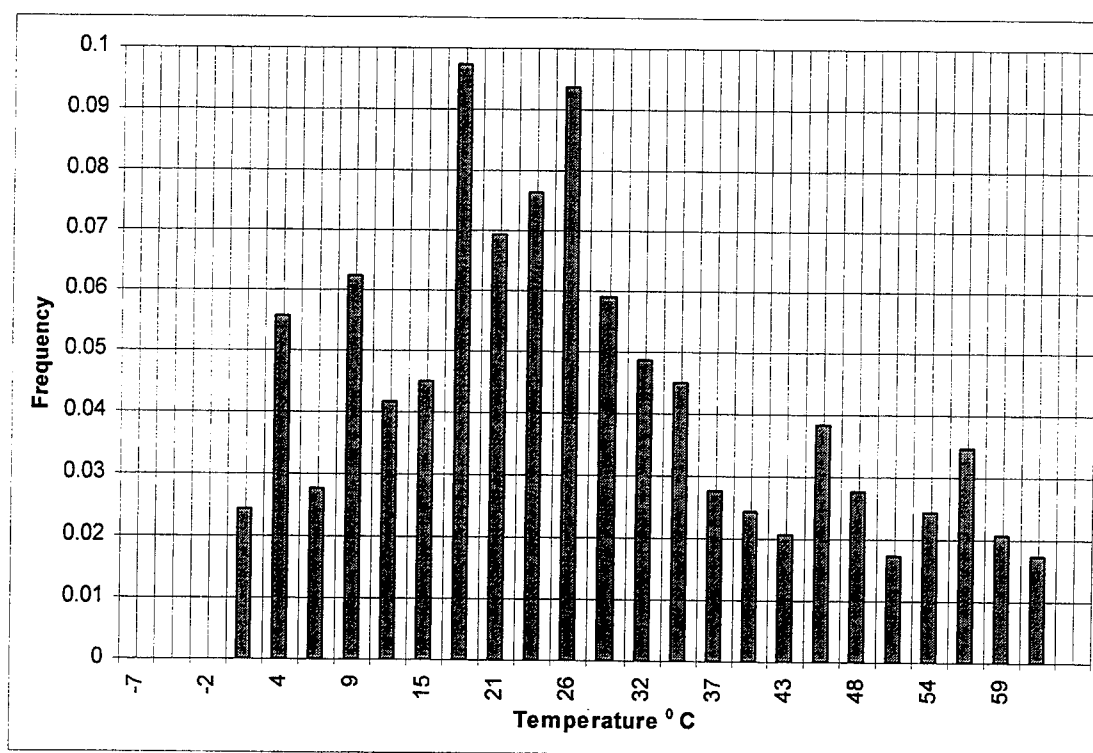
Figure 5.14 Highest Hourly Pavement Surface Temperature for Indiana (1993)
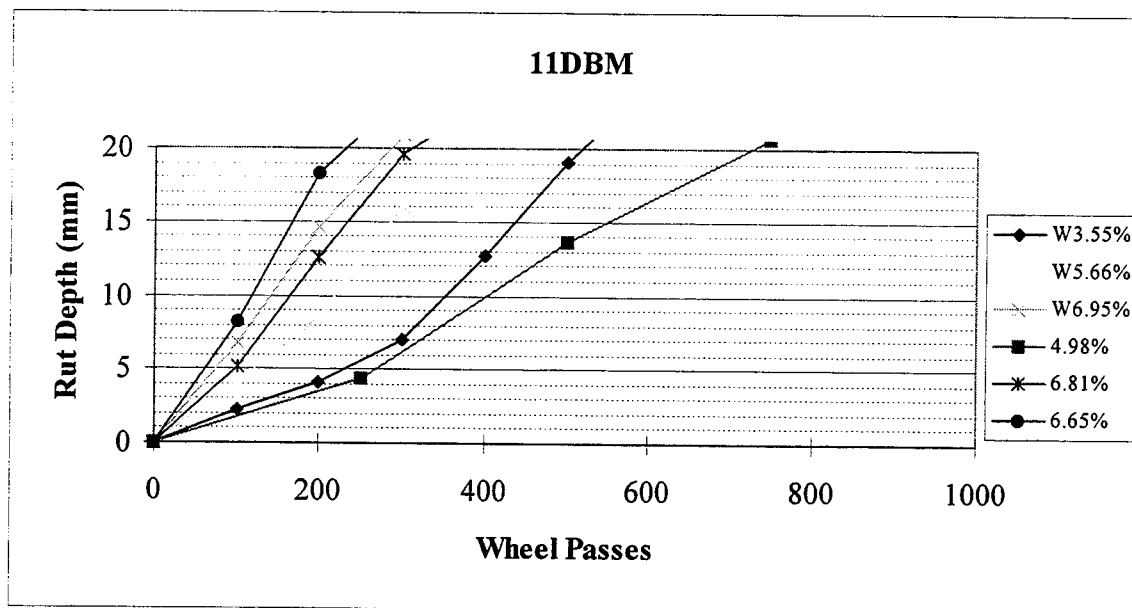
Figure 5.15 Mechanical Drum Mixer
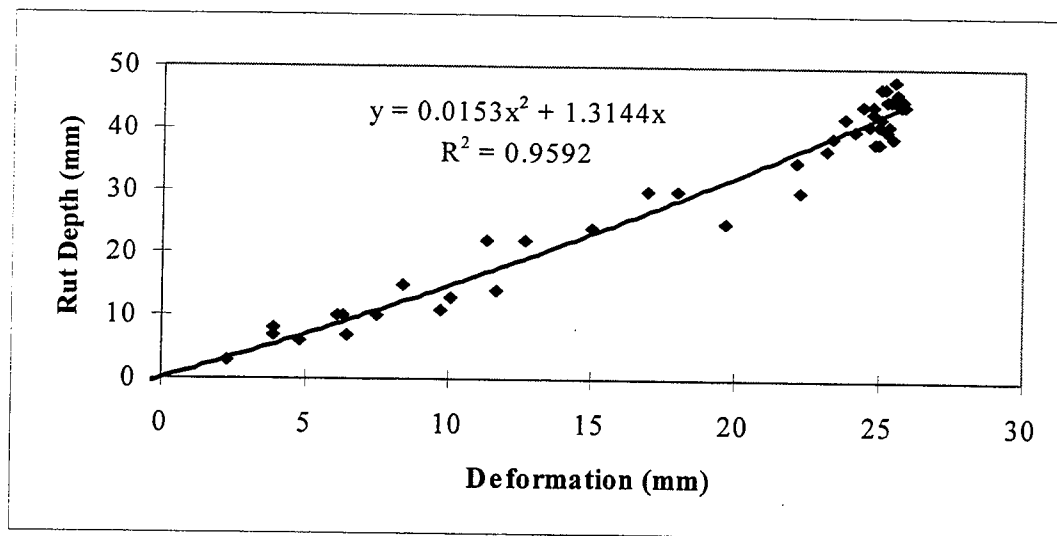
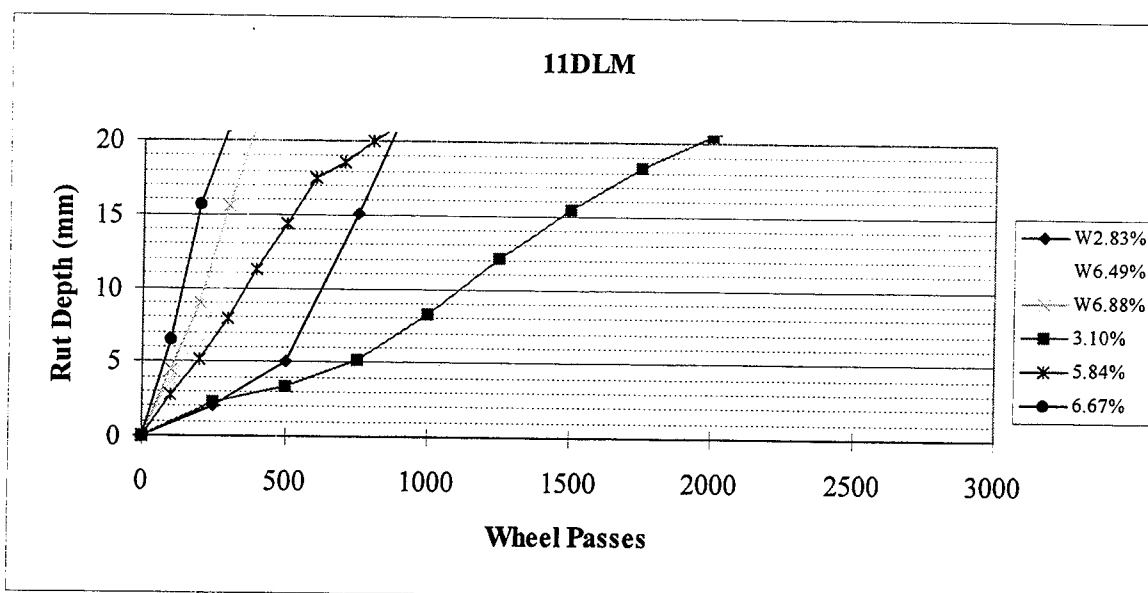Figure 5.16 Relationship Between PURWheel Deformation and Measured Rut Depth
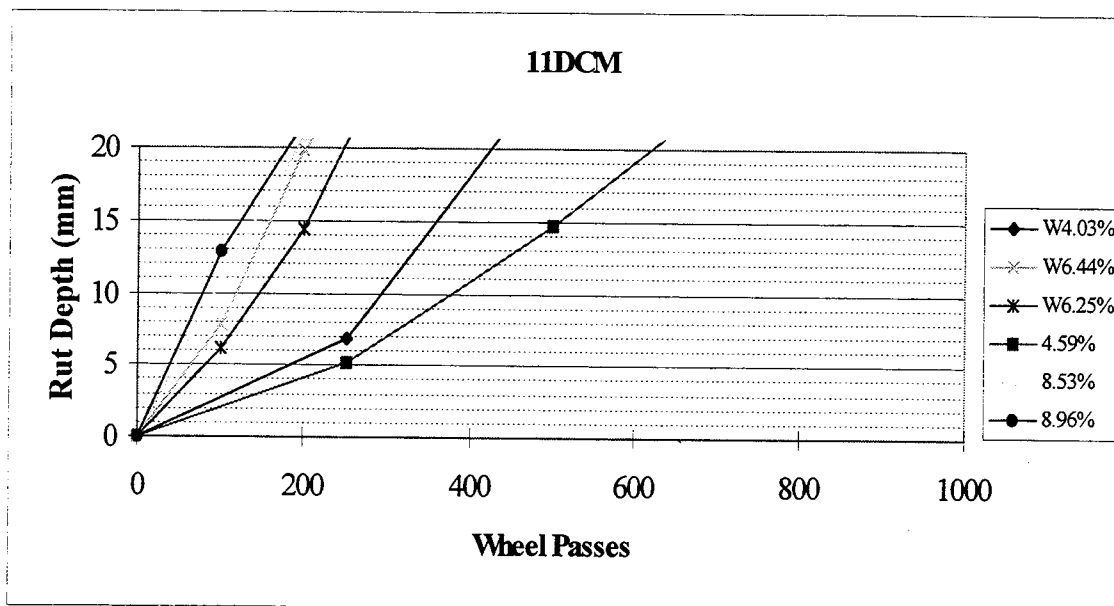
Figure 5.17 Wheel Track Test Results of Dolomite Surface Mixture, Control

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions (3 samples for either dry or wet conditions)
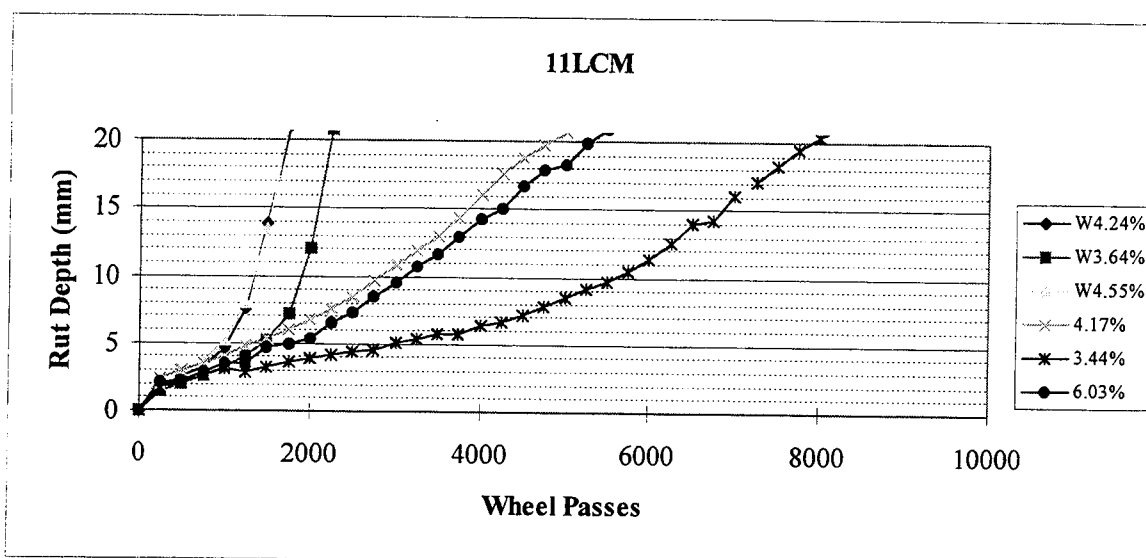

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions (3 samples for either dry or wet conditions)

Figure 5.18 Wheel Track Test Results of Dolomite Surface Mixture, Liquid Additive
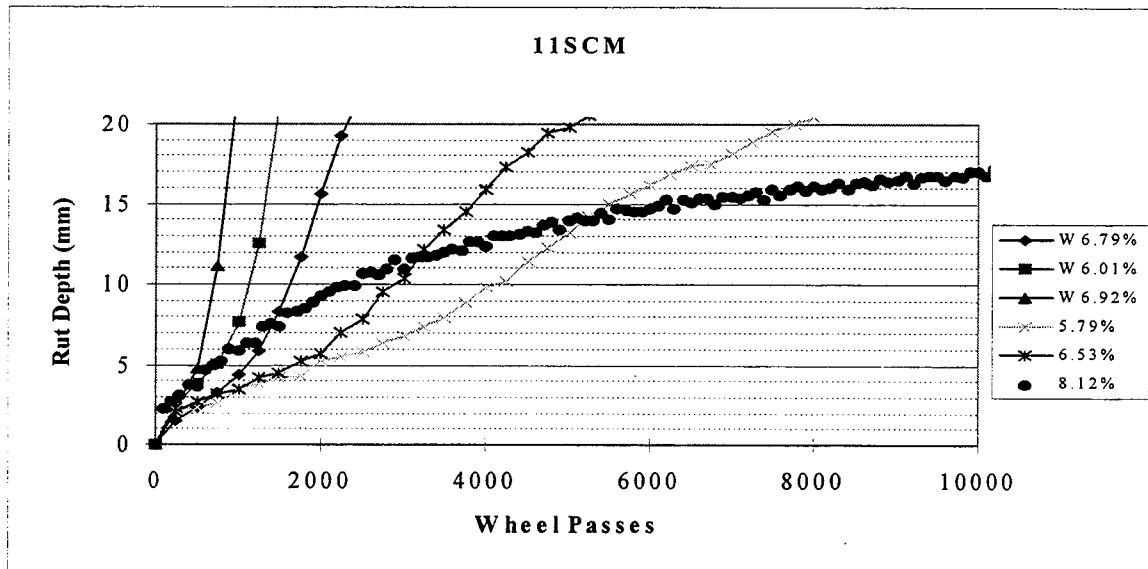
11DLM

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions (3 samples for either dry or wet conditions)

Figure 5.19 Wheel Track Test Results of Dolomite Surface Mixture, Hydrated Lime
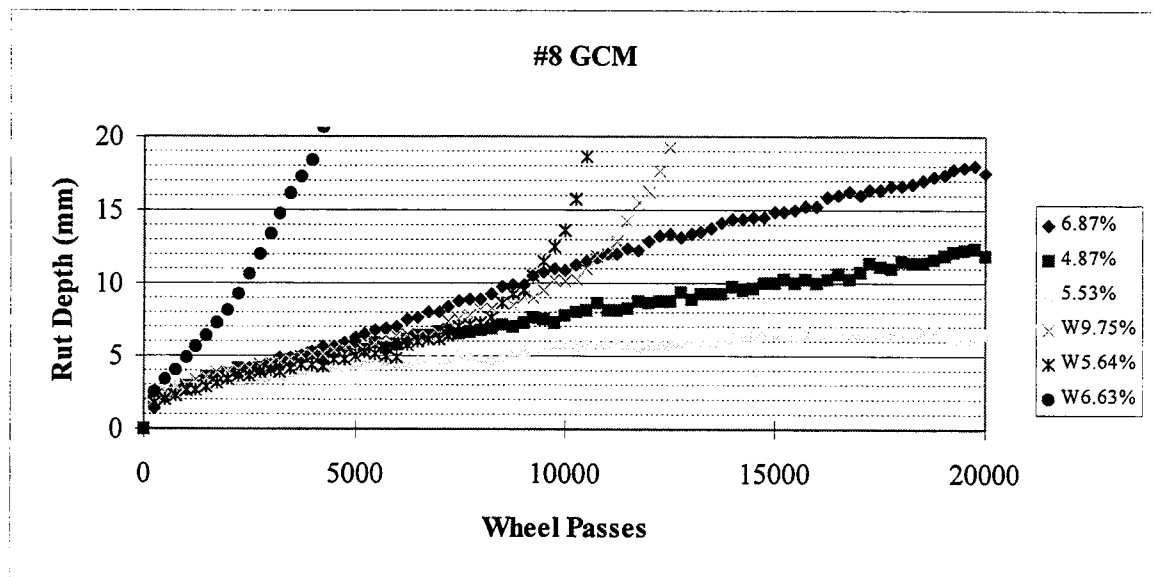
11LCM

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions (3 samples for either dry or wet conditions)

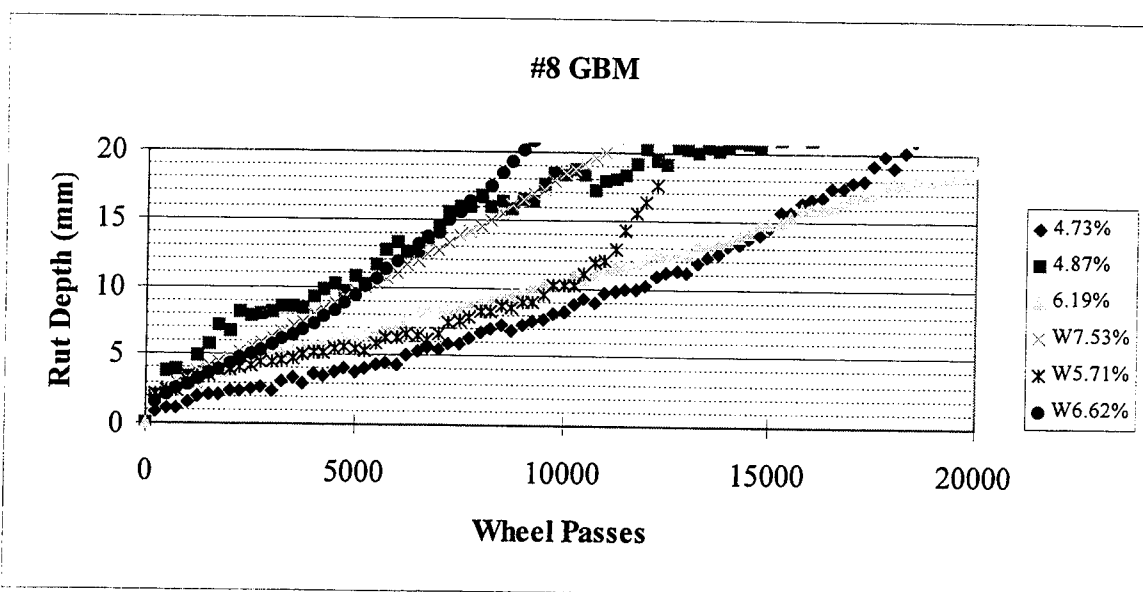Figure 5.20 Wheel Track Test Results of Limestone Surface Mixture, Control

