Wisconsin Highway Research Program

Using the Gyratory Compactor to Measure Mechanical Stability of Asphalt Mixtures

Ahmed Fatin Faheem Mahmoud
Professor Hussain Bahia
Department of Civil and Environmental Engineering
University of Wisconsin-Madison

October 2004

WHRP 05-02

Using Gyratory Compactor to Measure Mechanical Stability of Asphalt Mixtures

Wisconsin Highway Research Program 0092-01-02

By

Ahmed Faheem, Research Assistant
Hussain U. Bahia, Associate Professor
University of Wisconsin – Madison
Department of Civil and Environmental Engineering
1415 Engineering Drive, Madison, WI 53706-1490

Submitted to

Wisconsin Department of Transportation
Division of Transportation Infrastructure Development
Research Coordination Section
4802 Sheboygan Ave., Box 7065, Madison, WI 53707-7910

October 2004

Disclaimer

This research was funded through the Wisconsin Highway Research Program by the Wisconsin Department of Transportation and the Federal Highway Administration under Project # 0092-01-02. The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Wisconsin Department of Transportation or the Federal Highway Administration at the time of publication.

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. This report does not constitute a standard, specification or regulation.

The United States Government does not endorse products or manufacturers. Trade and manufacturers' names appear in this report only because they are considered essential to the object of the document.

ACKNOWLEDGEMENTS

There are many people who contributed to the completion of this project. Some of the more important contributors include the members of the Wisconsin Highway Research Program Flexible Pavement Technical Oversight Committee. Their feedback and support, especially Ms. Judie Ryan (WisDOT), Mr. Jack Weigel (Payne and Doland), and Dr. Erv Dukatz (Mathy Construction) are gratefully acknowledged.

Additional thanks to Mr. James Bongard and Ms. Linda Richardson of the Wisconsin Department of Transportation for driving all the miles to the project sites and conducting countless nuclear density tests.

The following Wisconsin based companies and organizations that were cooperative in working on the field studies and supplying labor and materials: Payne & Dolan (Waukesha), Inc., Mathy Construction (Onalaska), B. R. Amon and Sons Inc. (Elkhorn), and Pitlick and Wick Inc (Eagle River).

Within the UW-Asphalt Research Group, there were many that gave much of their time to assist on the project. Anthony Stakston, and Hussain Ajideh are more specially recognized for having conducted the compaction part of the report.

The authors would also like to thank Ms. Jackie Jiran for her support in finishing the final version of this report and for her detailed review of the document.

Technical Report Documentation Page

1. Report No.
WHRP 05-02

2. Government Accession No.

3. Recipients Catalog No.

4. Title and Subtitle
Using Gyratory Compactor to Measure Mechanical Stability of Asphalt Mixtures

5. Report Date
October 2004

6. Performing Organization Code
0092-01-02

7. Author(s)
H.U. Bahia, Associate Professor and B. C. Paye, Research Assistant

8. Performing Organization Report No. WHRP 03-

9. Performing Organization Name and Address
University of Wisconsin – Madison
Department of Civil and Environmental Engineering
1415 Engineering Drive
Madison, WI 53706-2507

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
WisDOT SPR# 0092-01-02

12. Sponsoring Agency Name and Address
Wisconsin Department of Transportation
Division of Transportation Infrastructure Development
Research Coordination Section
4802 Sheboygan Ave., Box 7065, Madison, WI 53707-7910

13. Type of Report and Period Covered
Final Report, 2001-2003

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

In this study several asphalt mixtures were produced using four different aggregate sources, different asphalt contents, and different aggregate gradations. Every mixture was compacted using the SGC. To evaluate if the densification results from the SGC can be related to rutting of mixtures, the new axial compression test procedure for rutting measurements recommended by the National Cooperative Highway Research Program project 9-19 and used in the AASHTO 2002 pavement design manual, was also used for evaluating the rutting behavior for laboratory produced samples.

Densification curves produced by the SGC were used to determine volumetric properties of the mix as well as for the calculation of the construction and the traffic densification indices. The construction densification index (CDI), which is the value of the area under the densification curve from density at 8 gyrations to density of 92% Gmm, represents the work done during the construction period to achieve 8 % air voids. The traffic densification index (TDI), which is the value of the area under the densification curve from 92% density to 98% density, represents the work needed to resist traffic loading during pavement service life. Two more indices are calculated, construction force index (CFI) and traffic force index (TFI). CFI is related to the amount of work done to raise the density of the mix to 92%. The TFI is the amount of work done to increase the density of the mix from 92% to 98%.The results from the mixture rutting tests were used to estimate the rutting rate and the flow number (FN), which is the point at which the mixture starts to exhibit tertiary flow. The flow number, which is considered an important mixture property, is shown to have a strong correlation to the TDI derived from the mixture volumetric behavior measured in the SGC. The main finding of the study is that SGC appears to give information that can be used to characterize the stability of the mixtures. Such information could be used as an initial screening criterion to select mixture for various traffic ESAL levels, in addition to indicating an expected performance level.

17. Key Words
SUPERPAVE, RUTTING RESISTANCE,
MIXTURE COMPACTION, DENSIFICATION

18. Distribution Statement
No restriction. This document is available to the public through the National Technical Information Service, 5285 Port Royal Road
Springfield, VA 22161

19. Security Classif. (of this report) Unclassified
Unclassified

20. Security Classif. (of this page) Unclassified
Unclassified

21. No. of Pages:

22. Price

Executive Summary

The purpose of this study was to use the gyratory compactor as an indicator of the mechanical stability of the asphalt mixtures. The goal of the project was to identify and suggest limits to be used as screening criterion to select mixture for various traffic levels.

Background

The current procedure of evaluating Wisconsin asphalt mixtures depend heavily on the volumetric properties of the hot mix asphalt (HMA), which is felt does not produce a reliable enough estimate of the expected performance of the mixtures in the field. Several approaches have been introduced lately to try and characterize the performance related properties of asphalt mixtures. The majority of these efforts are focused on developing special equipment to test the HMA at conditions similar to those acting on the pavements due to moving traffic. Because the Superpave gyratory compactor (SGC) is used routinely for compaction, and because it has components to measure load and densification, this study was intended to further develop its use as a basis for measuring the stability of asphalt mixtures without the need for new equipment or additional time.

Process

In this study several asphalt mixtures were produced using four different aggregate sources, different asphalt contents, and different aggregate gradations. Each mixture was compacted using the SGC (Pine Model) to evaluate if the densification results from the SGC can be related to rutting of mixtures, the new axial compression test procedure for rutting measurements recommended by the National Cooperative Highway Research Program project 9-19 and used in the AASHTO 2002 pavement design manual, was also used for evaluating the rutting behavior in laboratory produced samples.

Densification curves produced by the SGC were used to determine volumetric properties of the mix as well as for the calculation of the construction and the traffic densification indices. The construction densification index (CDI), which is the value of the area under the densification curve from density of 8 gyrations to density of 92% Gmm, represents the work done during the construction period to achieve 8 % air voids. The traffic densification index (TDI), which is the value of the area under the densification curve from 92% density to 98% density, represents the work needed to resist traffic loading during pavement service life. Two more indices are calculated, construction force index (CFI) and traffic force index (TFI). CFI is related to the amount of work done to raise the density of the mix to 92%. The TFI is the amount of work done to increase the density of the mix from 92% to 98%.

The results from the mixture rutting tests were used to estimate the rutting rate and the flow number (FN), which is the point at which the mixture starts to exhibit tertiary flow in repeated creep test.

Findings and Conclusions

The flow number, which is considered an important mixture property, is shown to have a strong correlation to the TDI and TFI derived from the mixtures volumetric behavior measured in the SGC. The main finding of this study is that SGC appears to give information that can be used to characterize the stability of the mixtures. Such information could be used as an initial screening criterion to select mixture for various traffic ESAL (Equivalent Single Axle Load) levels, in addition to indicating an expected performance level.

Recommendations

The findings of this study indicated showed the gyratory compactor can be used as a measure of the mechanical stability of asphalt mixtures. It is recommended that further research be conducted to cover a wider range of mixtures. This will also create an opportunity to introduce more variables into the study such as changing the asphalt binder grades. Development of a correlation between laboratory and field data is also recommended for future study. With further research, the information in this study can be used to develop specific limits for pavements with different traffic ESAL levels should meet.

TABLE OF CONTENT

Abstract:

In this study several asphalt mixtures were produced using four different sources, different asphalt contents, and different gradations. Every mixture was compacted using the SGC. To evaluate if the results from the SGC can be related to rutting of mixtures, the new axial compression test procedure for rutting measurements recommended by the National Cooperative Highway Research Program project 9-19 and used in the AASHTO 2002 pavement design manual, was also used for evaluating the rutting behavior in the laboratory for the same mixtures.

Densification curves produced by the SGC were used to determine volumetric properties of the mix as well as the calculation of the construction and the traffic densification indices. The construction densification index (CDI), which is the value of the area under the densification curve from density of 88% to density of 92%, represents the work done during the construction period to achieve 8 % air voids. The traffic densification index (TDI), which is the value of the area under the densification curve from 92% density to 98% density, represents the work needed to resist traffic loading during pavement service life. Two more indices are calculated, construction force index (CFI) and traffic force index (TFI). CFI is related to the amount of work done to change the density of the mix to 92%. The TFI is the amount of work done to change the density of the mix from 92% to 98%.The results from the mixture rutting tests were used to estimate the rutting rate and the flow number (FN), which is the point at which the mixture starts to exhibit tertiary flow. The flow number, which is considered an important mixture property, is shown to have a strong correlation to the TDI derived from the mixtures volumetric behavior measured in the SGC. The main finding of the study is that SGC appears to give information that can be used to characterize the stability of the mixtures. Such information could be used as an initial screening criterion to select mixture for various traffic levels.

Chapter One

Literature Review

This literature review was conducted as Task 1 of this project. It documents information found and considered to be relevant to the project.

1.1 Superpave System and Superpave Mix Design

Superpave^{TM} (*Su*perior *Per*forming Asphalt *Pave*ment) is a product of the Strategic Highway Research Program (SHRP), which was initiated in 1987 as a five-year, $150 million project to improve the performance and durability of U.S. roads and make them safer for both motorists and highway workers. Superpave is a system for specifying selection of asphalt binders and mineral aggregates, designing asphalt mixtures, and predicting performance of HMA pavements. The system incorporates performance based asphalt materials characterization, accounting for design environmental conditions to improve HMA performance by controlling rutting, low temperature cracking and fatigue cracking of pavements (1-3).

The Superpave gyratory compactor (SGC) is the compaction device used in Superpave mix design. The SGC was developed on the basis of a Texas gyratory compactor with modifications using the principles of a French compactor (2). The SGC is used to produce specimens for volumetric analysis, while recording density data throughout the compaction procedure. Among various requirements for the design of asphalt mixtures, the number of gyrations representing different levels of density is most important and unique to Superpave. The number of gyrations is specified for N_{ini} and requiring less than 89% G_{mm}, representing construction densification, N_{des} at 96% G_{mm} to represent initial trafficking and basis for volumetrics, N_{max} requiring less than 98% G_{mm}, representing the service life of the pavement, in accordance with predicted traffic ESALs based on a 20 year service life. The design procedure is provisional at the present time. It considers the volumetric properties of the mixture only as documented in the current AASHTO MP2.

Wisconsin, like many other states, is implementing the Superpave technology. Minor modifications were made to the original specifications inclusive of AASHTO MP2 (4).

1.2 Evaluations of Current Superpave Mix Design

Being part of a new technology, Superpave mix design has been one of the areas that has generated much discussion within the asphalt paving academia and industry over the past few years. Many studies have been conducted on the Superpave mix design methodology to supplement, refine, and/or further develop various aspects of the procedure and test equipment (5-20).

As traffic loads (i.e., axle loads, tire loads, and tire pressures, are increasing), it is necessary to look into aspects of mixture design that would consider the mechanical properties of the mixture (8) and their response to different traffic conditions. It has been noted that the Superpave volumetric mix design procedure may not be sufficient for relating mix properties to pavement performance, or for producing adequate mix materials aimed at meeting desired levels of performance (11).

One limitation of the Superpave mix design procedure is that it considers volumetric properties only, while it is known that it is the mixture's mechanical properties that directly relate to the performance of asphalt pavements. Although efforts are being made to develop separate tests for measuring mechanical properties of mixtures, the procedures being developed involve new equipment, which will be an added cost and probably require an extensive amount of training prior to their operation. Since the Superpave gyratory compactor (SGC) is a key component of the current design procedure and its use is now widely understood, it would be desirable to utilize the equipment for the purpose of acquiring mechanical properties of the mixture in testing. Proper interpretation of the results will lead to the establishment of standard requirements serving as a supplement to the volumetric design. Attempts have been made in this regard (7, 9, 10, 14, 19, 20).

Another problem within the current Superpave mix design procedure has to do with construction. Field experience with Superpave mixtures indicates that some of the mixtures are very difficult to compact and require specialized or additional compaction rollers. In fact, there is no other measurement requirement than density at completion of the construction for the pavement to meet prior to being open to traffic, primarily at 92% G_{mm}. It is, therefore, desirable to include as part of the supplementary standard a workability requirement based on a measurement of the mechanical properties. Efforts have also been made to give the workability or constructability a consideration (10, 19).

The following presents some studies that are considered to be closely related to this ongoing project.

1.3 Utilization of Densification Curve

Bahia et al. (10) reevaluated the Superpave volumetric mixture design procedure. This study found that the current interpretation of the results from Superpave gyratory compactor (SGC) and consideration of design criteria are biased towards the performance under traffic and do not provide a proper account for the constructability of asphalt mixtures. It is believed that the SGC data are underutilized in the procedure. This study took a new look at mixture design requirements using the SGC results to optimize the densification characteristics in construction and under traffic.

Six job mix formula (JMF) blends were used. The blends represented a high and low fine aggregate angularity range. This was accomplished by varying the amount of natural sand versus that of manufactured sand for high volume (WisDOT HV, $>2\times10^6$ ESALs) and medium volume (MV, 0.25 to 2×10^6 ESALs), respectively. One asphalt binder with a penetration grade of 120-150, which is equivalent to PG 58-28, was used. The Superpave procedure was performed for each mixture. A standard asphalt content was used while varying the aggregate gradation to look into the sensitivity of densification characteristics to the change in asphalt content. The materials and design conditions in the study are typical in Wisconsin.

Continuous curves of densification for % G_{mm} versus the number of gyrations for data from SGC were plotted as shown in Figure 1. In interpreting the results, concepts of compaction energy index (CEI) and traffic densification Index (TDI) were introduced.