11SCM

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions(3 samples for either dry or wet conditions)

Figure 5.21 Wheel Track Test Results of Slag Surface Mixture, Control
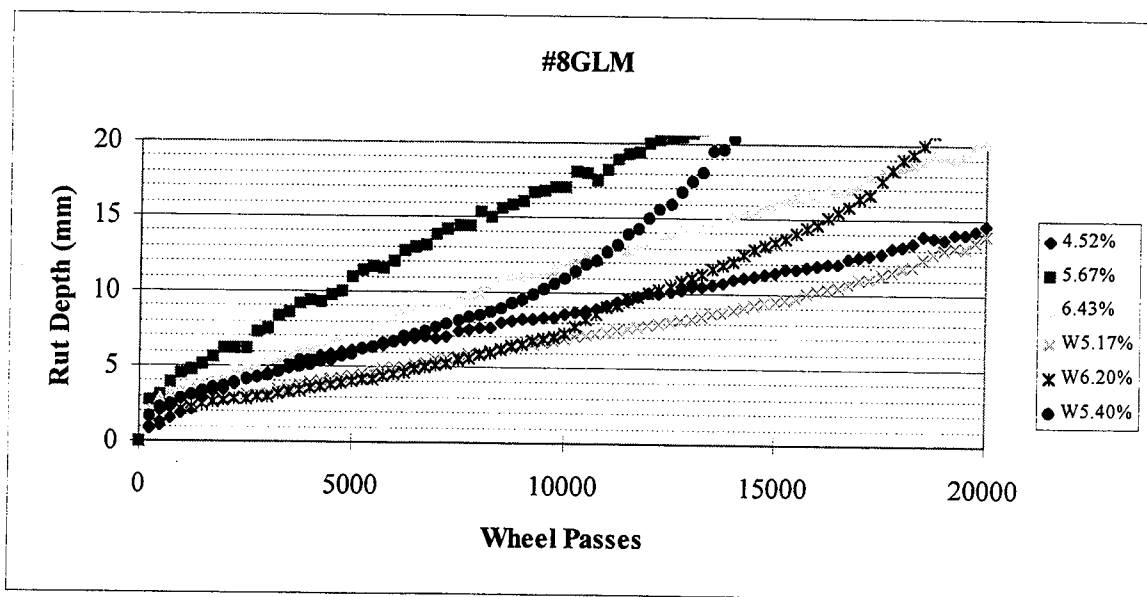
#8 GCM

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions (3 samples for either dry or wet conditions)

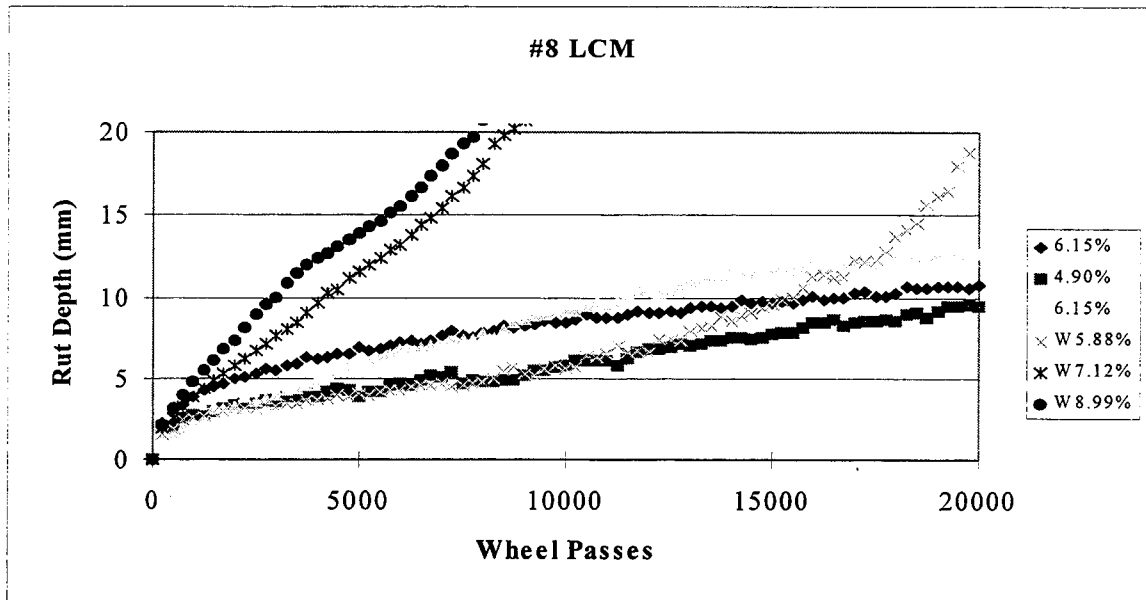Figure 5.22 Wheel Track Test Results of Gravel Binder Mixture, Control

#8 GBM

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions(3 samples for either dry or wet conditions)

Figure 5.23 Wheel Track Test Results of Gravel Binder Mixture, Liquid Additives
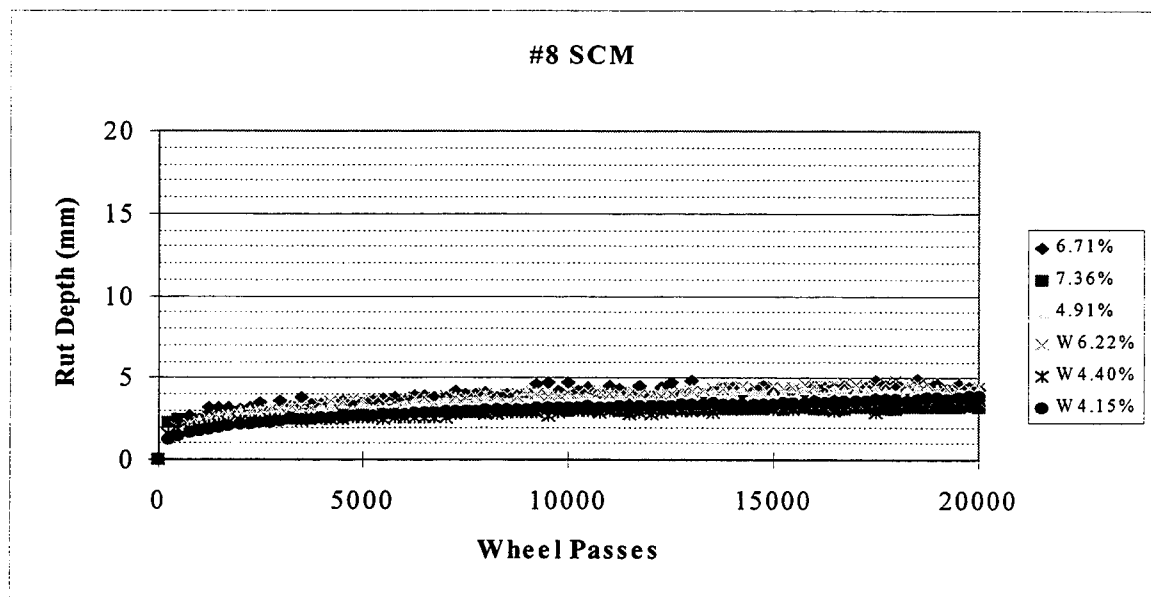
#8GLM

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions (3 samples for either dry or wet conditions)

Figure 5.24 Wheel Track Test Results of Gravel Binder Mixture, Hydrated Lime
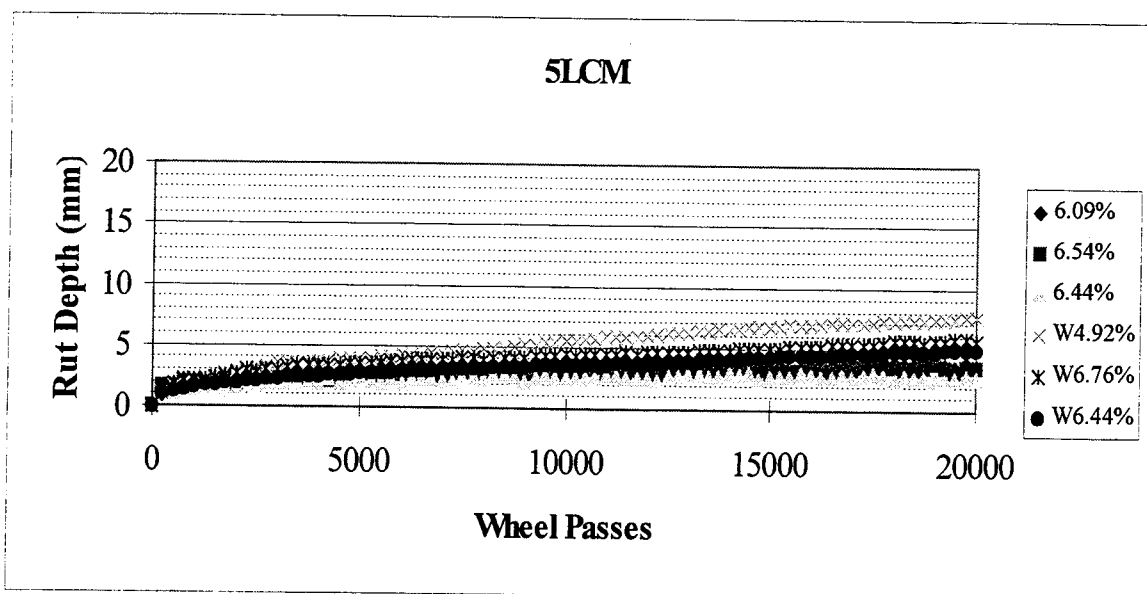
#8 LCM

Legend:
- ◆ 6.15%
- ■ 4.90%
- 6.15%
- ✕ W 5.88%
- ✱ W 7.12%
- ● W 8.99%

Rut Depth (mm) vs Wheel Passes

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions (3 samples for either dry or wet conditions)

Figure 5.25 Wheel Track Test Results of Limestone Binder Mixture, Control

#8 SCM

Legend:
- ◆ 6.71%
- ■ 7.36%
- 4.91%
- ✕ W 6.22%
- ✱ W 4.40%
- ● W 4.15%

Rut Depth (mm) vs Wheel Passes

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions (3 samples for either dry or wet conditions)

Figure 5.26 Wheel Track Test Results of Slag Binder Mixture, Control

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions (3 samples for either dry or wet conditions)

Figure 5.27 Wheel Track Test Results of Limestone Base Mixture, Control

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions (3 samples for either dry or wet conditions)

Figure 5.28 Wheel Track Test Results of Limestone Base Mixture, Liquid Additives

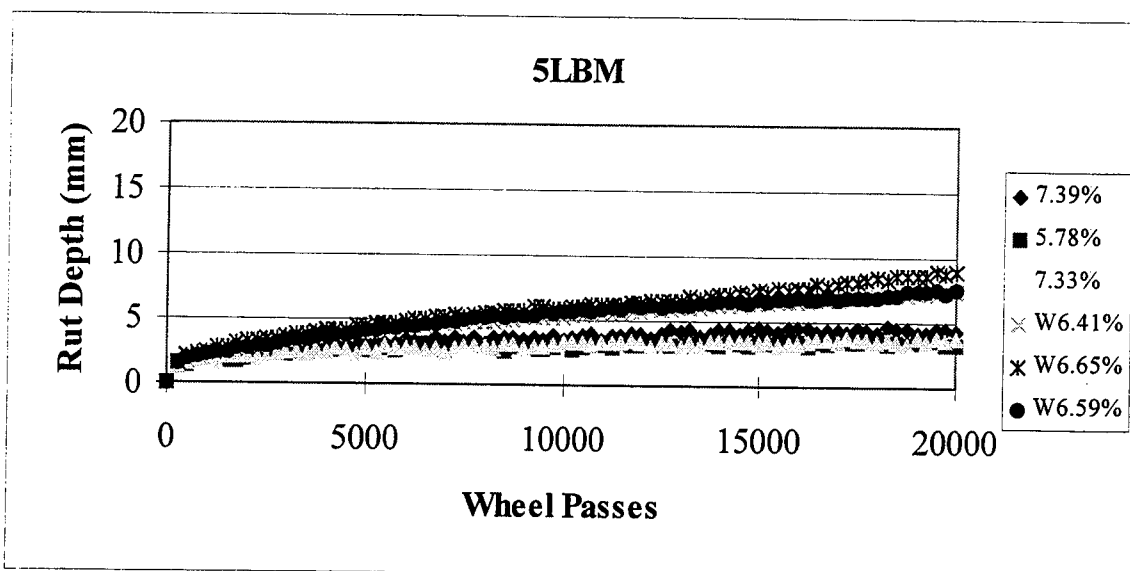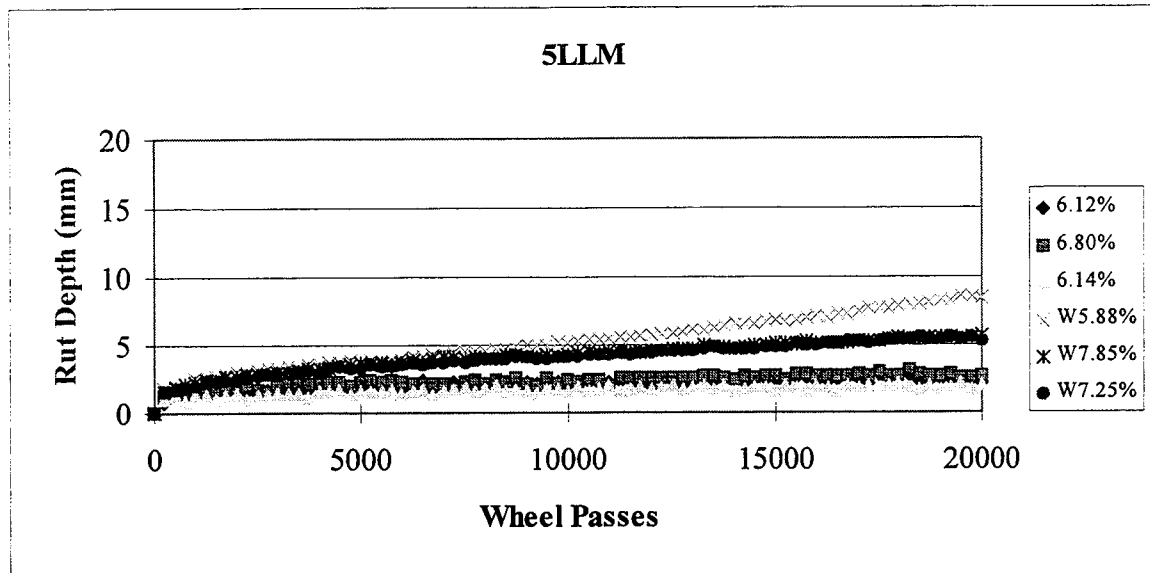Figure 5.29 Wheel Track Test Results of Limestone Base Mixture, Hydrated Lime

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions (3 samples for either dry or wet conditions)
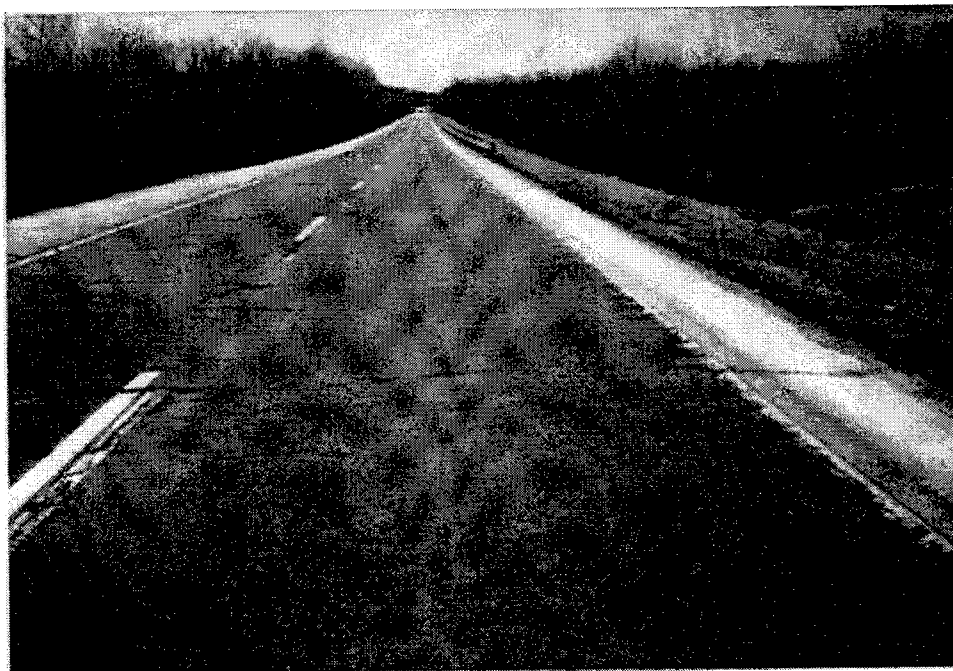

Figure 5.30 Typical Rutting and Corrugation Distress on I-64

CHAPTER 6 INFLUENCE OF TESTING TEMPERATURE AND MOISTURE ON PURWHEEL RESULTS

Permanent deformation is an important factor in flexible pavement performance. According to Huang (1996), most of the permanent deformation occurs in the upper layers due to the increase in traffic loads and tire pressure. The current research involved developing a technology for predicting and evaluating permanent deformation using a laboratory wheel tracking device (PURWheel). The development is based on conducting a laboratory wheel track tests to define key mix parameters related to deformation. Laboratory wheel track tests were conducted wet and dry and at different temperature. A finite element method (FEM) analysis was conducted to model permanent deformation occurred in the PURWheel tests.

6.1 Wheel Track Testing Results and Analysis

6.1.1 Temperature and Moisture Effects

Results from laboratory wheel tests are shown in Figure 6.1 to Figure 6.10. The summary of deformation rates is shown in Table 6.1. It is obvious that damage occurs much faster with wet conditions and temperature is an important factor in identifying rutting potential. For both #11 limestone and dolomite mixes, the number of wheel

passes required to reach a 12.7 mm (1/2 in.) rut increases as the testing temperature decreases. At 60^0 C, both mixes deformed rapidly without a creep deformation stage. This shows that the mix has already lost its integrity and can not resist the 620 kPa tire loading. At 50^0 C, the limestone mix is more stable than the dolomite mix.

Asphalt cement consistency is sensitive to the change of temperature. As a consequence, asphalt mixture stiffness is reduced at high ambient temperatures Mixture temperature susceptibility is depicted in Figure 6.11 and Figure 6.12. These figures indicated that there is a semi-log relationship between number of wheel passes required to reach a 12.7 mm rut and temperature. The rate of deformation at 40^0 C is ten times greater than that at 25^0 C.

6.1.2 Analysis for the Effect of Temperature and Moisture

Moisture condition is of importance in the evaluation process for asphalt concrete rutting/stripping potential. From Figure 6.11 and Figure 6.12, the performance-temperature relationship for the dry and wet conditions are represented by two essentially parallel curves through the test temperature range. These results indicate that additional rutting damage results from moisture over the temperature range of 25^0 C to 60^0 C. This maybe due to the hydraulic scouring mechanism and excessive pore pressure caused by the moving wheel loading. Additive rutting damage caused by moisture can be determined by subtracting it from the dry rutting damage. From Table 6.1, the Wet/Dry ratio of the deformation rates for both limestone and dolomite mixes are equal to 0.58 at

60^0 C. This means that both mixes experienced the same relative moisture damage in the wheel track test. From Figure 4.10, the same conclusions can be drawn for AASHTO T-283 test results, since the tensile strength ratio (TSR) for both mixtures is the same (TSR = 68%) and both AASHTO T-283 and PURWheel tests have the same conditioning temperatures at 60^0 C.

A regression analysis was performed to relate the effects of moisture and temperature to rutting. Moisture condition was used as a class variable. The form of this model for both the #11 limestone and #11 dolomite mixtures was as follows:

$$\text{Log}_{10} (\text{WHEEP}) = A + B*\text{TEMP} + C*\text{MOISTURE} + D*\text{TEMP}*\text{MOISTURE} \qquad (6.1)$$

where:

WHEEP = Number of wheel passes at a 12.7 mm rut,

TEMP = Test temperature, ^{0}C,

MOISTURE = Moisture conditions (dry and wet), and

A, B, C, D, = Regression constants.

Table 6.2 to Table 6.4 summarizes the model statistics for the #11 limestone and #11 dolomite mixtures. Overall, the temperature effect was significant for both mixtures at the 99 percent level. The moisture condition was statistically significant for the limestone and dolomite mixes at the 90 and 99 percent levels, respectively. The interaction term was not significant for either mix. This implies that additional rutting damage results from moisture over the test temperature range (25^0 C to 60^0 C).

6.2 Finite Element Modeling for the Wheel Tracking Test

The finite element method (FEM) of analysis includes a geometric model, material model, boundary conditions, and a load model. The finite element method of analysis is a tool for numerical modeling that can be applied to many engineering problems, such as structural mechanics, heat transfer, ground water seepage, and many other areas.

In this study, the FEM software ABAQUS (ABAQUS, 1995) was selected to analyze the rutting behavior of asphalt mixtures. ABAQUS is a commercial finite element program. This program has been used previously to analyze flexible pavements and showed excellent agreement between FEM predicted pavement response and measured pavement response (Zaghloul, 1993). Also, the software has been utilized to model asphalt pavement rutting in accelerated pavement tests (Huang, 1996).

6.2.1 Model Geometry

In the study of PURWheel tests, a three dimensional finite element mesh was generated to represent a test slab of asphalt mixture. The cross section dimensions of PURWheel test slab is shown in Figure 6.13. This model consists of a 38 mm thick slab that is 305 mm wide and 305 mm long. The maximum size specimen that can be tested in the PURWheel is 622 mm long by 305 mm wide by 102 mm thick.

6.2.2 Boundary Conditions

Boundary conditions for the finite element model can be considered in two parts. First, the contact between the bottom of slab and the steel box surface was modeled as a contact pair. As a result, nodes on the bottom of the slab are able to slide along the interface. Second, plaster of paris is used as a grout around the slab perimeter. Therefore, the end and side interface was modeled as a bonded contact. For this condition the nodes are constrained, being unable to separate from or slide along the vertical surface.

6.2.3 Element Types

In this analysis, the asphalt concrete slab was modeled using the eight-nodded three-dimensional stress/displacement elements. Finer meshing was generated in regions of high stress gradient. The three dimensional mesh used in the analysis is shown in Figure 6.14.

6.2.4 Loading Models

The PURWheel tests in this research utilized a pneumatic wheel. A 175 kg load was applied on the wheel at a tire pressure of 793 kPa. The gross contact area was 27.5 cm^2. This results in a gross contact pressure of 620 kPa. An actual tire print is shown in

Figure 6.15. In the FEM the contact area was modeled as a rectangular area 6.35 cm long and 4.32 cm wide.

Initially, a step load function was used in the analysis to simulated the moving wheel load in PURWheel. The duration of the step load function was 0.0728 second which corresponds to a speed of 33 cm/sec. Figure 6.16 shows the step load function used in the analysis. The length of time from T_0 to T_1 is a function of wheel speed and the length of the contact area between the loading wheel and the slab. The step load function was applied at the first set of elements and moved longitudinally to the next set of elements in the wheel path. When the loading step is applied to the last set of the elements, a single wheel pass was complete. The loading step was then reversed starting from the last set of elements and moved toward the first set of elements. A loading cycle was then complete. The load cycle was repeated for the desired repetitions.

This loading sequence simulated the cyclic moving wheel loads in the PURWheel. However, due to significant computer memory and running time requirement, an alternate load cycle was adopted. The alternate load cycle consisted of using a single step load function to approximate the wheel loading (Huang, 1996). The total loading time of the single step was 364 seconds which is equal to the cumulative loading time for 5000 wheel passes at 33 cm/sec. This approximation reduced the computation time from an estimated 40 hours to a reasonable amount of time (2 to 4 hours). . Figure 6.17 shows a 3-D view of deformed slab cross section modeled by FEM.

6.2.5 Material Properties

Asphalt pavement deformation which occurs as a result of repeated loading is dependent both on the temperature and the period of time for which the load is applied (Croney and Croney, 1992). In order to simulate pavement permanent deformation, a creep model was used to characterize the material properties of the asphalt mixtures (Huang, 1996). The creep rate model in ABAQUS is:

$$\dot{\varepsilon} = A\sigma^n t^m \tag{6.2}$$

Where:

$\dot{\varepsilon}$ = creep strain rate

σ = the uniaxial equivalent deviatoric stress

t = the total time

A, m, n = parameters related to material properties

According to Huang (1996), the parameter A changes the intercept of the creep curve without changing the slope of the creep curve on a log-log scale. As a result, the parameter A in the current analysis was backcalculated by matching the intercept of measured deformation curves. Parameter n is associated with the contact pressure. Huang (1996) selected a value of n of 0.8 for tests with a 620 kPa contact pressure. Since the current analysis was also conducted with a contact pressure of 620 kPa, the same value of n was selected. The parameter m in the creep model defines the slope of the

creep curves on a log-log scale. This parameter is important and is the primary parameter utilized to study mixture rutting potential.

6.2.6 Model Verification

A backcalculation technology was used to obtain the creep model parameters, A and m (Huang and White, 1996). Parameter m was estimated first to match the slope of PURWheel deformation curves. After the parameter m was determined, the A value was estimated by matching the deformation curves occurring during the post compaction stage which is described in Chapter Five.

The verification study was conducted by using test results of both the PURWheel and the Accelerated Pavement Tester (APT) results on the same #8 gravel binder mixture. Both APT and PURWheel tests were conducted using the same contact pressure (620 kPa) and the same temperature (38^0 C). Parameters for the creep model were obtained based on PURWheel test results. These parameter values and material properties used in the analysis were as follows:

Modulus of Elasticity = 3.1×10^6 kPa (450,000 psi)

Poisson's Ratio = 0.3

Creep Model Parameter A = 2.60×10^{-4}

n = 0.8

m = -0.52

Figure 6.18 shows the fitted curves and deformation data from the PURWheel

tests. Once the parameters for the creep model have been obtained, those parameters can

be utilized in the APT finite element analysis (Huang, 1996). Figure 6.19 shows the

results of predicted deformation curves for the APT tests based on backcalculated creep

rate model parameters and material properties from PURWheel tests.

6.2.7 Effect of Temperature

Two mixtures, #11 limestone and #11 dolomite surface mixes, were select for

backcalculation of material parameters in the creep model. Table 6.5 lists the

backcalculated material parameters for the two mixtures at each temperature. Figure 6.20

through Figure 6.29 show the fitted curve and deformation data from the PURWheel

tests.

Figure 6.30 shows the effects of temperature on parameter m. Parameter m is

smaller (more negative) at lower temperature than at higher temperature. The limestone

mix has better rut resistance than the dolomite mix at high temperature (50 and 60^0 C).

At 50^0 C and higher temperatures the asphalt cement has low stiffness and the aggregate

structure provides the majority of the rutting resistance.

Regression analyses were conducted to correlated the parameter m with the rutting

susceptibilities of the mixtures at different test temperature. It is found that parameter m

is strongly related to the test temperature. Figure 6.30 shows the effects of temperature

on parameter m along with the linear regression equations. The coefficient of

determination (adj. R^2) for the equation is about 0.94 for the limestone and dolomite mixtures. It is clear that parameter m increases (less negative) with increase of temperature, and the dolomite mix is more susceptible to rutting when temperature is higher than 50^0 C.

Parameter A for both mixtures is a constant at the different test temperature levels. this means that parameter A does not appear to be influenced by the change of temperature. The dolomite mix has a greater value of parameter A which means the dolomite mix experienced more deformation at the post compaction stage.

6.5 Summary

PURWheel tests show the abilities of the machine to evaluate the rutting/stripping potential of asphalt mixtures under various temperature/moisture conditions. In a comparison of two Indiana #11 surface mixtures, limestone and dolomite, the limestone mix is shown to have a lower susceptibility to rutting than that of the dolomite mix at 50 and 60^0 C. Moisture damage was shown to occur over a range of temperatures from 60^0 C to the room temperature.

Results of model verification studies show that the creep model can successfully characterize the pavement material behavior through a reasonable approximation of loading and material properties. Based on deformation data from the PURWheel tests, material parameters in the creep model were backcalculated. Good agreement was

obtained between FEM predicted deformation and that measured of the same mixture in APT tests.

In the analysis for a single tire pressure, parameter n was fixed at 0.8 while material parameters A and m were backcalculated by matching the deformation caused by post-compaction and creep slope of measured deformation curves in the PURWheel tests.

The material parameter m is strongly related to the temperature and aggregate type. Regression analyses show that parameter m increases with increase of temperature and the dolomite mix is more susceptible to rutting at high temperature.

Table 6.1 Wheel Track Test Results Summary (Wheel Passes @ 12.7 mm Rut)

Types of Agg.	Dry Test (Air Voids, %)	Est. Passes @ 6% Air Voids	Wet Test (Air Voids, %)	Est. Passes @ 6% Air Voids	Wet/Dry Ratio
#11 Limestone 60°	2600 (4.17)	2532	1300 (4.24)	1477	0.58
	5170 (3.4)		1840 (3.64)		
	2850 (6.03)		1290 (4.55)		
#11 Limestone 50° C	11500 (3.15)	14733	6000 (3.72)	6373	0.43
	12700 (3.78)		7400 (3.54)		
	>20000 (3.91)		5600 (4.32)		
#11 Limestone 40° C	13500 (5.02)	16530	16300 (3.54)	8509	0.51
	>20000 (4.64)		17500 (4.63)		
	16750 (6.85)		7250 (5.90)		
#11 Limestone 30° C	40000 (7.26)	51596	30000 (7.40)	18000	0.35
	25000 (9.21)		18107 (6.82)		
	40000 (7.60)		18393 (6.24)		
#11 Limestone 25° C	270257 (6.39)	280799	142192 (6.93)	112939	0.40
	409215 (6.59)		76564 (7.26)		
	384910 (7.18)		131965 (7.91)		
#11 Dolomite 60°	350 (4.59)	257	291 (4.03)	146	0.57
	82 (8.53)		108 (6.44)		
	70 (8.96)		133 (6.25)		
#11 Dolomite 50° C	1576 (5.92)	1278	780 (4.99)	598	0.47
	200 (9.25)		525 (6.13)		
	460 (7.08)		566 (6.43)		
#11 Dolomite 40° C	7750 (5.68)	9833	5600 (4.57)	5767	0.59
	12500 (4.73)		5600 (4.46)		
	9500 (5.07)		6100 (5.07)		
#11 Dolomite 30° C	28000 (6.74)	37752	17864 (6.29)	18485	0.49
	30000 (6.74)		13337 (6.08)		
	40000 (5.81)		40000 (4.53)		
#11 Dolomite 25° C	132663 (6.93)	164311	40249 (6.67)	71310	0.43
	155412 (5.60)		84284 (6.61)		
	195342 (6.04)		75303 (5.65)		

Table 6.2 Statistical Values for Temperature/Moisture Regression Models

Mixture	R-Square	Adj. R-Sq.	Root MSE	Mean
Limestone	0.9022	0.8532	0.6221	9.7083
Dolomite	0.9912	0.9868	0.2796	8.5481
Type I Tests				
Mixture	Full Model F-value (Pr>F)	TEMP F-value (Pr>F)	MOISTURE F-value (Pr>F)	TEMP*MOISTURE F-value (Pr>F)
Limestone	18.44(0.0020)	51.05(0.0004)	4.14(0.0880)	0.13(0.7321)
Dolomite	224.76(0.0001)	659.29(0.0001)	14.85(0.0084)	0.14(0.7256)

Note: number of samples=10
TEMP: PURWheel test temperature
MOISTURE: dry or wet

Table 6.3 Parameter Estimates - #11 Limestone Mix

Variable	df	Estimate	Std. Error	T Stat.	Prob. > $\lvert T \rvert$
INTERCEPT	1	13.5821	0.9332	14.5549	0.0001
TEMP	1	-0.1043	0.0217	-4.7987	0.0030
MOISTURE	1	1.2529	1.3197	0.9494	0.3791
TEMP*MOISTURE	1	-0.0110	0.0307	-0.3578	0.7321

Note: number of samples=10
TEMP: PURWheel test temperature
MOISTURE: dry or wet

Table 6.4 Parameter Estimates - #11 Dolomite Mix

Variable	df	Estimate	Std. Error	T Stat.	Prob. > |T|
INTERCEPT	1	15.3722	0.4194	36.6496	0.0001
TEMP	1	-0.1748	0.0098	-17.8960	0.0001
MOISTURE	1	0.8897	0.5932	1.4999	0.1843
TEMP*MOISTURE	1	-0.0051	0.0138	-0.3678	0.7256

Note: number of samples=10
        TEMP: PURWheel test temperature
        MOISTURE: dry or wet

Table 6.5 Backcalculated Material Parameters

Types of Aggregate	Test Temperature, ^{0}C	Model Parameter		
		$A \times 10^{-4}$	n	m
#11 Limestone	60	2.0	0.8	-0.34
	50	2.0	0.8	-0.59
	40	2.0	0.8	-0.65
	30	2.0	0.8	-0.78
	25	2.0	0.8	-0.89
#11 Dolomite	60	2.6	0.8	-0.11
	50	2.6	0.8	-0.23
	40	2.6	0.8	-0.65
	30	2.6	0.8	-0.78
	25	2.6	0.8	-0.89

11DCM

1. Legends represent % air void contents of the samples
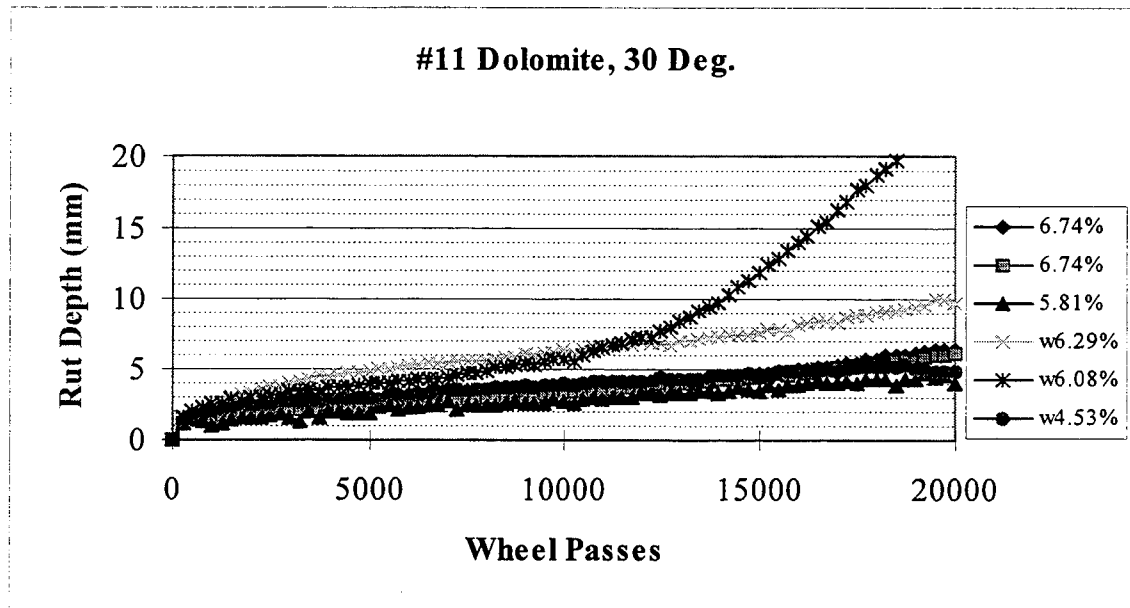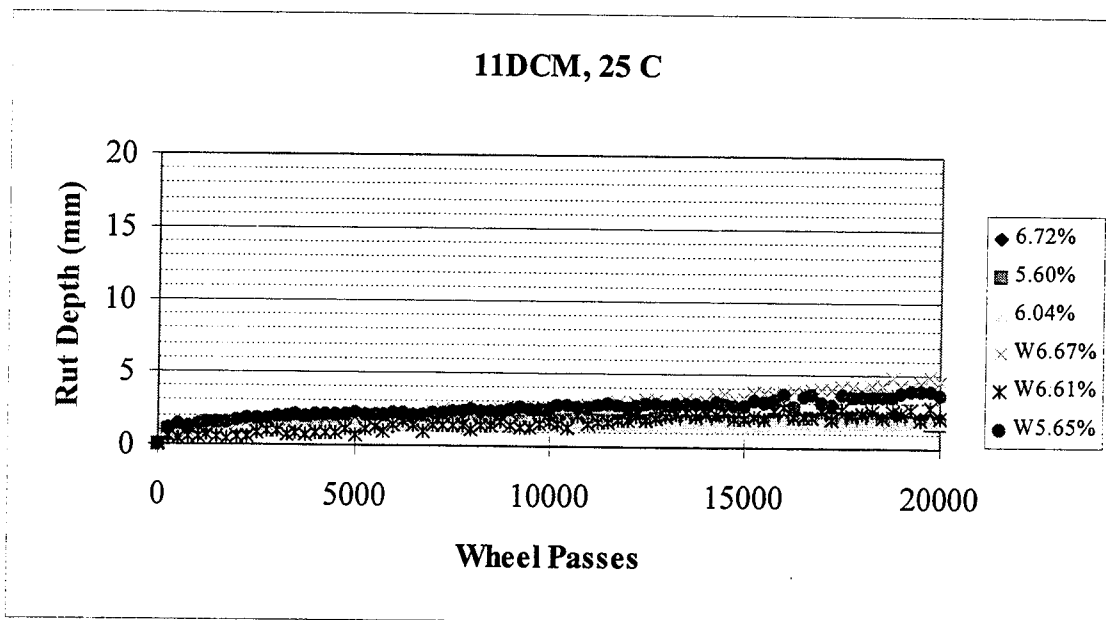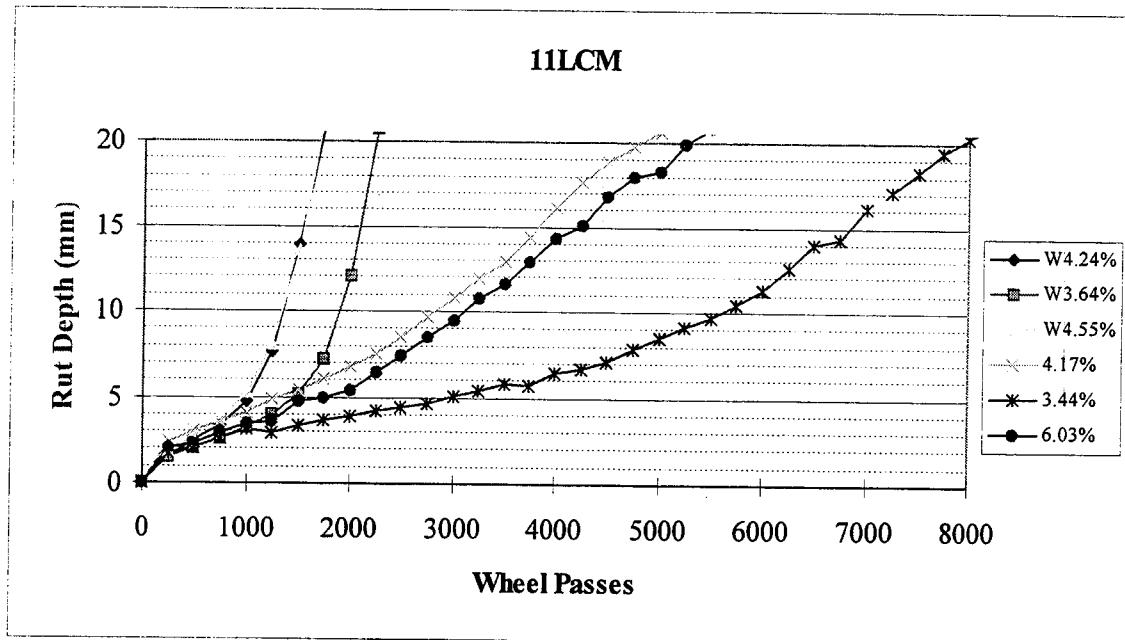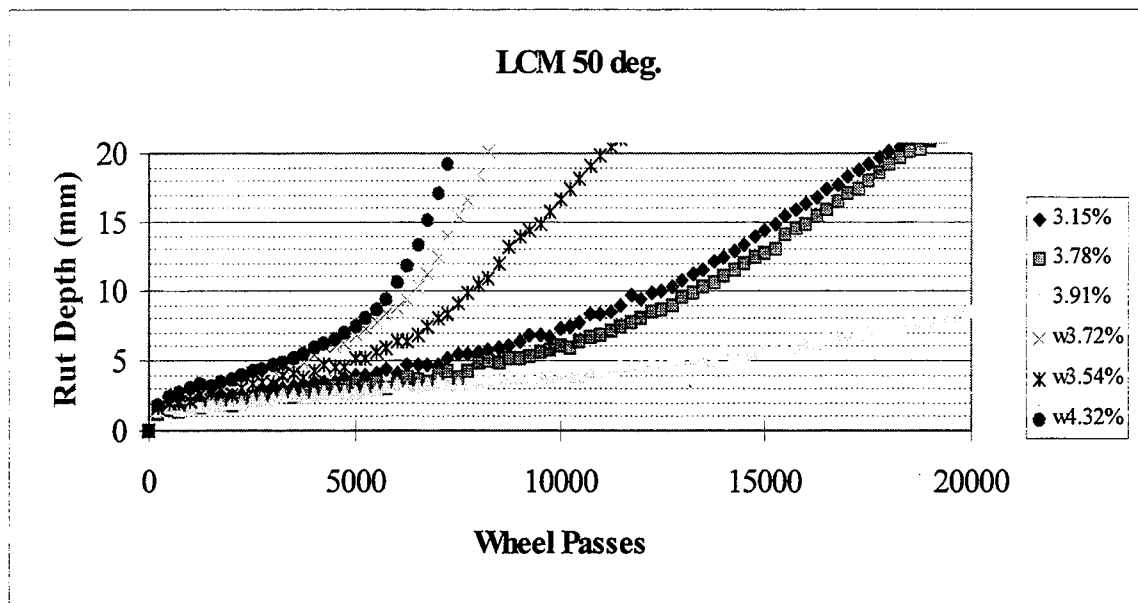2. "W" represents wet test conditions