1.3.1 Compaction Energy Index (CEI)

The Compaction Energy Index (CEI) is defined as the area from the 8th gyration to 92% of G_{mm} in the densification curve as shown in Figure 1. It is theorized that CEI represents the work applied by the roller to compact the mixture to the required density during construction. The number of eight gyrations is selected to simulate the effort applied by a typical paver during the process of laying down the mixture, while the 92% of G_{mm} is the density at the completion of construction and the pavement is open to traffic, as required by WisDOT specifications. Mixtures with lower values of CEI have better constructability and are desired; while too low a value of CEI could be an indication of a tender mixture and should be avoided.

1.3.2 Traffic Densification Index (TDI)

The Traffic Densification Index (TDI) is defined as the area from 92%, through 96%, to 98% of G_{mm} in the densification curve (see Figure 1). After a pavement is opened to traffic at 92% of G_{mm}, it continues to densify under traffic loads. The current mixture design procedure requires that the mixture be compacted to 96% of G_{mm} (4% air voids) at optimum asphalt content using N_{des} gyrations which the mixture is expected to reach under traffic during the early life of the pavement. The 98% of G_{mm} is considered the critical density, at which the mixture is approaching the plastic failure zone. In the study, the effect of traffic at the design density, or the amount of effort required to densify the mixture between 92% and 96% of G_{mm} is not emphasized. Instead, TDI is the amount of the total effort required to compact the mixture to a terminal density of 98% of G_{mm}. Mixtures with higher TDI values in this range are more desirable because they are expected to take more traffic during their life span. Figure 2 shows differences in CEI and TDI for two mixtures.

Although the concept of using CEI and TDI appeared to be logical and useful, there were still some doubts about using the volumetric measurements without measuring force or stress in sample to evaluate mixture behavior. These concerns lead to the development of a device that could be inserted on top of the mixture sample and could generate information about the stress distribution during compaction. The device was called the Gyratory Plate Load Assembly (GLPA).

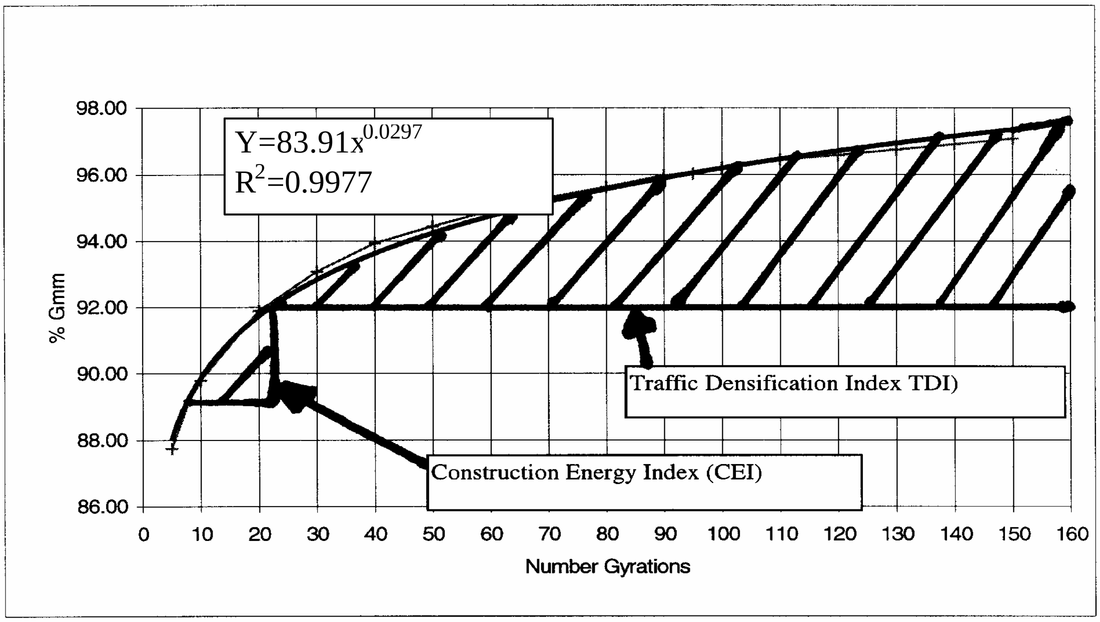


Figure 1.1 Illustration of CEI and TDI Indices

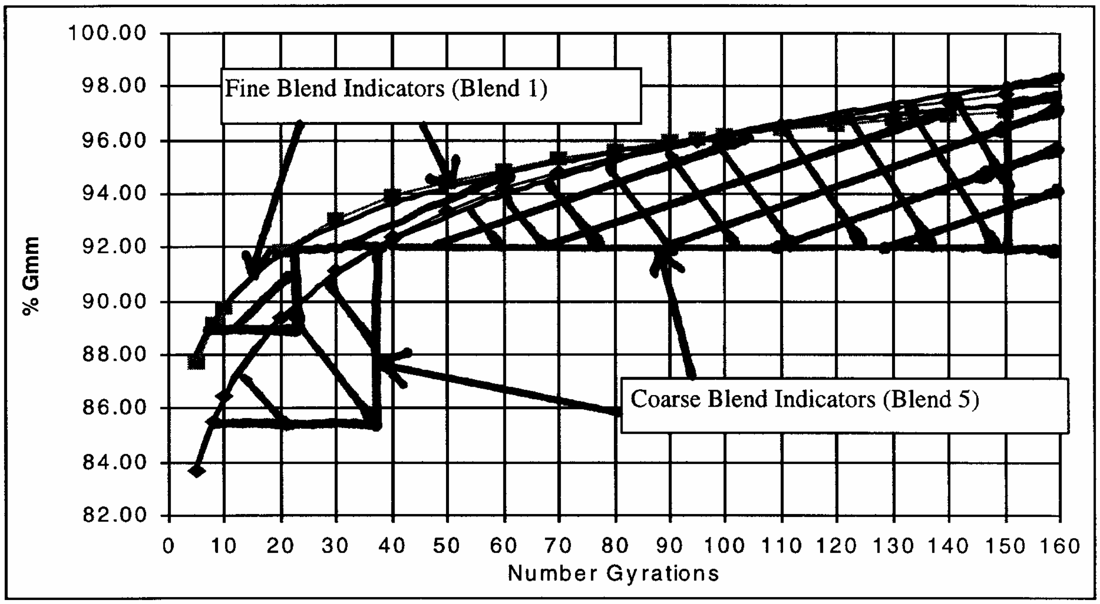


Figure 1.2 Differences in CEI and TDI Indices for Two Mixtures

1.4 Design and Use of Gyratory Load-Cell Plate Assembly (GLPA)

In view of the need for measuring mechanical properties, an accessory device to Superpave gyratory compactor (SGC), known as gyratory load-cell plate assembly (GLPA), was developed at the University of Wisconsin Asphalt Research Group. A work plan was conducted to document and describe the development of this accessory device and the interpretation of results from SGC testing using the GLPA (20).

1.4.1 Design of GLPA

Figure 3 shows a sketch of GLPA. The plate includes three load-cells equally spaced on the perimeter of a double-plate assembly, which can be inserted on the sample of mixture in a SGC mold as shown in Figure 4. The load-cells allow measuring the variation of forces on top of the sample during gyration such that the position or eccentricity of the resultant force from the gyratory compactor can be determined in real time. The two dimensional distributions of the eccentricity of the resultant force can be used to calculate the effective moment required to overcome the internal shear frictional resistance of mixtures when tilting the mold to conform to the 1.25 degree angle.

During the compaction process, readings were taken at a rate of 50 readings per gyration from each load-cell using signal conditioning and acquisition hardware controlled by the graphical programming language LabVIEW®. Deflection readings can also be recorded in real time by the system through the serial communication port of the SGC device.