Figure 6.1 Wheel Track Test Results of Dolomite Surface Mixture, 60^0 C

DCM 50 deg.
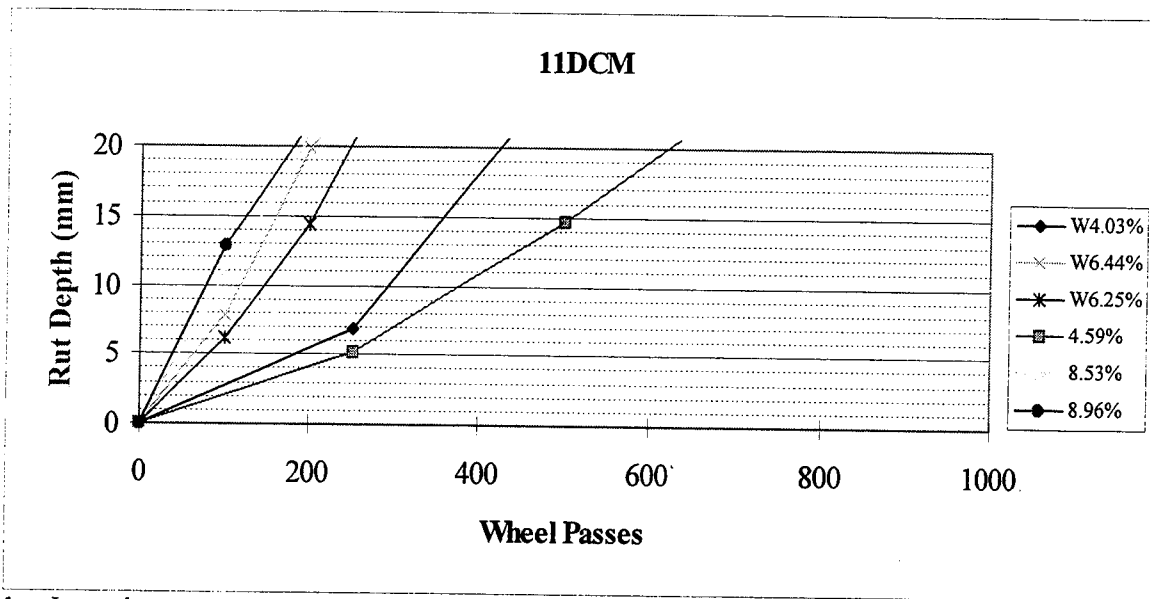
1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions
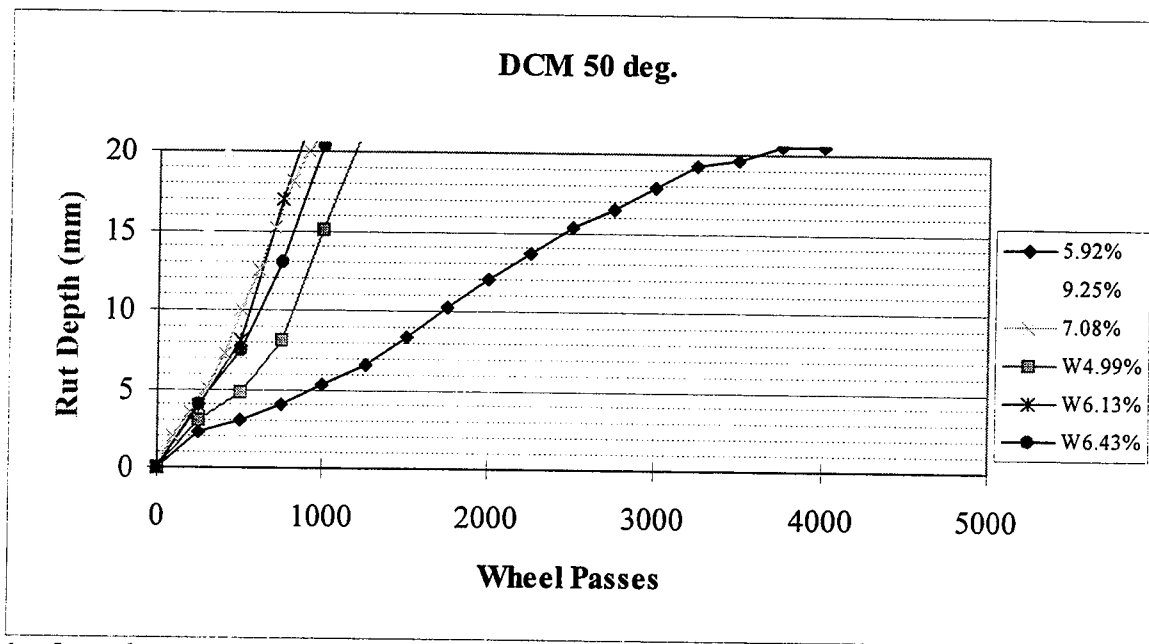
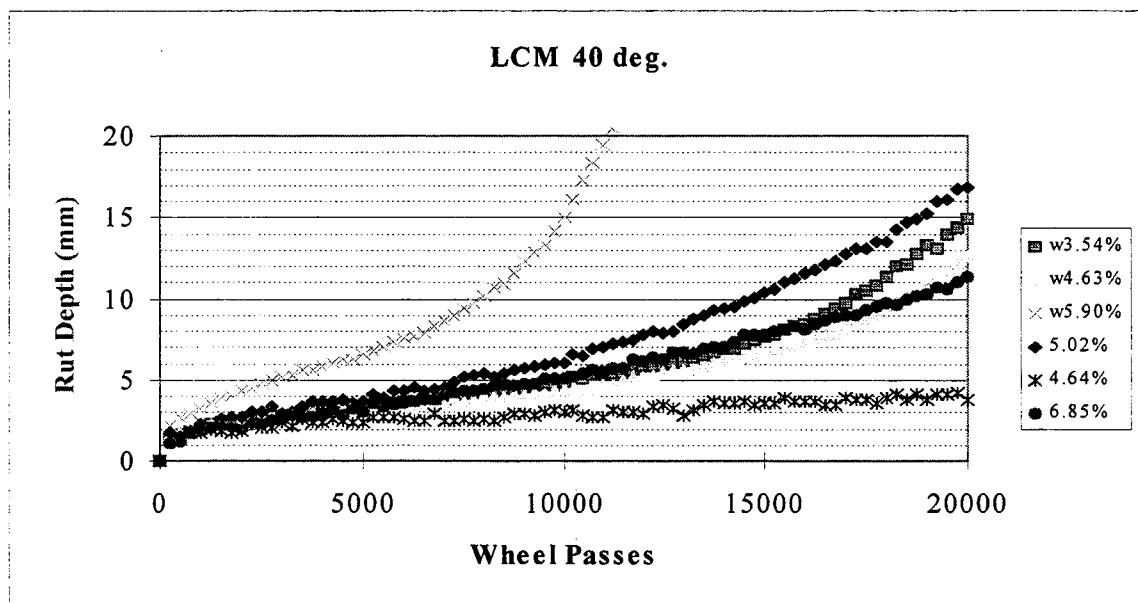Figure 6.2 Wheel Track Test Results of Dolomite Surface Mixture, 50^0 C
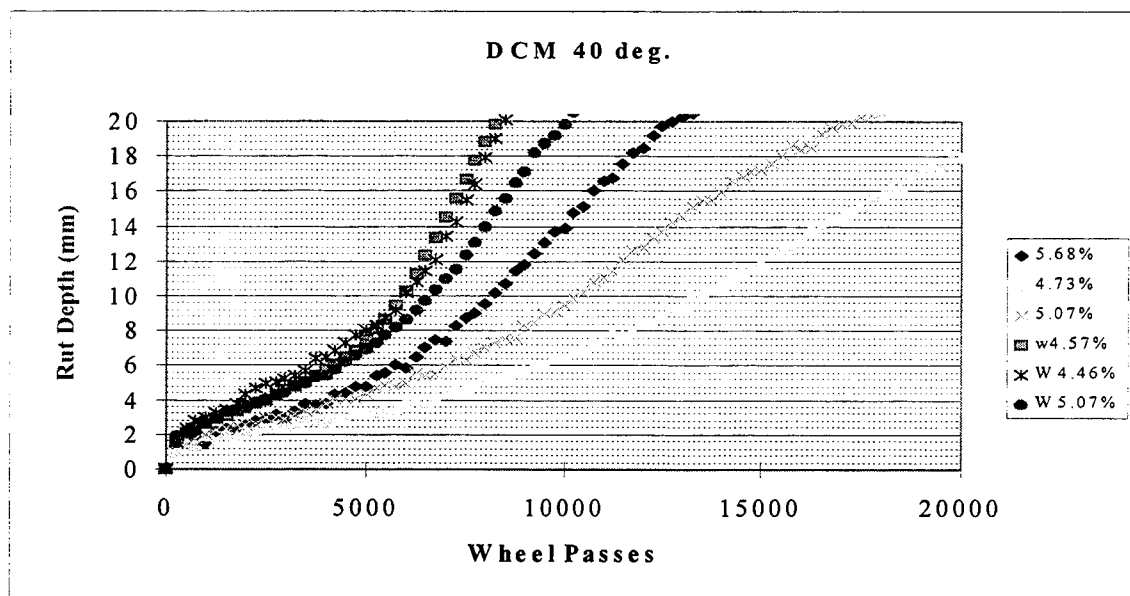
DCM 40 deg.

Legend:
- ♦ 5.68%
- 4.73%
- ✕ 5.07%
- ▦ w4.57%
- ✳ W 4.46%
- ● W 5.07%

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions

Figure 6.3 Wheel Track Test Results of Dolomite Surface Mixture, 40^0 C

#11 Dolomite, 30 Deg.

Legend:
- ♦ 6.74%
- ▦ 6.74%
- ▲ 5.81%
- ✕ w6.29%
- ✳ w6.08%
- ● w4.53%

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions

Figure 6.4 Wheel Track Test Results of Dolomite Surface Mixture, 30^0 C

11DCM, 25 C

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions

Figure 6.5 Wheel Track Test Results of Dolomite Surface Mixture, 25⁰ C

11LCM

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions

Figure 6.6 Wheel Track Test Results of Limestone Surface Mixture, 60⁰ C
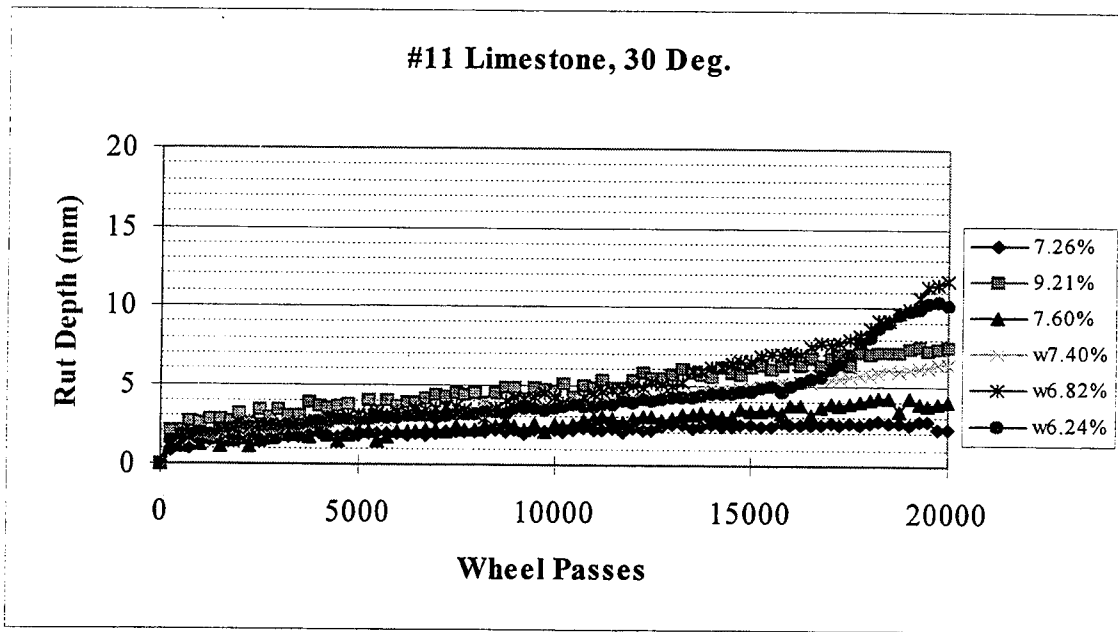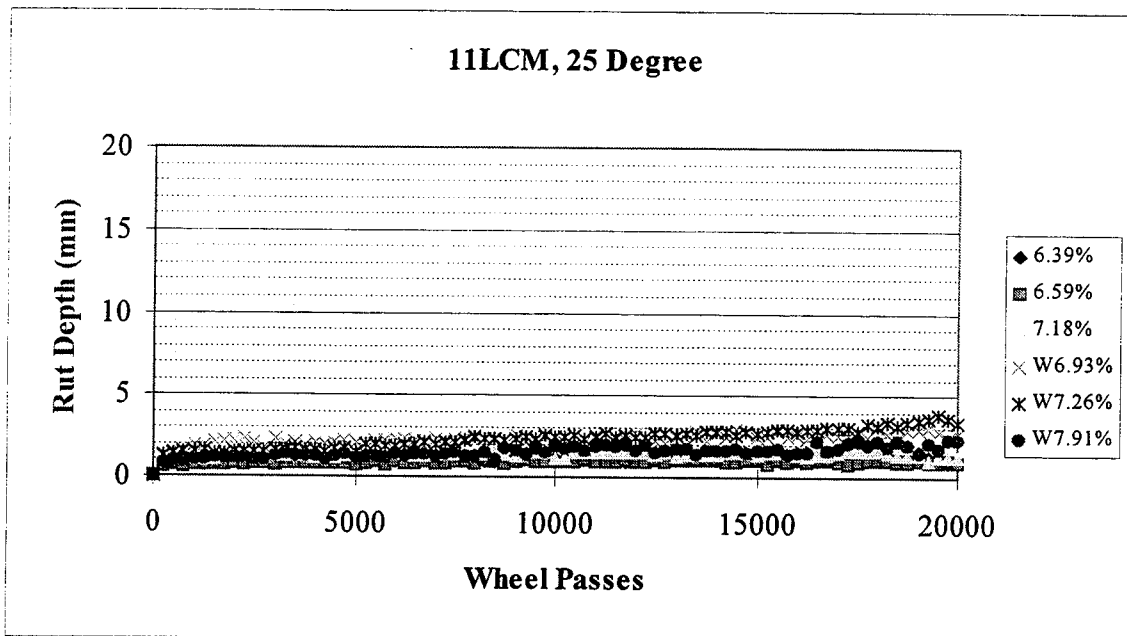
1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions

Figure 6.7 Wheel Track Test Results of Limestone Surface Mixture, 50^0 C


1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions

Figure 6.8 Wheel Track Test Results of Limestone Surface Mixture, 40^0 C

Figure 6.9 Wheel Track Test Results of Limestone Surface Mixture, 30⁰ C

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions

Figure 6.10 Wheel Track Test Results of Limestone Surface Mixture, 25⁰ C

1. Legends represent % air void contents of the samples
2. "W" represents wet test conditions
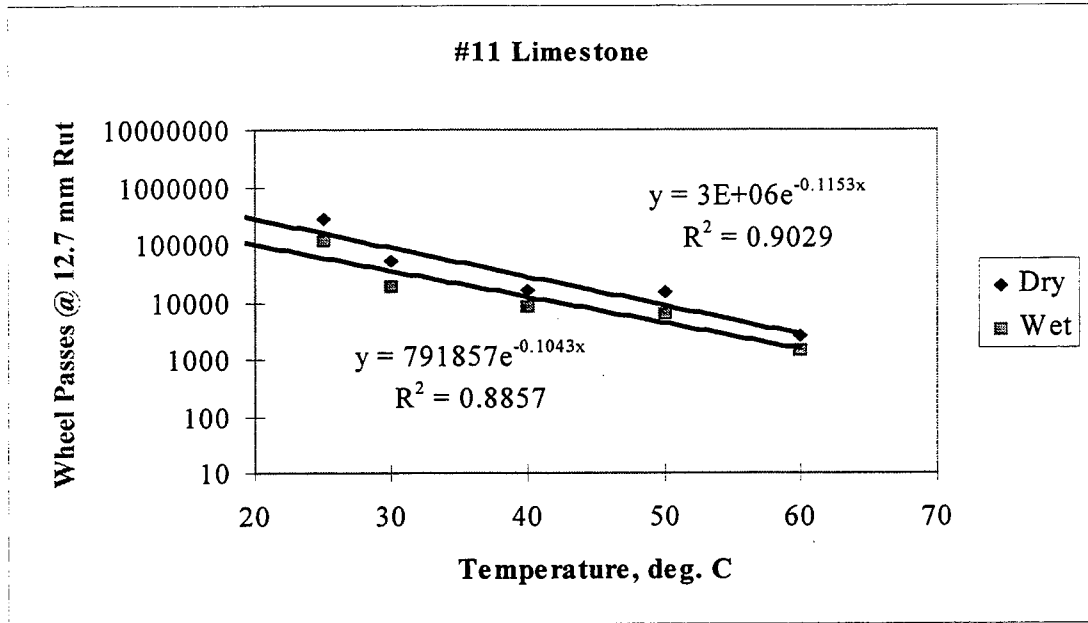
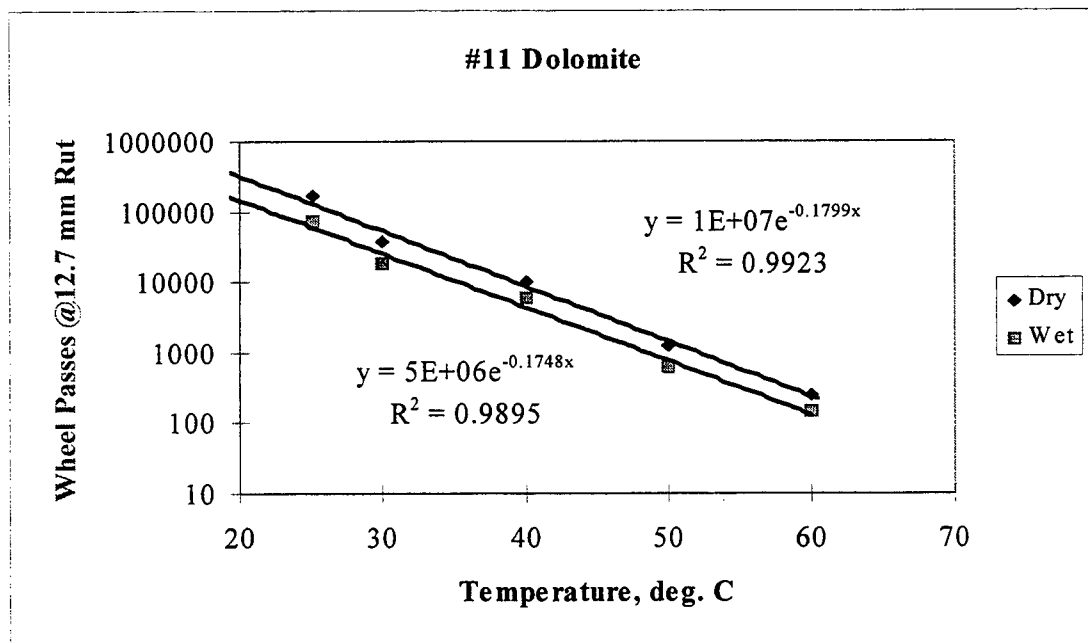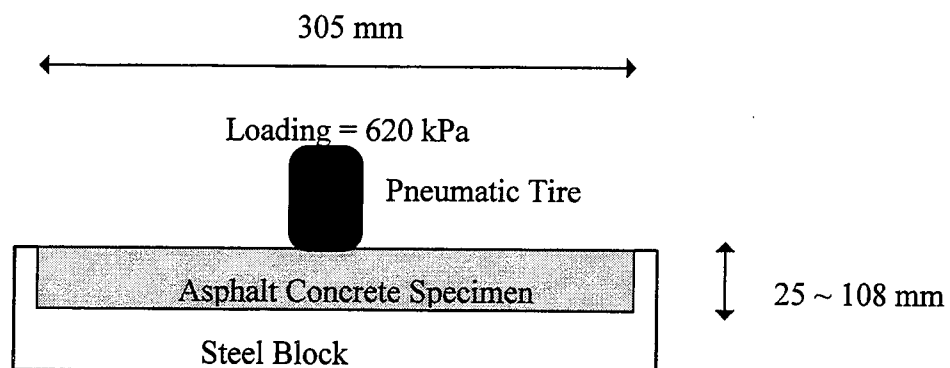Figure 6.11 Temperature-Rutting Rate Relationship for #11 Limestone Mix

Figure 6.12 Temperature-Rutting Rate Relationship for #11 Dolomite Mix

Cross Section of WTD Test Pit
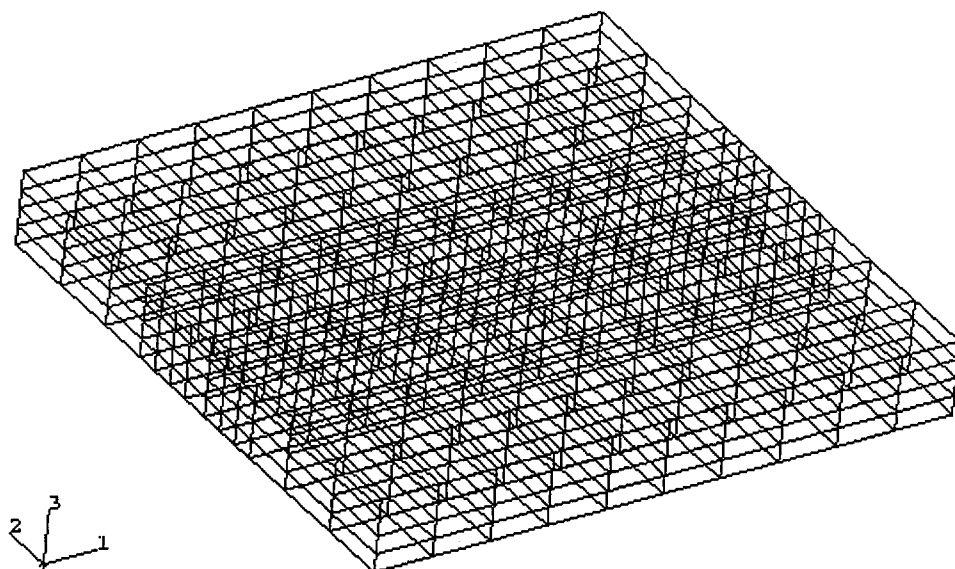
Figure 6.13 Cross Section of PUR Wheel Test Pit

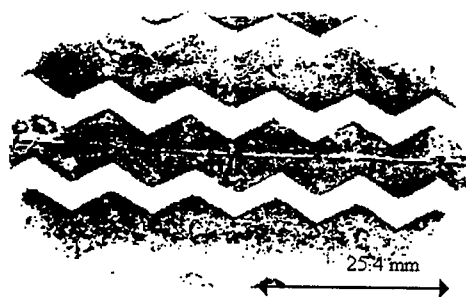Figure 6.14 3-D View of Finite Element Mesh
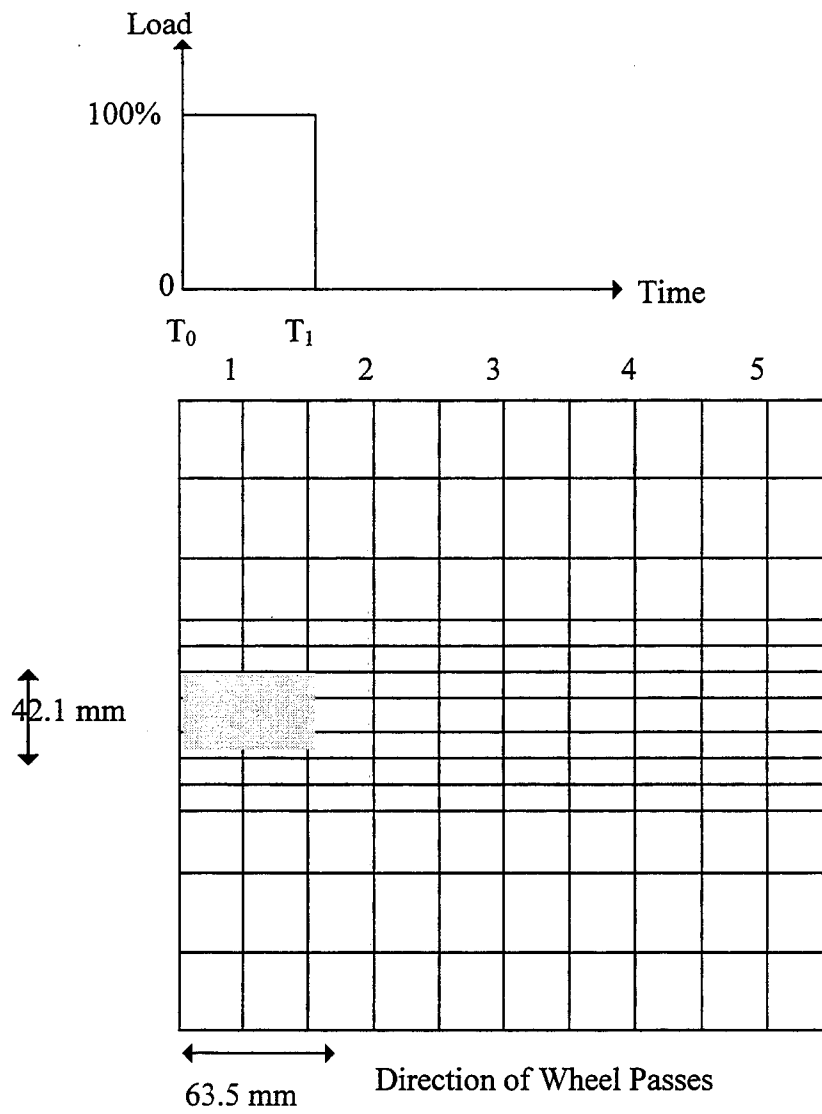
25.4 mm

Figure 6.15 PURWheel Tire Print

Figure 6.16 Step Load Function in the FEM. Analysis

DISPLACEMENT MAGNIFICATION FACTOR = 1.00
TIME COMPLETED IN THIS STEP   488.   TOTAL ACCUMULATED TIME   488.
ABAQUS VERSION: 5.5-1   DATE: 07-MAY-97 TIME: 17:46:18
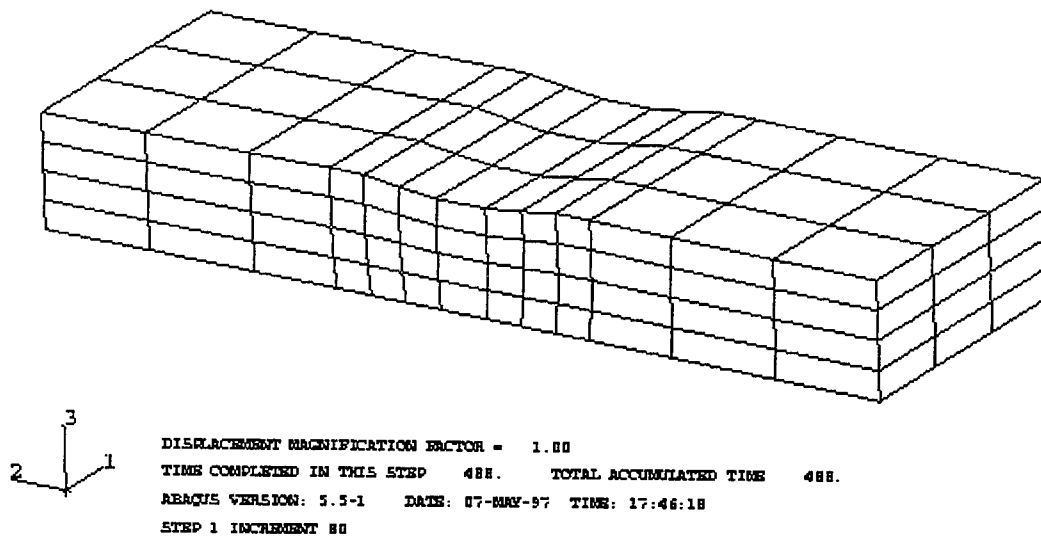STEP 1 INCREMENT 80

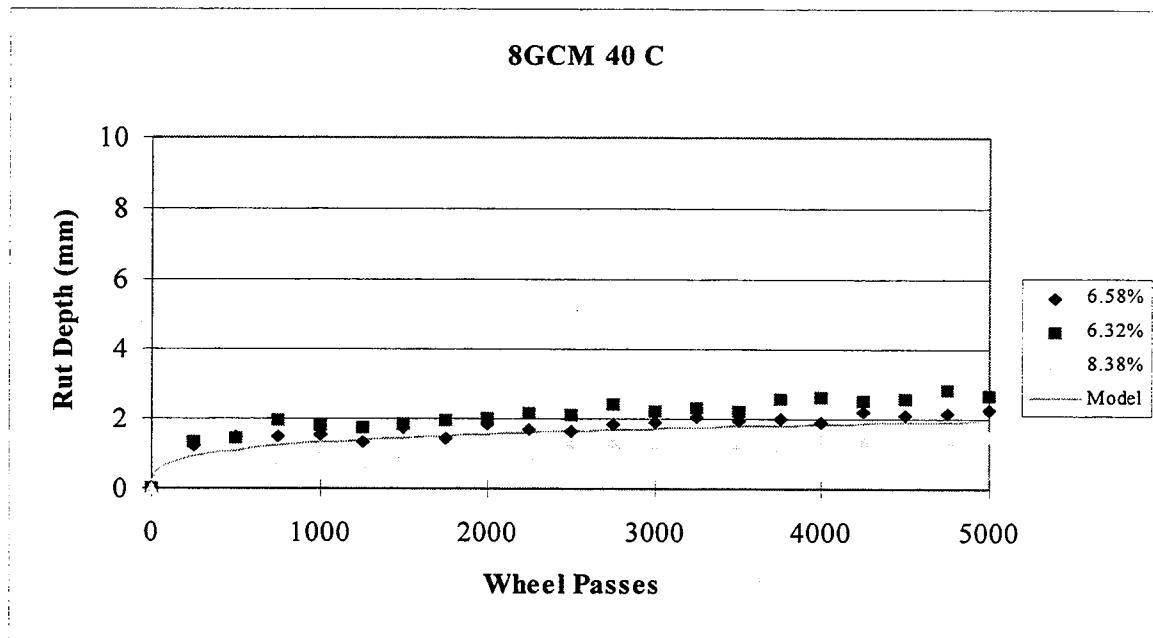Figure 6.17 Permanent Deformation Response of the Finite Element Model (Cross Section View)

Figure 6.18 Creep Model Fitted Curves (#8 Gravel Mix)
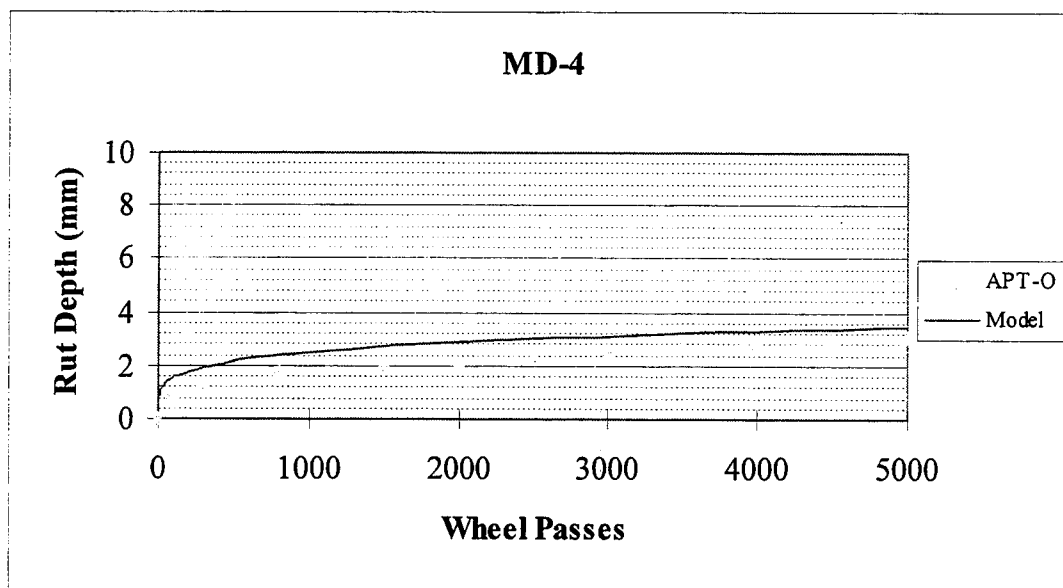
Figure 6.19 APT Test Results and Predicted Deformation Curves

Figure 6.20 Fitted Curves (#11 Limestone Surface Mixture, 60⁰ C)

Figure 6.21 Fitted Curves (#11 Limestone Surface Mixture, 50⁰ C)

Figure 6.22 Fitted Curves (#11 Limestone Surface Mixture, 40^0 C)

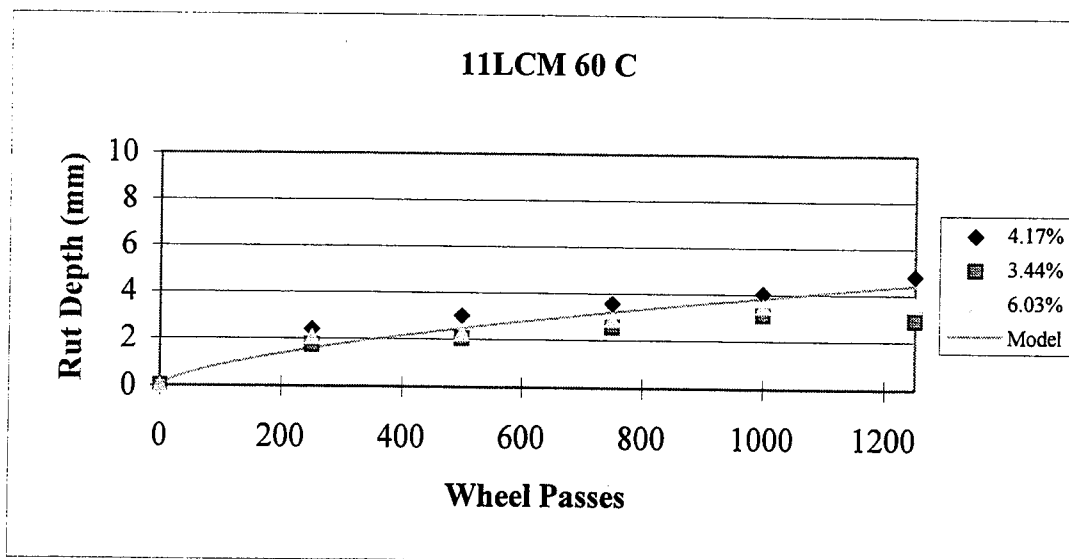Figure 6.23 Fitted Curves (#11 Limestone Surface Mixture, 30^0 C)

Figure 6.24 Fitted Curves (#11 Limestone Surface Mixture, 25^0 C)