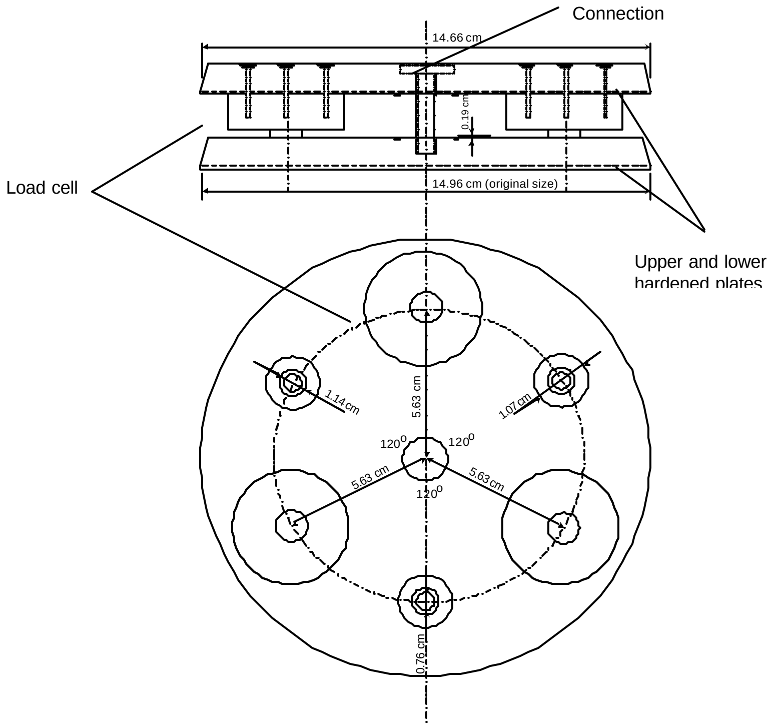


Figure 1.3 Gyratory Load-Cell Plate Assembly (GLPA)

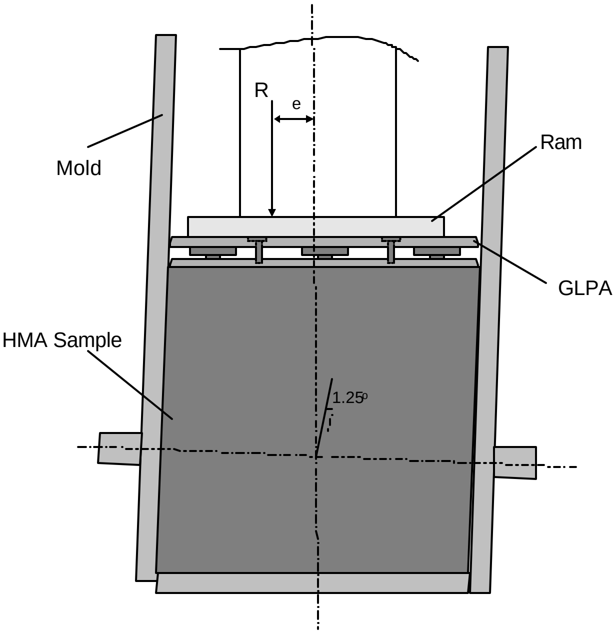


Figure 1.4 GLPA in the SGC Mold during Gyration

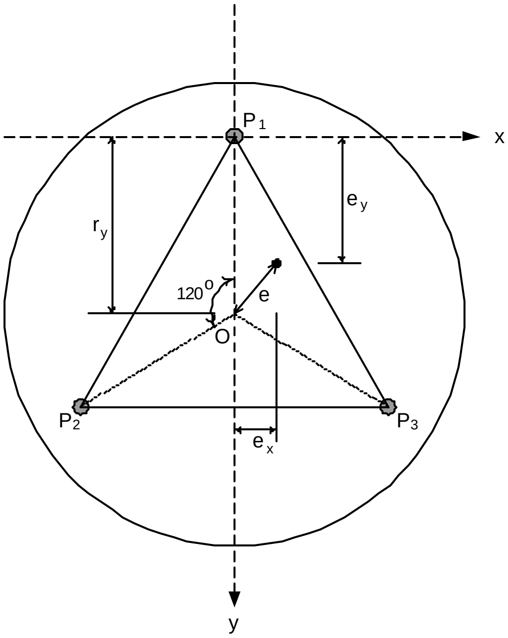


Figure 1.5 Eccentricity Point Calculated Based on Load-Cell Forces P_1, P_2 and P_3

Based on the readings from the load-cells, the two components of the eccentricity of the total load relative to the center of the plate (e_x and e_y) can be calculated for each of the 50 points collected during each gyration. The calculations are simply done with general moment equilibrium equations along two perpendicular axes passing through the center of one of the load-cells as shown in Figure 5 using Equation [1]:

$$\begin{aligned} &\sum M_x = 0 \Rightarrow e_y \\ &\sum M_y = 0 \Rightarrow e_x \\ &e = \sqrt{e_x{}^2 + (r_y - e_y)^2} \end{aligned} \qquad [1]$$

as shown in figure 5 P_1, P_2, P_3 are load-cell forces; e_x and e_y are x- and y-components of the eccentricity, e; and r_y is location of the plate center point with respect to the x-axis.

1.4.2 Interpretation of Testing Results

The data acquired from the GLPA can be interpreted in different ways. The two main outcomes of the GLPA is the calculation of the frictional resistance (FR), and the resistive effort (w). The "frictional resistance" is a measure of the strength of the mixture against shear forces. The resistive effort is a measure of the resistance of the mixture to compaction. The following sections show in greater detail how each measure is calculated. For the purpose of this study the "resistive effort" is the one that is used to characterize the mechanical stability of the mixtures.

1.4.3 Calculation of Frictional Resistance (FR)

In calculating the internal shear frictional resistance (FR) of the mixture, it is assumed that at any gyration the sample is fully constrained, and the energy due to surface traction is negligible. The energy balance for the mixture sample at any gyration cycle can be written using the following equations:

$$W = U \qquad [2]$$

Where;

W is the work of external forces

U the total strain energy of sample, and

$$\frac{1}{2}Mq = \frac{1}{2}tgV \qquad [3]$$

Where;

M is the applied moment during gyration,

q The tilt angle (in radians),

g The gyration angle,

V The sample volume at any cycle equaling area A multiplied by height h.

As shown in Figure 6, the moment, M, is R times e, which is measured by the GLPA. The bulk frictional resistance, represented by the value of t applied to the sample, can be determined from Equation [3]. Since the angle g ?is equal to the gyration angle q, Equation [3] can be simplified to calculate the frictional resistance, FR, as follows:

$$FR = t = \frac{Re}{Ah} \qquad [4]$$

Where;

A The sample cross-section area

h The sample height at any gyration cycle.