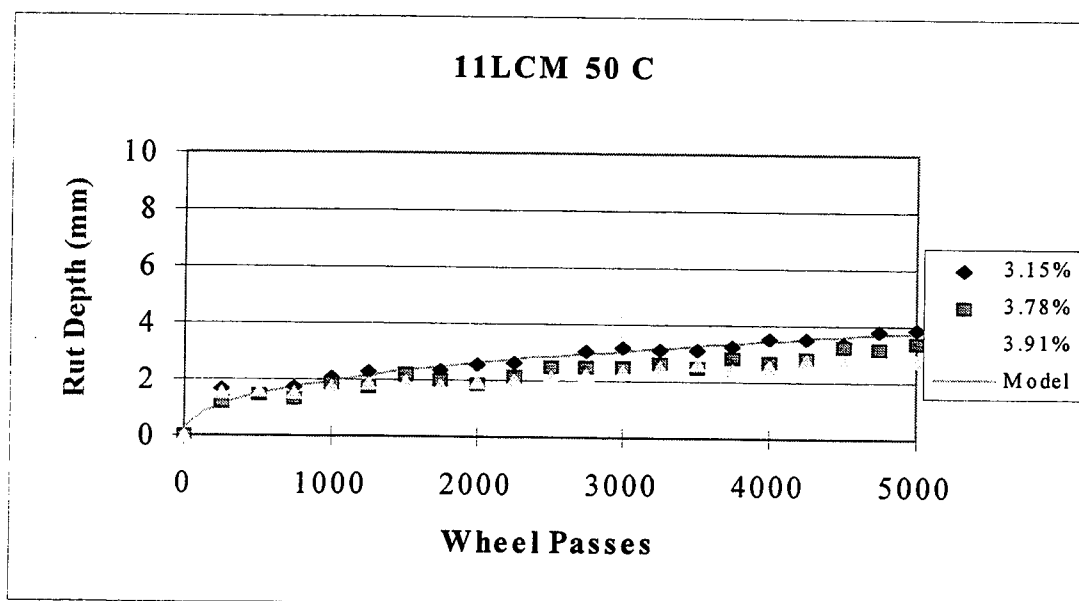Figure 6.25 Fitted Curves (#11 Dolomite Surface Mixture, 60^0 C)

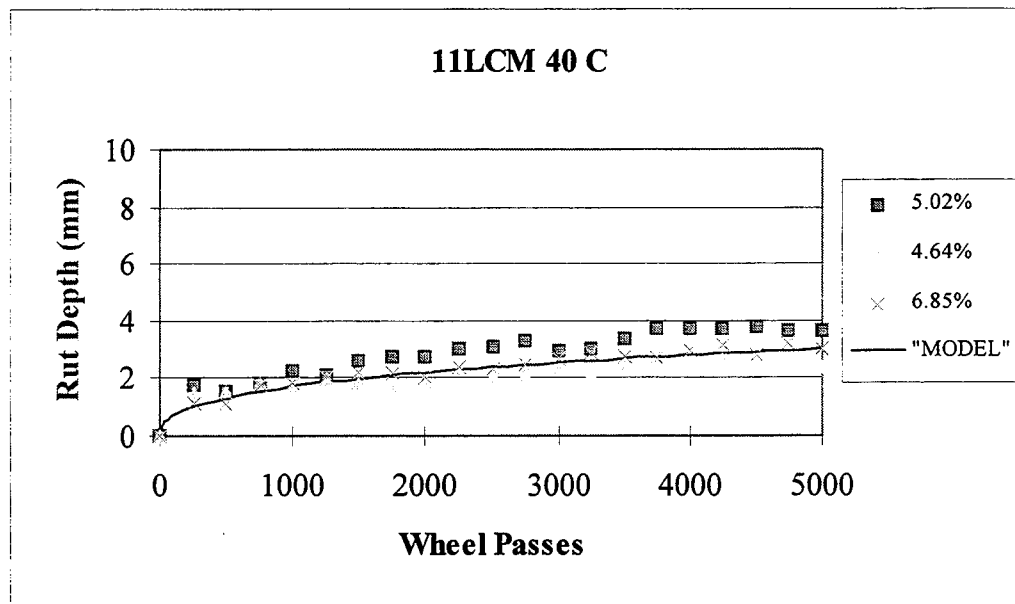Figure 6.26 Fitted Curves (#11 Dolomite Surface Mixture, 50^0 C)

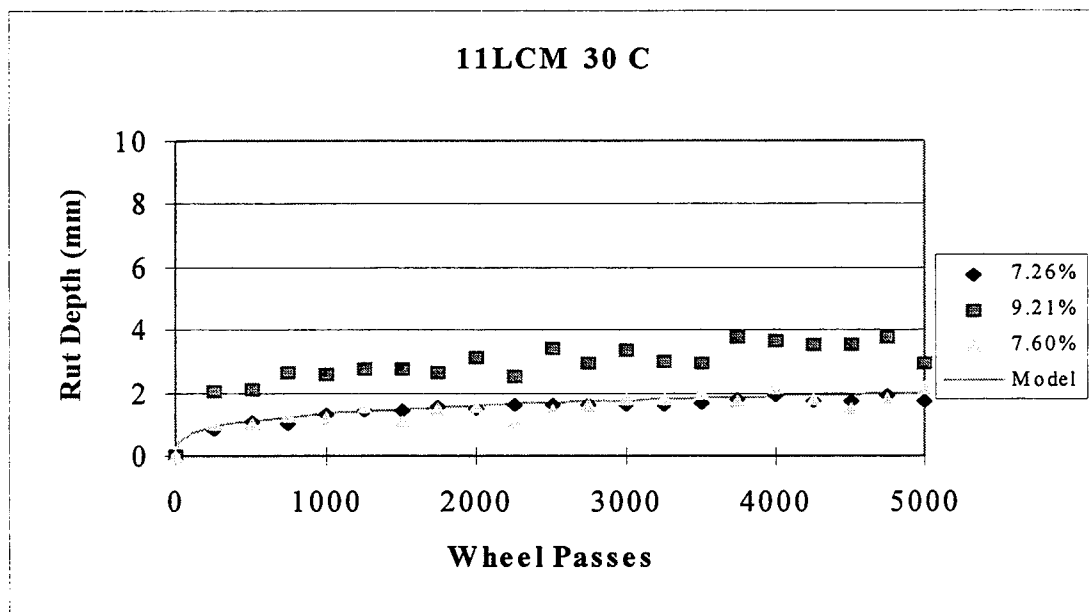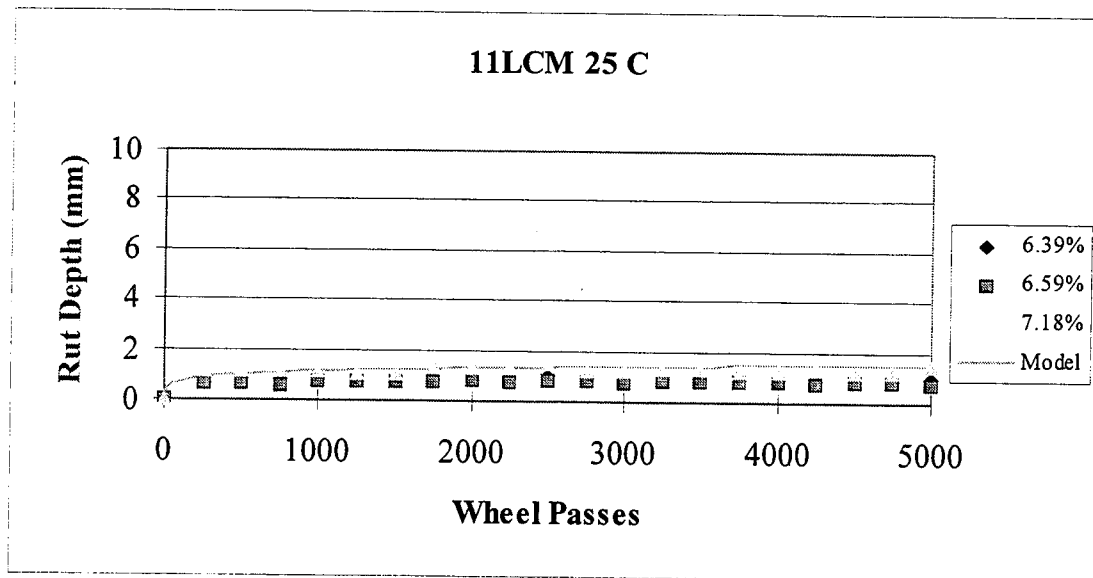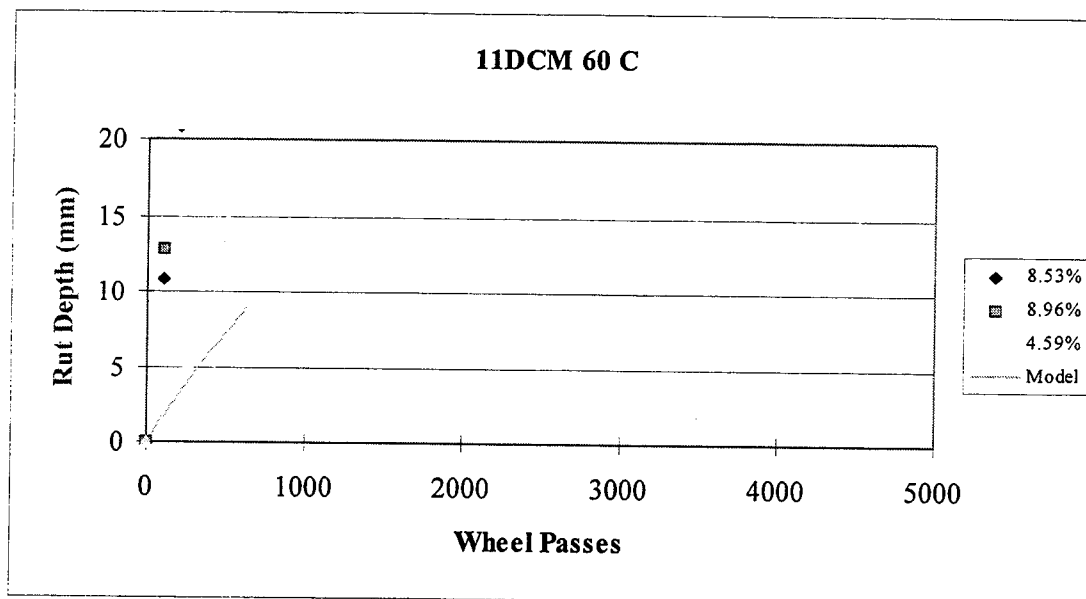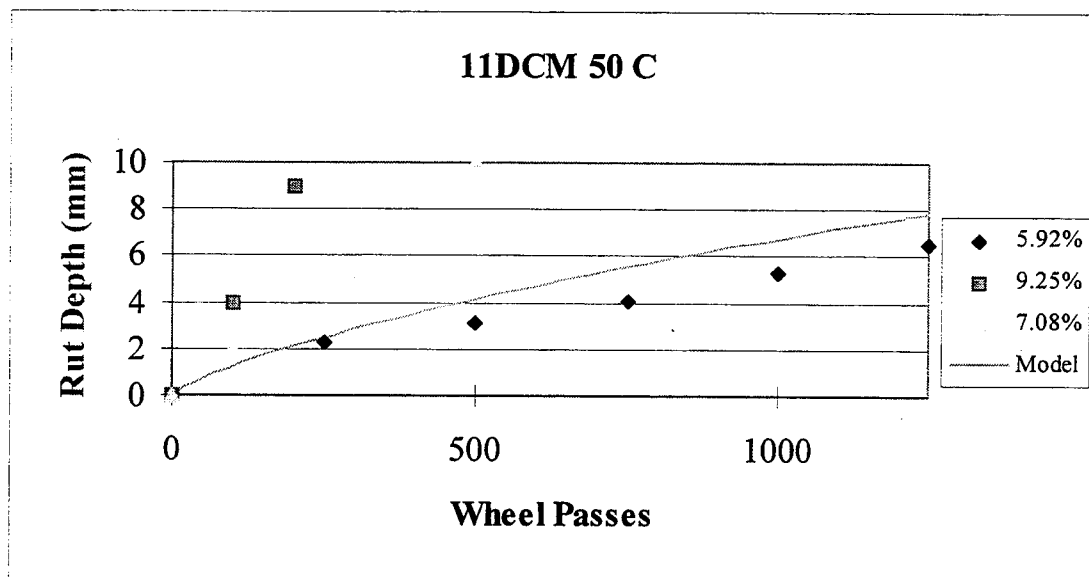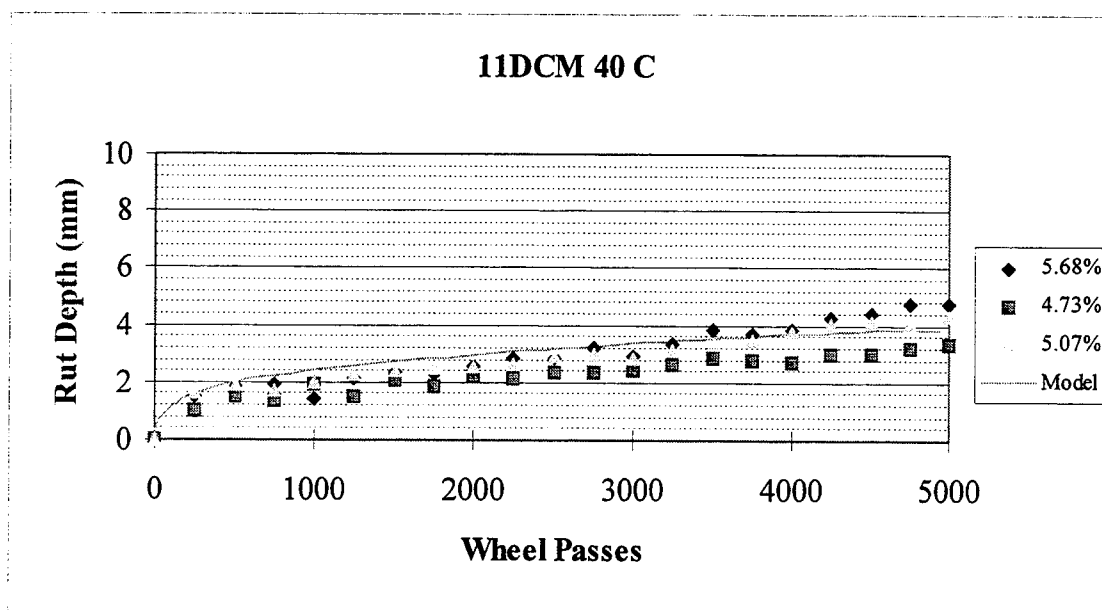Figure 6.27 Fitted Curves (#11 Dolomite Surface Mixture, 40^0 C)
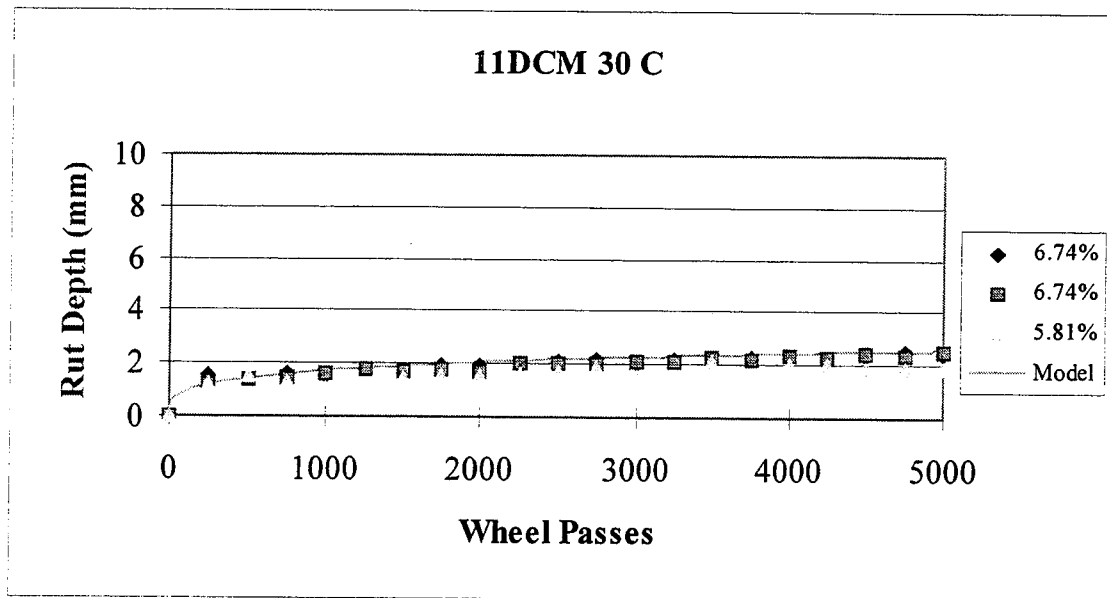
Figure 6.28 Fitted Curves (#11 Dolomite Surface Mixture, 30^0 C)
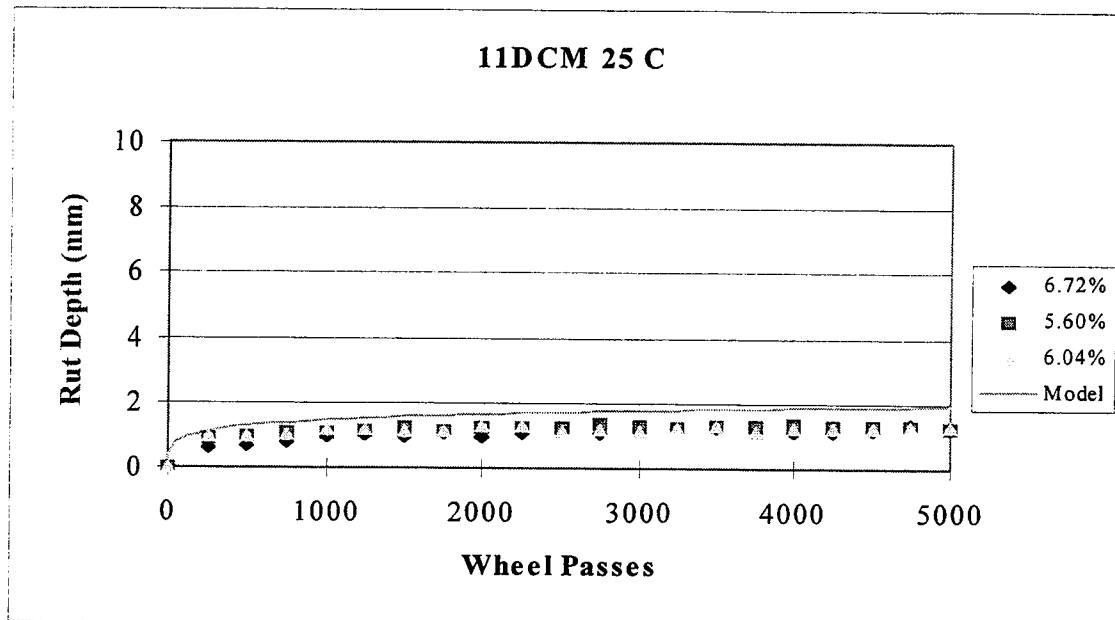
Figure 6.29 Fitted Curves (#11 Dolomite Surface Mixture, 25^0 C)
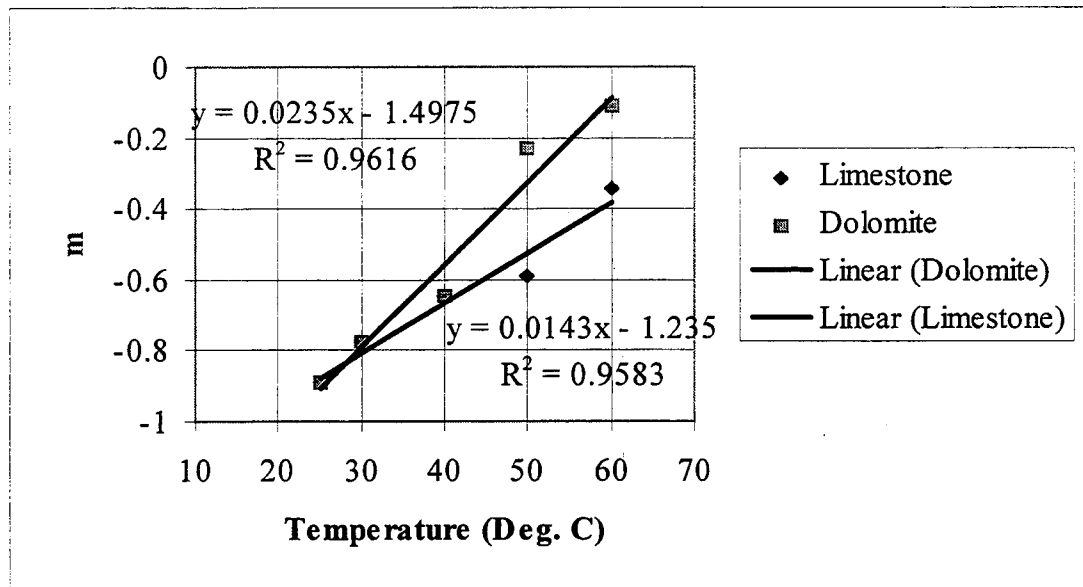
Figure 6.30 Effect of Temperature on Parameter m

CHAPTER 7 EVALUATIONS OF 1996 SUPERPAVE PROJECTS

After five years of research, the Strategic Highway Research Program (SHRP) produced the Superpave (Superior Performing Asphalt Pavements) asphalt specification and mix design system. The Superpave mix design component is a comprehensive method of designing paving mixes based on performance requirements established by the traffic, environmental conditions, and pavement structural section at any particular pavement site (Cominsky et al., 1994). The basic concept of the Superpave mix design method is to enhance pavement performance through the selection of the asphalt binder and aggregates that achieve a desired level of performance. As originally proposed, the Superpave mix design method included a volumetric design for limited traffic. For medium and high volume traffic the volumetric mix design was to be combined with a more complete analysis of the mixture including shear and indirect tensile tests. However, the Superpave volumetric mix design method is currently being used to design mixtures for all levels of traffic.