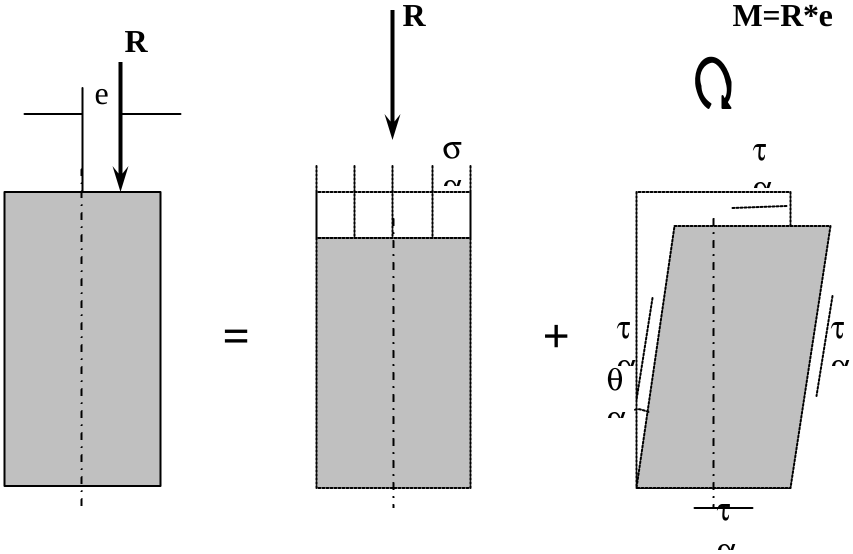


Figure 1.6 Applied External Forces and the Stress Distributions Used in Energy Relations

Asphalt mixtures with varying aggregate gradations, and asphalt contents were tested during this study. Test data were plotted in % G_{mm} and FR versus the number of gyrations as shown in Figure 7, in which data for two of the mixtures with the same aggregate structure but different asphalt contents were used. It is found that the FR is sensitive to asphalt content, aggregate gradation, and air voids. More importantly, it is found that there is no direct relationship between density and FR. Since it is believed that FR is a good indicator of stability of asphalt mixtures, Figure 7 is called volumetric-stability plot.

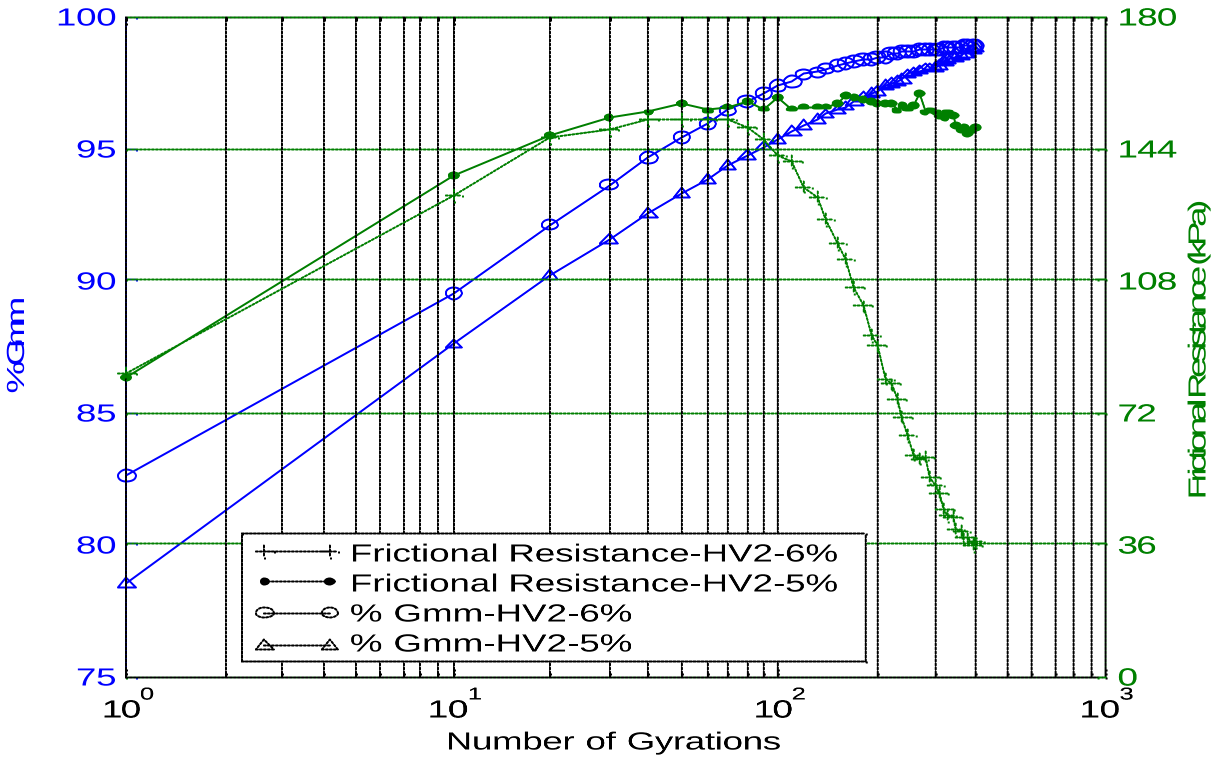


Figure 1.7 Volumetric-Stability Plot for HV2 Mixtures at 5 and 6% Asphalt Contents

1.4.4 Calculation of the Resistive Effort

Focusing on the effect of fine aggregate angularity (FAA) on the properties of asphalt mixtures, Delage (19) conducted a study using Superpave gyratory compactor (SGC) with the gyratory load-cell plate assembly (GLPA). New ways of interpreting the testing data collected with the GLPA were attempted.

In interpreting the data from SGC testing with GLPA, a concept of resistive effort, denoted by w, is used as defined in the following equation:

$$w = \frac{4ePq}{Ah} \qquad [5]$$

where;

w the resistive effort

e the eccentricity of resultant force

P the magnitude of resultant force

q the angle of tilting (1.25°)

A the area of specimen

h the height of specimen at any given gyration.

In essence, w is the work done by SGC per unit volume per gyration, assuming the material is perfectly viscous or plastic. The resistive effort has a unit of stress. Typical examples of resistive effort as a function of the number of gyrations are shown in Figure8.

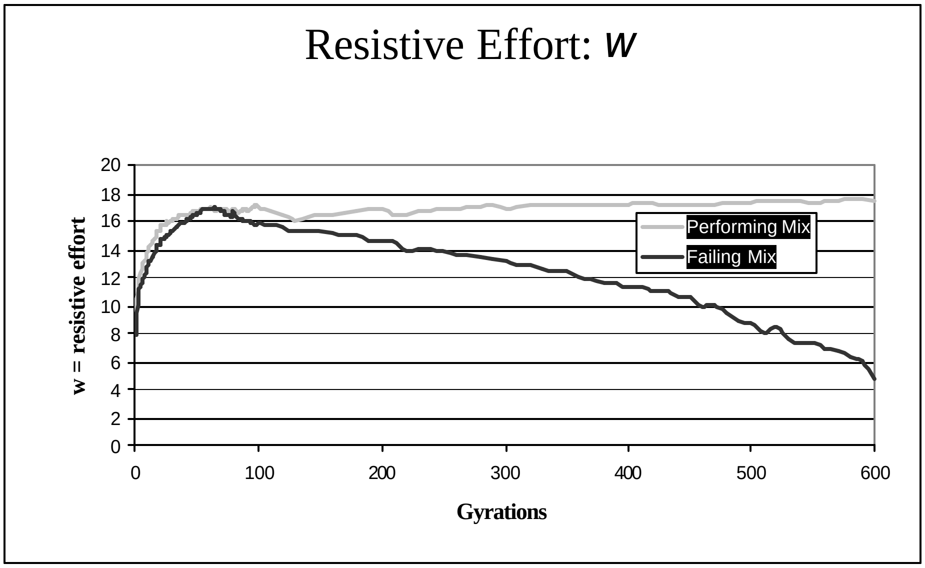


Figure 1.8 Sample Resistive Effort Curves

1.4.5 Densification indices and interpretation of stress data

1.4.5.1 Densification indices

Delage (19) study proposes a new method for analyzing data from SGC testing with GLPA using a technique similar to the energy indices proposed by Bahia et al. (10). The resistive effort curve is divided at 92% G_{mm} into a construction side and a traffic side. Under 92% G_{mm}, it is desirable for the mixture to have a low resistive effort. This will enable the ease of compaction by the contractor. At above 92% G_{mm}, it is desirable for the resistive effort of the mixture to be high. The high level of resistive effort is an indicator of the high resistance of mixture to distortion under traffic, which will reduce rutting. To quantify the resistive efforts above and below 92% G_{mm}, the area under the resistive effort curve between N_{ini} and 92% G_{mm} is calculated and termed the compaction force index (CFI), and the area between 92% and 98% G_{mm} is calculated and termed the traffic force index (TFI). It is also suggested that the construction energy index (CEI) relating to the compaction curve be renamed the construction densification index (CDI). In this way, the CDI and TDI relate to the densification curve, and the CFI and TFI relate to the resistive effort curve. Figure 9 illustrates the four indices used as response variables in the study.

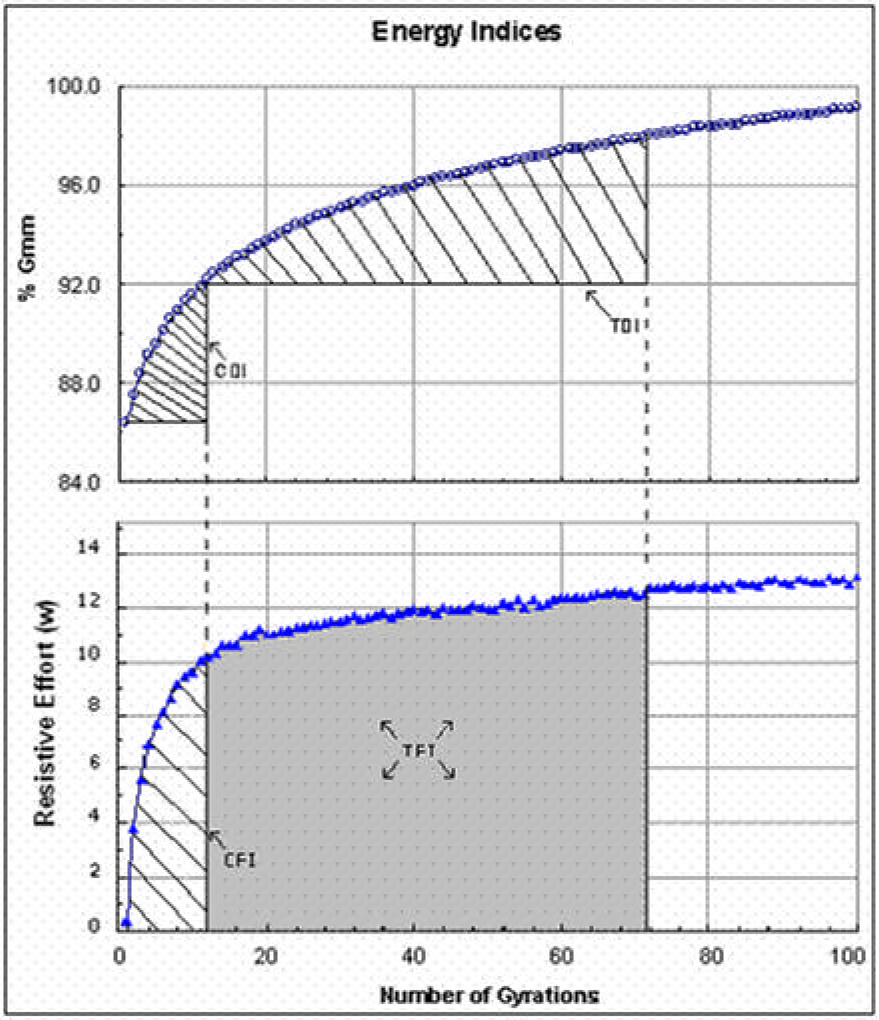


Figure 1.9 Response Variables: CDI and TDI, CFI and TFI

Some of the important findings from Delage's study are that the results do not support the common belief that higher values of FAA will always result in better performing mixtures; that the effect of FAA is highly dependent on the source of the aggregates and their gradation; and that the volumetric properties cannot not capture the true effect of fine aggregate angularity on mixture constructability and traffic resistance.

Delage's study was expanded to include more sources of aggregates and different asphalt binder grades. The study was also expanded to include several types of mixtures ranging from WisDOT E1.0 (1 million ESALs) type mixture to E30.0 (30 million ESALs) mixtures. The analysis of the results focused on comparing the GLPA results with the volumetric results to evaluate a potential need and benefit for the GLPA. Also the study was intended to propose criteria for mixture acceptance based on the best energy indices.

1.4.5.2 Interpretation of the Results

The development of the GLPA provided an opportunity to measure the true stress conditions that an asphalt mixture is subjected to in the gyratory compactor. Publications about the use of the energy indices and the measurements of the stresses in the SGC have resulted in a significant interest among asphalt researchers. Several studies were conducted to seek the best approach for use of the SGC results with and without a force device.

In the year 2000 NCHRP project 9-16 started which included a detailed evaluation of a variety of procedures to evaluate asphalt mixtures using the gyratory compactor. As a result of the NCHRP 9-16 project (2), an evaluation of the GLPA and a gyratory compactor with force measuring device was conducted. It was proposed that the number of cycles to maximum stress be used as a parameter between good and poor performing mixtures. Some correlations with field performance showed that the parameter correlates well with rutting observed in the field. A sliding scale was proposed as a criterion for measuring rutting potential. Recently the GLPA device was further modified by FHWA to place the data collector within the plate. The new device has also been re-named as the Pressure Distribution Analyzer (PDA).

Other researchers have also proposed alternatives to the PDA using gyratory compactors equipped with force measuring devices. Dessouky et al. (3) and Bayomy et al. (4) developed another procedure to estimate the shear stress in an asphalt mix during compaction using a SGC equipped with a force measuring device. This procedure is based on equilibrium analysis of the mix and steel mold during compaction. The measured shear stress and the mix densification characteristics were used to calculate the energy consumed in forming contacts among aggregate particles. This energy is quantified using an index referred to as the Contact Energy Index

The contact energy index is calculated after defining the reference gyration (N_{G1}), which is taken as the point where the change in the slope of the force versus gyrations at any two consecutive gyrations is less or equal to 0.001%. It is intended to minimize the confounding of densification effects on the shear deformation of a mixture. The TDI and TFI are referenced to the 92 % Gmm and the 98 % Gmm and are intended to be inclusive of both distortion and densification between these two well known reference densities of 8 % voids and 2 % voids.

It is very difficult to decide which of these indices are better and which one should be used, and there is a need for further validation data before such judgment could be made. It is however important to remember that TDI does not require a force measuring device.