One of the objectives of this study is to evaluate the stripping/rutting potential of Superpave mixtures using the Purdue laboratory wheel (PURWheel) tracking device (WTD) and to examine the possibility of using Superpave Gyratory Compactor (SGC) samples for the AASHTO T-283 test. In order to achieve this objective in a short period

of time, six mixes from five different Superpave construction projects were included in the research. Two mixtures (19.0 mm and 9.5 mm) from the same project were tested.

7.1 Asphalt Mixtures

A summary of the Superpave mix designs included in the study are shown in Table 7.1. All six Superpave mixes were plant sampled materials and the mix design results were provided by the project contractors. Base on the Superpave mix design criteria, the design asphalt content for each mix was selected at 4% air voids.

7.2 WTD Test Results

Specimens prepared for WTD testing are compacted to 6 ~ 8% air voids with the Purdue linear compactor (described in Chapter Five). Specimen dimensions are typically 29.0 cm wide by 31.0 cm long. The thickness is 3.8 cm for 9.5 mm and 12.5 mm mixes and 5.1 cm for 19.0 mm and 25.0 mm mixes. A temperature of 60^0 C was selected for the 9.5 mm and 12.5 mm mix tests. For 19.0 mm and 25.0 mm mixes, the test temperature was selected at 57.5^0 C. The test environment can be either hot/wet or hot/dry. A pneumatic tire is loaded to achieve a gross contact pressure of about 620 kPa with a 793 kPa tire pressure. The wheel velocity selected for these tests was 34 cm/sec (1.1 ft/sec). In this study, each specimen was subjected to 20,000 wheel passes or until a 20.0 mm deformation developed.

Results for the WTD tests are summarized in Table 7.2. Graphic results from WTD tests are shown in Figure 7.1 to Figure 7.6. Triplicate samples were prepared and tested to include the effect of sample variation. As previously described, a 12.7 mm rut depth criteria (Chapter Five) was applied in evaluating WTD results. The 12.7 mm total rut depth is equivalent to a transducer measured rut depth (deformation) of 8.9 mm in the PURWheel. Wheel passes at 6% air void contents to achieve the deformation criteria was interpolated from the triplicate tests. The wet/dry ratio is calculated from the ratio of wet and dry tests at 6% air voids.

The fine aggregate angularity of both R-22170 mixes was 40 percent. Mixtures for project R-22170 were designed for a traffic level of less than three million ESALs. These two mixes exhibited the poorest performance of mixtures tested. The fine aggregate angularity of the other four mixtures was 45 or higher. Examination of the PURWheel results show that a higher percentage of natural sand causes progressively poorer performance.

7.3 AASHTO T-283 Test

Results from AASHTO T-283 tests are summarized in Table 7.3 and Table 7.4 for the 102 mm and 150 mm specimens, respectively. Test procedures for preparing and testing 102 mm specimens was previously described in Chapter Four. The 150 mm specimens were prepared using a Superpave gyratory compactor. Subsequently, these specimens were tested using the same test procedures as those used for the 102 mm

specimens. The tensile strength ratios (TSR) of the six Superpave mixes are all above 80 percent (minimum Superpave TSR). In fact, the TSR values range from 85 to 94 for the 102 mm specimens and 91 to 103 for the 150 mm specimens.

The TSR results for the six Superpave mixes are shown in Figure 7.7. Most of the mixes have a higher TSR value when the test was conducted using 150 mm SGC specimens. This might due to the fact that the larger specimens are less affected by the conditioning procedures. The test results also show the larger specimens (150 mm) have lower tensile strength than the 102 mm specimens (Table 7.3 and Table 7.4). This means the tensile strength is related to the specimen size. More evaluation is needed prior to adoption of SGC specimens for testing in AASHTO T-283.

7.4 Summary

Results from WTD and AASHTO T-283 tests for the Superpave mixes show the stripping/rutting potential of the mix can be minimized through better selection of materials as well as the mixture gradations. The fine aggregate angularity and/or gradation appear to be related to the mixture instability. Comparison of the TSR results for the 102 mm and 150 mm specimens indicates that 102 mm specimens are more sensitive to the current moisture conditioning procedures. Application of the 150 mm SGC specimen for AASHTO T-283 test still needs further evaluation before modification of the current test standard.

Table 7.1 Summary of Superpave Volumetric Mix Design Results

Project No.[1]	R-21467	R-22350	R-22687	R-22403	R-22170	R-22170
Mix Type	12.5 mm HV	9.5 mm HV	25.0 mm HV	19.0 mm HV	19.0 mm MV	9.5 mm MV
Binder Grade	PG 58-28	PG 58-34	PG 58-34	PG 70-28	PG 58-28	PG 58-28
Asphalt Content	5.3	6.3	4.6	5.4	4.5	5.6
Max. Spec. Gravity	2.606	2.428	2.522	2.469	2.470	2.505
VMA[2]	14.9	16.6	13.0	14.5	13.7	16.2
VFA[3]	72.9	73.8	68.0	72.1	71.6	72.7
FAA[4]	47.8	46.3	45.5	45.1	40.0	40.0
Sand Equivalency	94.0	70.6	93.5	94.0	95.9	96.0
Dust/Asp. Ratio	0.9	0.9	0.9	1.2	0.9	0.6
TSR[5], %	90.9	83.5	95.0	90.1	92.0	86.0

1. Mix design results provided by contractor
2. VMA : Voids in Mineral Aggregate
3. VFA : Voids Filled with Asphalt
4. FAA : Fine Aggregate Angularity
5. TSR : Tensile Strength Ratio

Table 7.2 Summary of WTD Test Results (at 12.7 mm Rut)

Project No.	Dry Test (Air voids, %)	Est. Passes @ 6% Air Voids	Wet Test (Air voids, %)	Est. Passes @ 6% Air Voids	Wet/Dry Ratio
R21467-12.5 mm (FAA=48)	50733 (7.68) 36662 (7.43) 29081 (10.2)	51236	20000 (7.62) 6250 (7.87) 3250 (9.39)	25514	0.50
R22350-9.5 mm (FAA=46)	57448 (7.78) 57400 (7.57) 124000 (7.31)	110818	12500 (8.03) 28356 (7.57) 8750 (6.80)	8768	0.08
R22170-9.5 mm (FAA=40)	1064 (6.95) 1205 (7.27) 4099 (5.03)	2703	214 (5.67) 224 (6.57) 201 (8.68)	218	0.08
R22403-19.0 mm (FAA=45)	177630 (2.53) 58973 (5.61) 107167 (5.57)	70274	61830 (6.08) 25464 (8.95) 32872 (4.84)	42371	0.60
R22170-19.0 mm (FAA=40)	186280 (6.21) 70118 (6.29) 110047 (5.69)	121554	16500 (7.03) 17000 (5.18) 35786 (8.69)	18009	0.15
R22687-25.0 mm (FAA=46)	110113 (8.2) 139243 (9.2) 90780 (10.2)	144311	60380 (6.08) 25231 (8.75) 33210 (6.84)	53873	0.37

Table 7.3 AASHTO T-283 Test Results (102 mm specimens)

	Dry			Wet				TSR, %
	Air Voids, %	ITS (kPa)	ITS(Average) (kPa)	Air Voids, %	Saturation, %	ITS, (kPa)	ITS(Average) %	TSR, %
R21467 Surface	8.07	1326	1402	7.43	64	1307	1247	89
	7.08	1532		7.01	62	1241		
	7.47	1347		8.33	65	1193		
R22350 Surface	7.73	658	659	7.40	63	610	597	91
	6.18	659		6.88	64	624		
	7.83	659		7.34	65	560		
R22170 Surface	6.64	784	798	6.89	79	684	695	87
	6.88	789		5.90	66	774		
	5.89	820		6.00	61	627		
R22403 Binder	5.70	685	681	6.51	59	553	582	86
	5.86	676		5.54	61	589		
	8.65	681		5.44	70	605		
R22170 Binder	5.87	715	674	6.17	61	594	574	85
	6.50	654		5.98	60	592		
	6.37	652		6.52	57	537		
R22687 Binder	6.99	688	695	7.01	64	709	651	94
	7.87	761		7.26	61	719		
	6.54	635		7.11	73	524		

Note: ITS: Indirect Tensile Strength
        TSR: Tensile Strength Ratio

Table 7.4 AASHTO T-283 Test Results (150 mm specimens)

	Dry			Wet				TSR, %
	Air Voids, %	ITS (kPa)	ITS$_{(Average)}$ (kPa)	Air Voids, %	Saturation, %	ITS, (kPa)	ITS$_{(Average)}$ %	
R21467 Surface	6.99	525	583	7.19	62	449	560	96
	7.14	546		7.04	61	484		
	7.13	680		7.06	65	747		
R22350 Surface	6.60	279	290	5.90	62	316	298	103
	6.45	287		6.17	59	296		
	6.15	304		6.09	59	280		
R22170 Surface	6.93	372	370	6.83	63	345	341	92
	6.81	367		7.38	71	296		
	6.61	373		6.17	67	383		
R22403 Binder	6.78	397	425	7.15	75	373	396	93
	6.63	458		6.85	75	389		
	7.02	419		6.08	59	427		
R22170 Binder	6.47	475	455	6.68	60	429	425	93
	6.85	441		6.70	66	455		
	7.00	454		6.72	61	391		
R22687 Binder	6.50	435	376	7.25	74	342	341	91
	7.26	293		6.35	72	359		
	6.40	400		7.04	79	321		

Note: ITS: Indirect Tensile Strength
        TSR: Tensile Strength Ratio

R21467 SURFACE MIXTURE
60 DEGREES C.
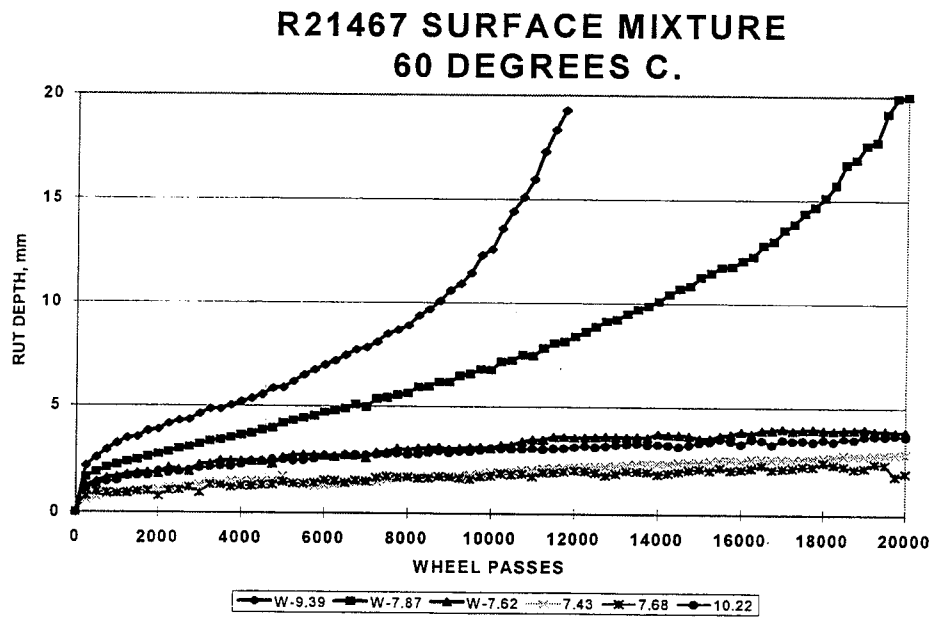
Figure 7.1 Wheel Track Test Results of R-21467, 12.5 mm Mixture

R22350 SURFACE MIXTURE
60 DEGREES C.
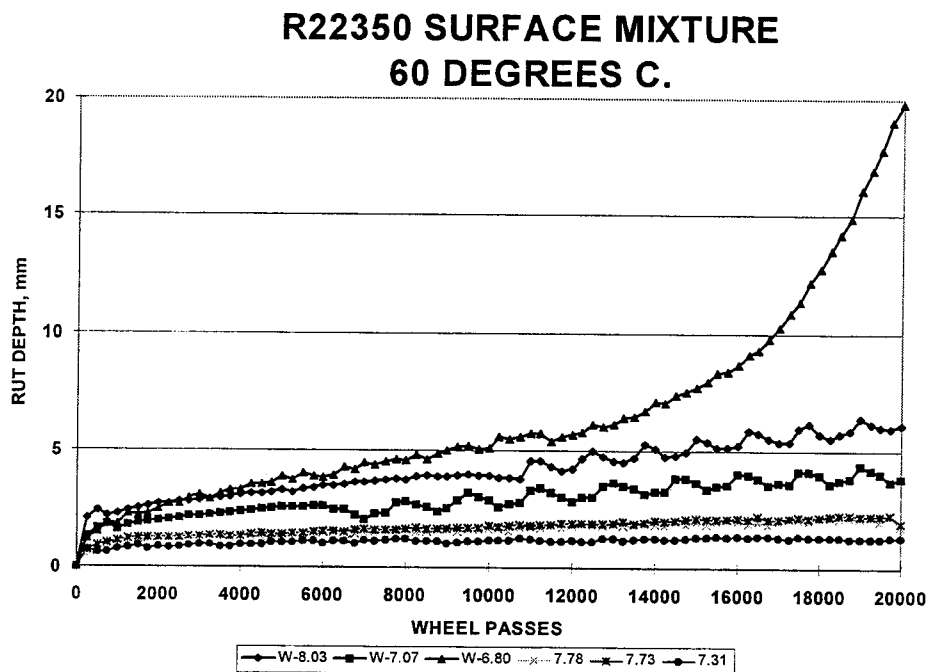
Figure 7.2 Wheel Track Test Results of R-22350, 9.5 mm Mixture

R22170 SURFACE MIXTURE
60 DEGREES C.
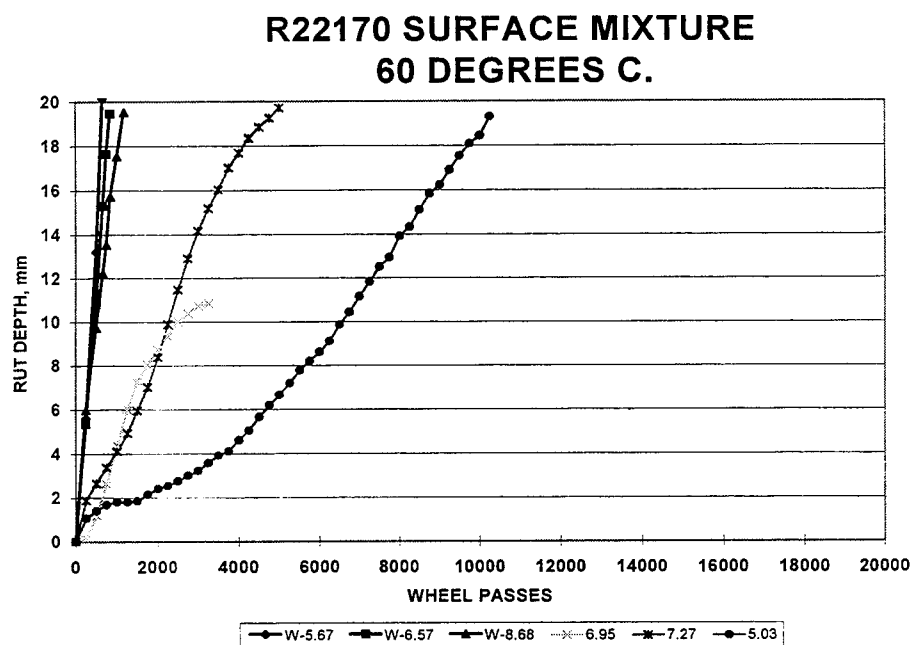
Figure 7.3 Wheel Track Test Results of R-22170, 9.5 mm Mixture

R22403, BINDER MIXTURE
57.5 DEGREES C.
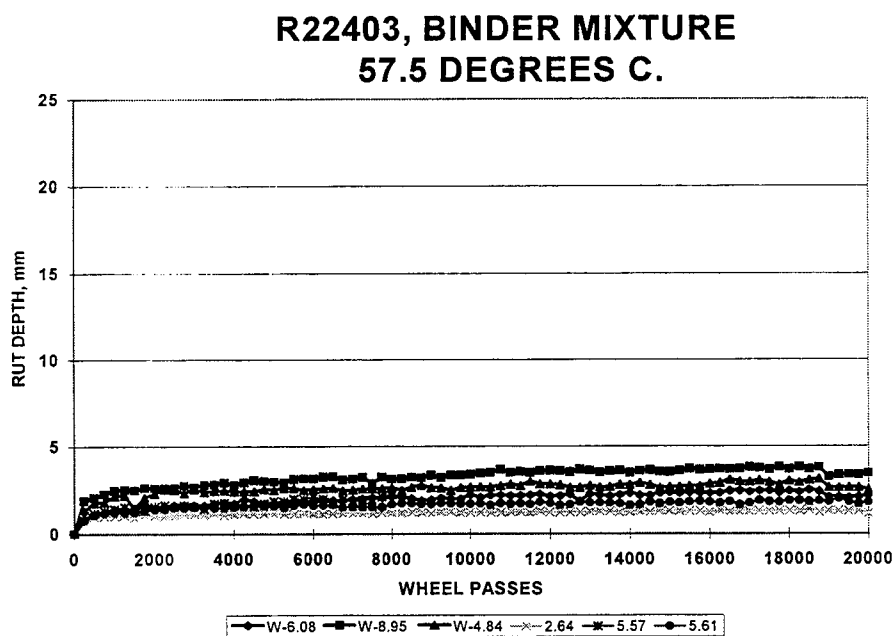
Figure 7.4 Wheel Track Test Results of R-22403, 19.0 mm Mixture

R22170, BINDER MIXTURE
57.5 DEGREES C.