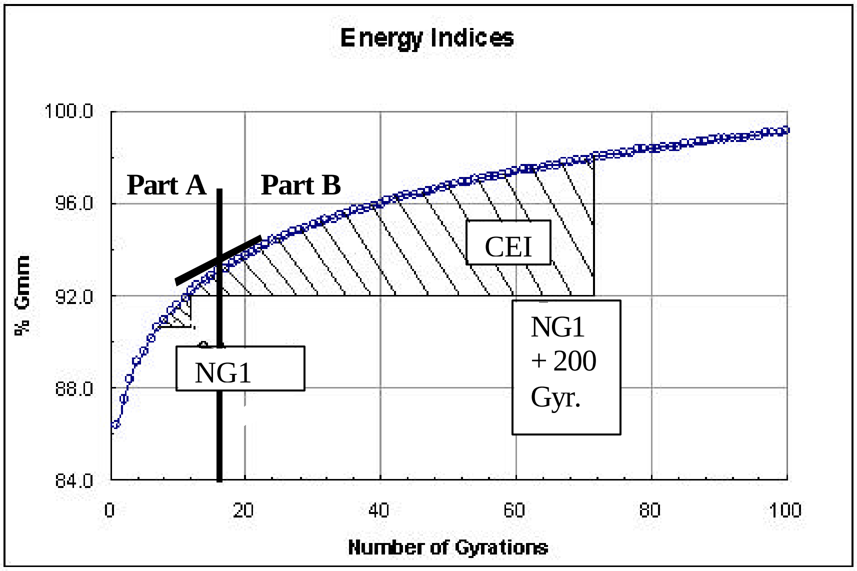


Figure 1.10 : Contact Energy Index.

This approach, which relies on developing experimental tools and analysis methods for the gyratory measurements to measure the shear stress during compaction and relating them to stability (10, 11, 12), is not new. McRea (10, 11) in the 1960's developed an equation to measure the shear stress during the compaction. This equation is based on equilibrium analysis of an asphalt specimen and has been used by many researchers to predict the stability and the performance of asphalt mix (13-17).

More recently, a study was conducted at the University of Idaho, and Washington State University (26,27) and included a more elaborate analysis of the stress distribution in the gyratory mold and a careful evaluation of the boundary assumptions used by Guler and co-workers. The study focused on the development of a method to estimate the aggregate structure stability in the Servopac gyratory compactor, which is equipped with a load cell that measures the load needed to apply the angle of gyration during compaction. The stability measure developed in this method is referred to as Contact Energy Index. This index is the multiplication of the shear force and the vertical deformation. It is used to estimate the aggregate structure stability irrespective of the type of the Superpave gyratory compactor design by means of the PDA. (29).

Prior to the development of the PDA (20), Bahia and co-workers proposed using the volumetric results from the gyratory compactor to calculate two indices (CDI and

TDI, Figure 1.9) derived from the compaction curves in order to evaluate the HMA behavior (10).

The important question, however, is whether we need the force measurements or not. This is important because the Superpave gyratory compactor (as described in AASHTO MP2) does not require a force measurement. The vast majority of the asphalt laboratories today do not own a gyratory with a force-measuring device. The question was the subject of a recent study at the University of Wisconsin to explore the correlations between TDI, which does not require a measure of the force in the gyratory, and the contact energy index and TFI, which require the a force measurement device in the gyratory. Figure 1.11 depicts the scatter plot of TDI versus TFI, contact energy index versus TDI, and contact energy index versus TFI.

There appears to be a very good correlation between TDI and TFI but no good correlation between contact energy index and the other measures. The lack of correlation with contact energy index could be explained mainly by the difference in the methods used to derive these parameters.

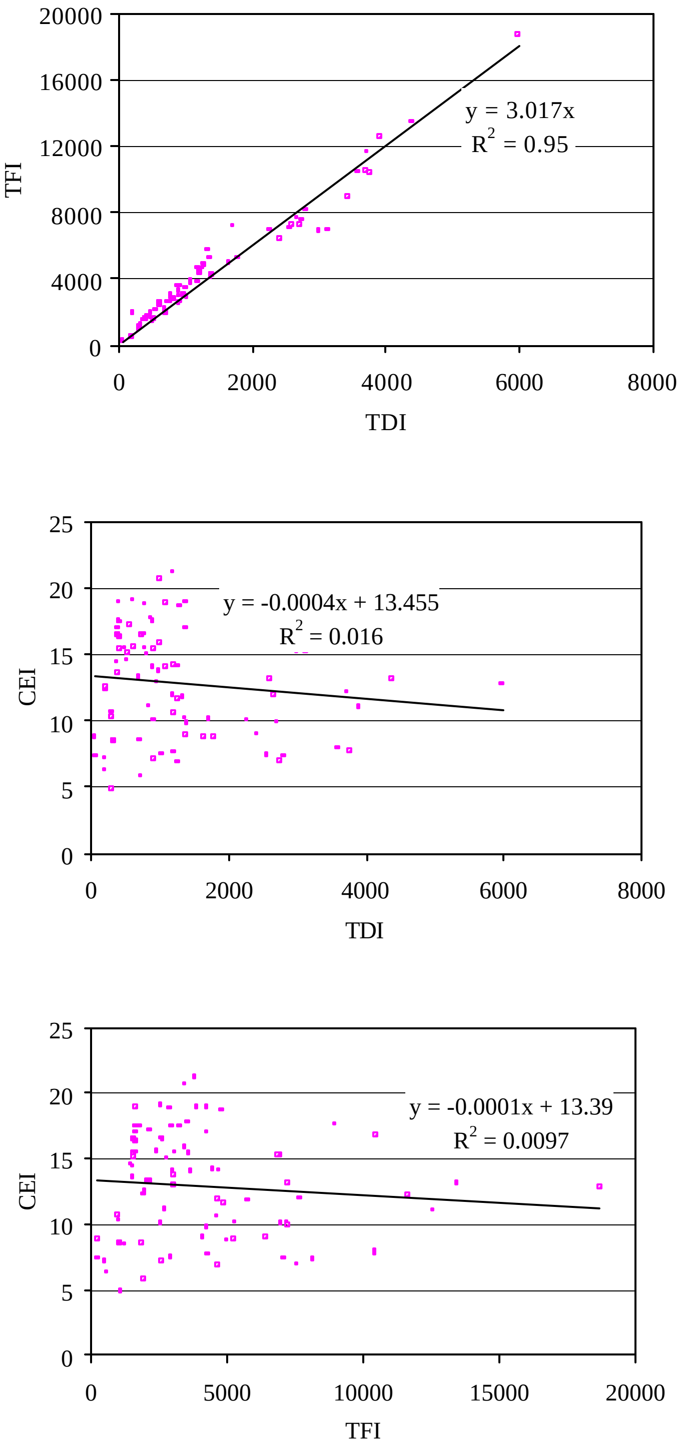


Figure 1.11. Correlations between the three Traffic Resistance Indices CEI, TDI and TFI for all mixtures.

1.5 Summary of SGC indices and densification

Based on the results collected in the study, conceptual suggestions for the revision of Superpave volumetric mixture design procedure are proposed. They are:

1. Construction Criteria: CDI at optimum asphalt content should be within the range of a minimum CDI to avoid tender mixtures and a maximum CDI to ensure acceptable workability.
2. Aggregate Criteria: With regard to the aggregate gradation, there is no need for the restricted zone, as it serves no clear purpose in the context of calculating densification rates. Also, it is not clear why the angularity of aggregates, coarse and fine (CAA, FAA), should be controlled if the densification criteria are met. The other source and consensus properties should remain the same to ensure the toughness, cleanness, and soundness of aggregates.
3. Sensitivity to Asphalt Content Variation: There is a need to avoid "critical mixtures" as defined by showing high changes in air voids with minor changes in asphalt content. It should be recognized that asphalt mixture production is a process that is difficult to control and is subject to much variation beyond the control of contractors. It is therefore necessary to control the sensitivity of mixtures to asphalt content so that construction and performance become more uniform and more predictable.