Legend: W-145.9, W-148.2, W-143.3, 147.2, 147.1, 148
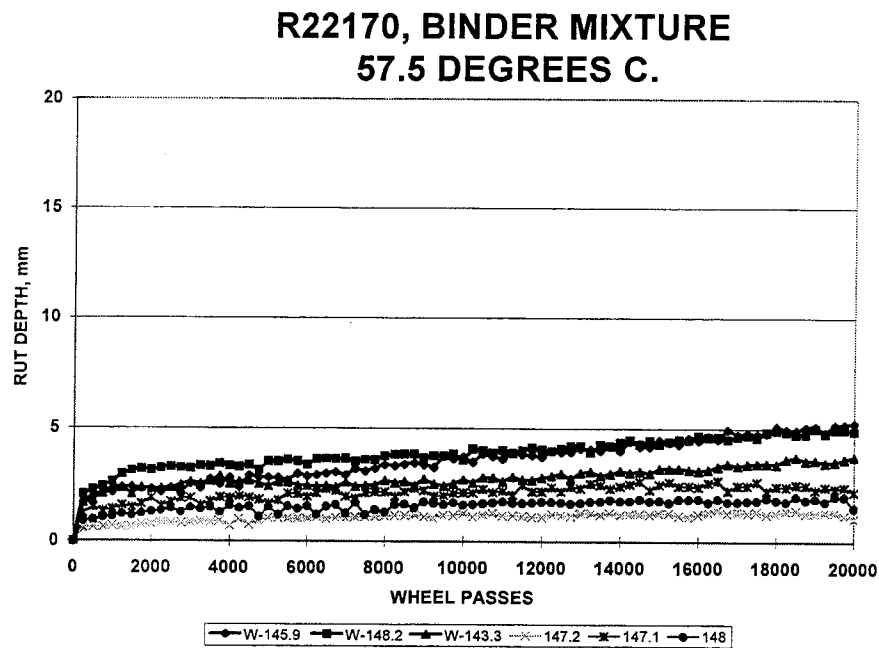
Figure 7.5 Wheel Track Test Results of R-22170, 19.0 mm Mixture

R22687, BINDER MIXTURE
57.5 DEGREES C.

Legend: W-6.08, W-8.95, W-4.84, 8.2, 9.2, 10.2

Figure 7.6 Wheel Track Test Results of R-22687, 25.0 mm Mixture

Figure 7.7 TSR Results for AASHTO T-283 Tests (Superpave Mixes)

Chapter 8 CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to determine factors influencing asphalt mixture stripping/rutting potential. Two major variables were selected for the research, aggregate type and antistripping additi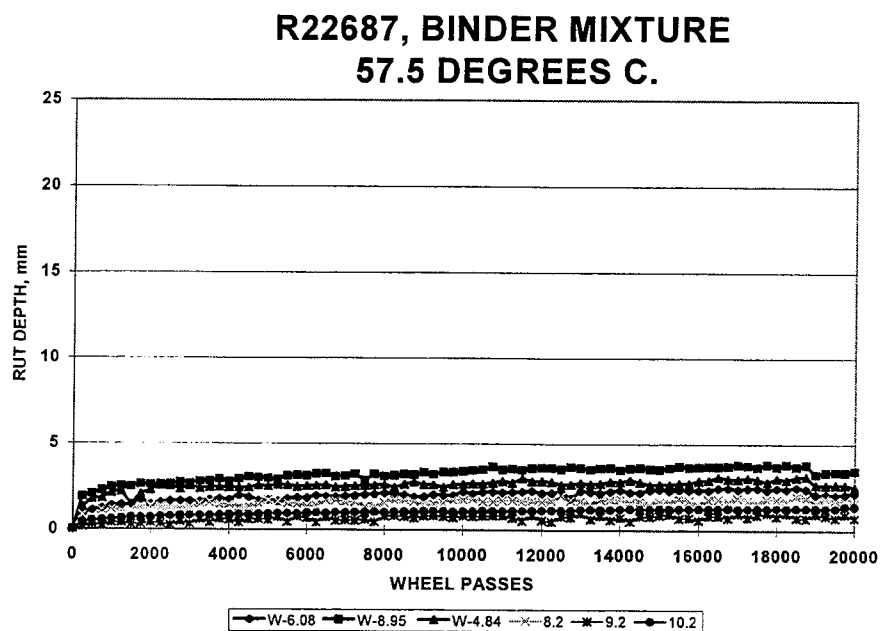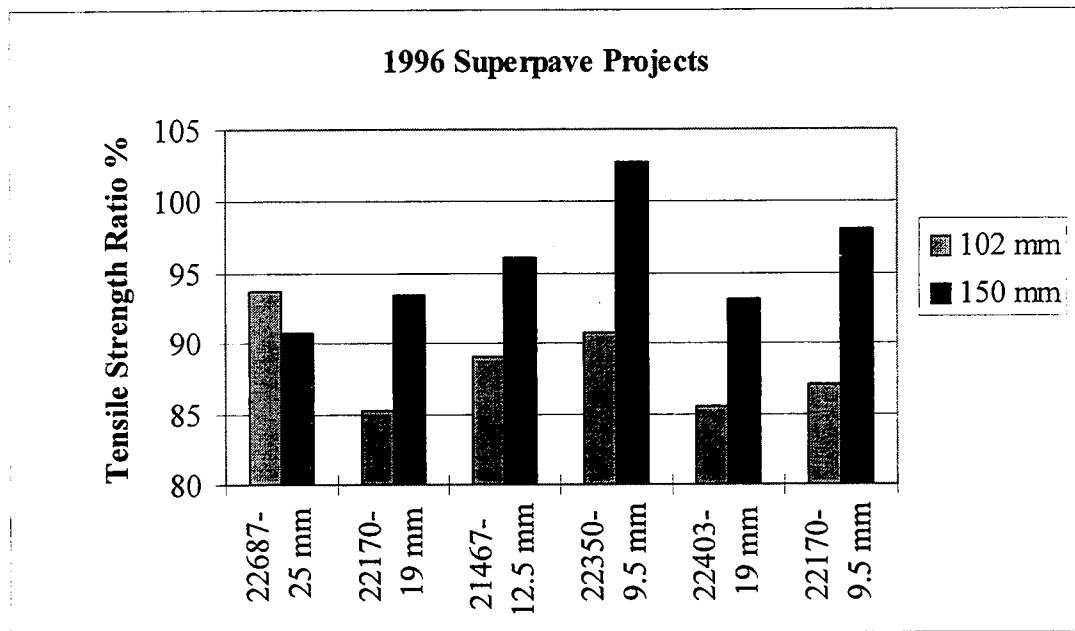ve. These variables was used in the design of experiment to characterize the bituminous mixture performance relative to environmental factors such as moisture and temperature. Both AASHTO T-283 and the PURWheel laboratory wheel tracking device were incorporated into the study. Currently, mixture stripping potential in the Superpave system is evaluated with AASHTO T-283. The PURWheel device was developed specifically for the study.

Results from AASHTO T-283 tests indicate that moisture conditioning has a significant effect on the stripping potential of the seven mixes tested. That is, the tensile strength of the mixtures was reduced after the environmental procedures in AASHTO T-283 tests.

Comparison of the results for the two antistripping agents based on TSR indicates that hydrated lime is more effective than the liquid chemical anti-stripping agent. Hydrated lime produces a slightly higher tensile strength for the mixtures before and after moisture conditioning. The liquid chemical anti-stripping agent increased the tensile strength for the mixtures after moisture conditioning. In some instances it also reduced

the tensile strength for the mixture before moisture conditioning. Currently mixture stripping potential in the Superpave system is evaluated with AASHTO T-283 and adopts a minimum TSR of 80% as a design criteria. The reduction of the dry indirect tensile strength by the antistripping agent should be considered as a negative modifier effect.

The PURWheel laboratory wheel tracking device was designed and fabricated to evaluate the stripping/rutting performance of bituminous mixtures. Two specimens can be tested simultaneously. The test environment can be either hot/wet or hot/dry. In this study specimens were compacted to 6 ~ 8% air voids with the Purdue linear compactor. Specimen dimensions are typically 29.0 cm wide and 31.0 cm long. Specimen depth varies depending on the type of mixture being tested. For example, surface, binder and base mixtures are 3.8 cm, 5.1 cm, and 7.6 cm, respectively. A pneumatic tire is loaded to achieve a gross contact pressure of about 620 kPa with a 793 kPa tire pressure. The wheel velocity selected for these tests was 33 ± 2 cm/sec (1.1 ft/sec or 1 mph). In this study, each specimen was subjected to 20,000 wheel passes or until 20.0 mm of deformation developed. A relationship was also developed between PURWheel "rutting" (downward deformation from initial surface elevation) and actual specimen rutting (straight-line rutting depth) for evaluating the rutting potential of the mix. The 8.9 mm PURWheel "rutting" is adopted in this for the relative performance evaluation of the mixtures tested at the same temperature.

Laboratory wheel tracking test results for all seven types of mixtures indicated that temperature and moisture conditions were significant. It is obvious that damage

occurs much faster with wet conditions. Both factors are important in identifying asphalt mixture stripping/rutting potential.

Aggregate type has a significant effect on the wheel track test results. Limestone and slag generally provided better performance than other types of aggregate in this study. Examination of the PURWheel performance of an Indiana #11 surface mixture shows that a higher percentage of natural sand causes progressively poorer performance. This is not true for binder mixtures for the amount of natural sand utilized.

The antistripping agents did not affect the rutting resistance of mixtures significantly. However, a comparison of hot/wet and hot/dry test results indicates the moisture damage is associated with excessive deformation. The maximum aggregate size and mixture gradation have significant effect on rutting resistance

From PURWheel tests, it is obvious that damage occurs much faster with wet conditions and temperature is an important factor in identifying rutting potential. For both #11 limestone and dolomite mixes, the number of wheel passes required to reach a 12.7 mm (1/2 in.) rut increases as the testing temperature decreases. At 60^0 C, both mixes deformed rapidly without a creep deformation stage. This shows that the mix has already lost its integrity and can not resist the 620 kPa tire loading. At 50^0 C, the limestone mix is more stable than the dolomite mix. Test results also indicate there is a semi-log relationship between number of wheel passes required to reach a 12.7 mm rut depth and temperature. The rate of deformation at 40^0 C is ten times greater than that at 25^0 C. This means, obviously, that rutting damage will accumulate in the summer at a greater rate, for the same amount of traffic.

The rutting phenomenon in the PURWheel was modeled through a reasonable approximation of loading and material properties. Results of model verification studies show that a creep model can successfully characterize the pavement material behavior. Based on deformation data from the PURWheel tests, material parameters in the creep model were backcalculated. Good agreement was obtained between predicted and measured deformation in APT tests for the same mixture. The material parameter m is strongly related to temperature and aggregate type. Regression analyses show the parameter m increases with increase of temperature. Mixtures with dolomite aggregate are associated with a higher (less negative) value of m.

FEM analysis shows that the effect of temperature can be modeled by a time dependent material model. The PURWheel has already shown its capability to evaluate rutting resistance of asphalt mixtures. Through appropriate level of loading and a reasonable range of temperatures, the asphalt mixture susceptibility to permanent deformation can be predicted within a short period of testing. This test can be utilized as an evaluation tool for the Superpave mix design system.

In this study, the Indiana #11 dolomite surface mix performed poorly in both wet and dry conditions. There is no question that combination and gradation of the aggregates caused instability of the mixture. This mixture was utilized on Interstate highway I-64 and the pavement exhibited distresses similar to those when the mixture was tested in the PURWheel WTD. Additional study is needed to correlate laboratory test results to field performance.

Results from PURWheel WTD and AASHTO T-283 tests for the Superpave mixes show the stripping/rutting potential of the mix can be minimized through better selection of materials as well as the mixture gradations. Comparison of the PURWheel performance shows that a higher percentage of natural sand causes progressively poorer performance. The PURWheel highlights the detrimental effect of moisture on rutting. In general, comparison of the AASHTO T-283 TSR and PURWheel results indicate that the TSR does not reflect a mixture's stripping/rutting potential as well as the PURWheel. Application of the 150 mm SGC specimen for AASHTO T-283 test still needs further evaluation before modification of the current test standard.

LIST OF REFERENCES

AASHTO, "Standard Specifications for Transportation Materials and Methods of Sampling and Testing", Part II, American Association of State Highway Officals, 1993.

Aschenbrener, T., and Currier, G., "Influence of Testing Variables on the Results From the Hamburg Wheel-Tracking Device," Final Report, No. CDOT-DTD-R-93-22, Colorado Department of Transportation, December 1993.

Aschenbrener, T., and Stuart, K., "Description of the Demonstration of European Testing Equipment for Hot Mix Asphalt Pavement," Final Report, No. CDOT-DTD-R-92-10, Colorado Department of Transportation, October 1992.

"Cause and Prevention of Stripping in Asphalt Pavements," Education Series No. 10, Asphalt Institute, College Park, MD, 1981.

ASTM, "1993 Annual Book of ASTM Standards," Philadelphia, 1993.

Bolzan, P.E., "Moisture Susceptibility Behavior of Asphalt Concrete and Emulsified Asphalt Mixtures Using the Freeze-Thaw Pedestal Test," Transportation Research Record 1228, Transportation Research Board, National Research Council, Washington, D.C., 1989, pp. 9-16.

Bonaquist, R., Churilla, C., Freund, D., "Effect of Load, Tire Pressure, and Type of Flexible Pavement Response," Public Roads, Vol. 52, No. 1, June 1988, pp. 1-7.

Cominsky, R.J., et al., "The Superpave Mix Design Manual for New Construction and Overlays," SHRP-A-407, Strategic Highway Research Program, National Research Council, Washington, DC, 1994

Croney, D. and Croney, P., "The Design and Performance of Road Pavements," Second Edition, McGraw-Hill Book Company, 1991, pp 15-19.

Decker, D.S., Goodrich, J.L., "Asphalt Cement Properities Related to Pavement Performance," Proceedings, The Association of Asphalt Paving Technologists, Vol. 58, 1989, pp. 503-518.

Fromm, H.J., "The Mechanisms of Asphalt Stripping from Aggregate Surfaces," Proceedings, The Association of Asphalt Paving Technologists, Vol. 43, 1974, pp. 191-223.

Graf, P.E., "Factors Affecting Moisture Susceptibility of Asphalt Concrete Mixes," Paper prepared for presentation at the Annual Meeting of the Association of Asphalt Paving Technologists, Clearwater, Florida, Feb. 17-19, 1986.

Gupta, Anil, "Temperature and Seasonal Corection Factors for Flexible and Rigid Pavements," A Thesis Submitted to the Faculty of Purdue University, August, 1987.

Gzemski, F.C., McGlashan, D.W., and Dolch, W.L., "Thermodynamic Aspects of the Stripping Problem," HRB, Highway Research Circular No. 78, 1968.

Habermann, J.A., "Design Features and a Preliminary Study of Purdue Linear Compactor and the PURWheel Tracking Device," M.S. Thesis, Purdue University, 1994.

Huang, H.M., "Analysis of Accelerated Pavement Tests and Finite Element Modeling of Rutting Phenomenon," A Thesis Submitted to the Faculty of Purdue University, August, 1995.

Huang, H.M., White, T.D., "Minimum Crushed Aggregate Requirements," Draft Finial Report, Joint Highway Reseach Project, FHWA/IN/JHRP-96/23, 1996.

Huang, Y.M., "Pavement Analysis and Design," Prentice Hall, Inc., 1993.

Hubbard, P., "Adhesion of Asphalt to Aggregates in the Presents of Water," HRB Proceedings, National Research Council, Washington, D. C., Vol. 18, Part I, 1938, pp 238-249.

Huekelom, W., Klomp, A.J.G., "Road design and Dynamic Loading," Proceedings, Association of Asphalt Paving Technologists, Ann Arbor, Michigan, 1964.

Indiana Department of Transportation, Standard Specification, 1995.

Kennedy, T.W., Roberts, F.L., and Lee, K.W., "Evaluation of Moisture Susceptibility of Asphalt Mixtures Using the Texas Freeze-Thaw Pedestal Test," ," Proceedings of the Association of Asphalt Paving Technologists, Vol. 51, 1982, pp.327-362.

Kennedy, T.W., "Use of Hydrated Lime in Asphalt Paving Mixtures," National Lime Association, Arlington, VA, March 1984.

Krugler, P., Mounce, J., Bentenson, W., et al, "Asphalt Pavement Rutting in the Western States: Two Texas Lectures and the WASHTO Report," Special Study 26.0, Texas State Department of Highways and Public Transportation, Jan. 1985.

Lottman, R.P., "Predicting Moisture-Induced Damage to Asphalt Concrete," TRB, NCHRP Report, No. 192, National Research Council, Washington, D.C., 1978.

Okamoto, P.A., Packard, R.G., "Effect of High Tire Pressures on Concrete Pavement Performance," 4th International Conference on Concrete Pavement Design and Rehabilitation, Purdue University, April 1989, pp. 61-74.

Parker, Jr.,F., Gharaybeh, F.A., "Evaluation of Indirect Tensile Tests for Assessing Stripping of Alabama Asphalt Concrete Mixtures," Transportation Research Record 1115, Transportation Research Board, National Research Council, Washington, D.C., 1987, pp. 113-124.

Pavement Management Systems Limited, "Study of Asphalt Cement Additives and Extenders," Roads and Transportation Association of Canada, January 1983.

Roberts, F.L., et al, "The effect of Tire Pressures on Flexible Pavements," Report 372-1F, Texas Transportation Institute, Texas A&M University, 1986.

Roberts, F.L., Kandhal, P.S., Brown, R.E., Lee, D-Y, Kennedy, T.W., "Hot Mix Asphalt Materials, Mixture Design, and Construction," NAPA Education Foundation Incorporated, 1991, pp 68-69.

Roberts, F.L., Kandhal, P.S., Brown, R.E., Lee, D-Y, Kennedy, T.W., "Hot Mix Asphalt Materials, Mixture Design, and Construction," NAPA Education Foundation Incorporated, 1991, pp 98-100.

SAS Institute Inc., "SAS System for Regression," Cary, NC, 1991.

Scheroman, J.a., Mesch, K.A., and Proctor, J.J., "The Effect of Multiple Freeze-Thaw Cycle Conditioning on the Moisture Damage in Asphalt Concrete Mixtures," Proceedings of the Association of Asphalt Paving Technologists, Vol. 55, 1986, pp.213-236.

Taylor, M.A. and Khosla, N.P., "Stripping of Asphalt Pavements: State of the Art," Transportation Research Record 911, Transportation Research Board, National Research Council, Washington, D.C., 1983, pp. 150-158.

Tunnicliff, D.G., Root, R.E., "Testing Asphalt Concrete for Effectiveness of Antistripping Additives," Proceedings of the Association of Asphalt Paving Technologists, Vol. 52, 1983.

Tunnicliff, D.G., Root, R.E., "Use of Antistripping Additives in Asphalt Concrete Mixtures," NCHRP Report #274, Transportation Research Board, National Research Council, Washington, D.C., December 1984.

Tunnicliff, D.G., "Performance of Antistripping Additives," Preprint of the Association of Asphalt Paving Technologists, Vol. 66, 1997.

Van Draat, W.E.F., Sommer, P., "Ein Geratzur Bestimmung der Dynamischen Elastizitats modulu von Asphalt," Strasse und Autobahn, Vol. 35, 1965.

White, T.D., "Stripping in HMA Pavements," Hot Mix Asphalt Technology, National Asphalt Pavement Association (NAPA), Fall 1987, pp. 18-20.

Williams, R.C., Duncan, G.R., Jr., White, T.D., "Sources, Measurement and Effects of Segregated Hot Mix Asphalt Pavements," Final Report, Joint Highway Reseach Project, FHWA/IN/JHRP-96/16, 1996.

Zaghloul, S.M., "Non-Linear Dynamic Analysis of Flexible and Rigid Pavements," A Thesis Submitted to the Faculty of Purdue University, May, 1993.