Based on the data, these ideas for revising the existing Superpave mixture design (AASHTO MP2) are presented. The proposed ideas include using energy indices (CDI and TDI) to balance a relatively low value of CDI with a high value of TDI. These criteria are intended to replace the existing % G_{mm} at N_{ini}, N_{des}, and N_{max}.

However, there is a need to develop a performance ctriteria to be compared against the densification indices. The best performance based test prosedure is to measure the mixture resistance to permanent deformation (rutting). For the purpose of this study the performance of the mixtures is measured by a test recommended by the NCHRP project 9-19. The following sections cover a literature review about rutting in the asphalt mixtures.

1.6 Background for Causes Affecting Rutting and Subsequent Testing

Rutting in asphalt pavements can be defined as a gradual development of longitudinal depressions in the wheel path with the increase of number of load repetitions. It is considered to be caused by a combination of densification and shear deformation, and can occur in any one or more of the pavement layers, as well as the subgrade. In case of poor compaction consolidation and densification are the main rutting mechanism. In case of appropriate compaction, of the pavement layer, a study at the AASHO road test in 1962, and test-track studies performed by Hofstra and Klomp (1972) indicated that the shear deformation rather than densification is the primary rutting mechanism. The use of excessive amount of asphalt cement is the most common cause rutting in the asphalt layer. This is because excessive asphalt binder will act as a high lubricant and prevent the internal friction and interlock between aggregate particles to carry the load. Hofstra and Klomp (1972) also found that the deformation in the asphalt-concrete layer was greatest near the loaded surface and gradually decreased with depth. This decrease with depth is explained by the increase in confining pressure which result in more resistance to plastic flow, and can also explained by the fact that shear stresses are smaller at increased depth.

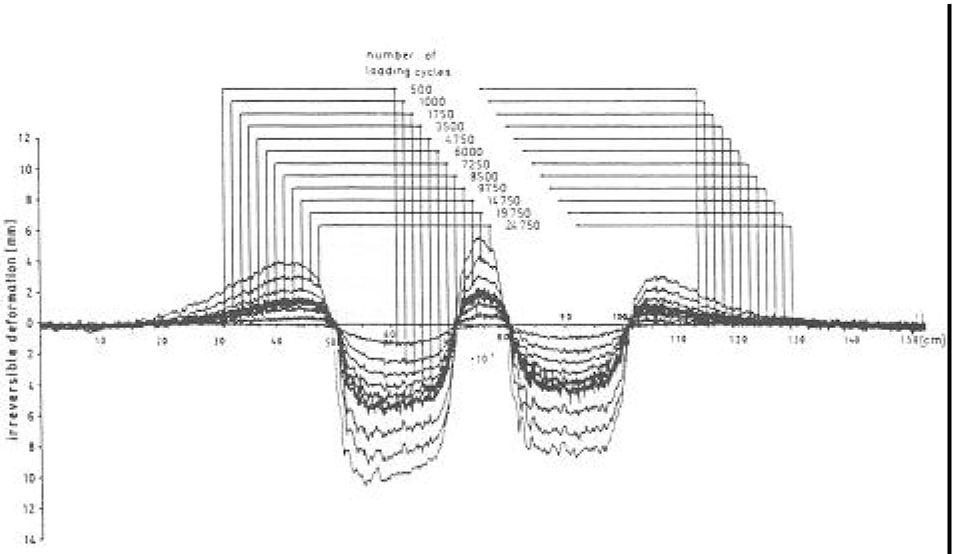
The resistance to rutting has also been related to layer thickness. Uge and Van de LOO (1974) reported that the deformation within an asphalt layer no longer increased with increasing layer thickness beyond a certain threshold (13cm, 5inches). Measurements at the AASHO Road Test indicated that the surface rut depth reached a limiting value for asphalt-concrete thickness of approximately 10 inches. Thicker layers did not exhibit additional rutting. These results suggest that the upper few inches of an asphalt pavement is the most critical for pavement rutting.

This early understanding of rutting behavior is confirmed in more recent studies. A study, by Eisnmann and Hilmer (1987) described how rutting is mainly caused by deformation flow with and without volume change in two main stages:

1- In the initial stage of trafficking the increase of irreversible deformation below the tires is greater than the increase in the upheaval zones indicating that some volume change is taking place

2- After the initial stage, volume decrement beneath the tires is approximately equal to the volume increment in the adjacent upheaval zone. This is an indication that the compaction under the traffic is completed for the most part and that further rutting is caused essentially by displacement with constancy of volume.

The second stage is considered to be representative of the deformation behavior for the greater part of the lifetime of a pavement. Many studies following, Eisnmann and Hilmer study confirmed their observations. Most recently Kaloush, and Witczak (2002) indicated that the rutting in this phase is considered shear rutting as it is due to lateral movement of mixtures under traffic loading



Effect of number of passes on transverse surface profile
(After Eisenmann and Hilmer, 1987)

Figure 1.12 Effect of Number of Passes on Transverse Surface Profile (After Eisenmann and Hilmer , 1987)

The review of the literature regarding the subject of permanent deformation indicates that the phenomenon is complex. Studies cite multiple causes for rutting including: (1) aggregate gradation, (2) aggregate absorption, (3) aggregate affinity for asphalt, (4) aggregate size, (5) coarse aggregate shape, (6) coarse aggregate texture, (7) fine aggregate shape (angularity), (8) mineral filler properties, (9) asphalt content, (10) performance grading, (11) plastic fines in the fine aggregate, (12) low air voids, and (13) performance graded asphalts (30,31,32). This list illustrates that there are many different factors that can cause or contribute to rutting. From this list, however, some factors appear to have a more significant impact than others, and will be addressed in greater detail through the nest three subsections.

1.6.1 Aggregates.

Surface texture of the aggregate plays an important role in rutting resistance, especially in thicker asphalt layers and hotter climate. Uge and Van de Loo (1974) reported that mixtures made from angular aggregates (obtained by crushing) deformed to a minor extent and were more stable than mixtures having the same composition and grading but made from rounded aggregate (river gravel). According to Uge and van de Loo, the most stable mixture was made of crushed aggregate and the least stable, of rounded aggregate. Interestingly, an intermediate composition, of which only the sand fraction was crushed, performed better than the formulation in which only coarse aggregate was crushed, although the former contained higher proportion of rounded components (70% versus 25%) this indicates that interparticle contact may be more significant factor than the extent of crushing.

Dense graded blends of aggregate are commonly considered more desirable to mitigate the effects of rutting. When properly compacted, mixtures with dense or continuous aggregate gradation have fewer voids and more contact points between particles than open or gap-graded mixtures. Brown and Pell (1974) concluded that gap graded mixture exhibit more deformation than a continuously graded mixture. They further argued that, because aggregate interlock becomes more important at higher temperatures, gap graded mixtures may be more susceptible to rutting at higher temperatures, a finding apparently confirmed by test-track results (32). This is considered the backbone of the theory behind using stone matrix asphalt (SMA) mixes. SMA is a gap-graded asphalt mix (minimizing medium-sized aggregate and fines) which combines strong, angular coarse aggregate with a high asphalt cement content — as much as 6 to 8% liquid asphalt. The result is a structurally strong mix incorporating a stone-on-stone skeleton. This stone-on-stone contact develops internal friction and resistance to shear, which easily resists rutting. (32)

With increased tire pressure, axle loads, and load repetitions, there has been a resurgence of interests in the use of “large-stone” mixtures. Davis (1988) has reported that some asphalt pavements constructed with soft asphalts, high volume concentration of aggregate, low air void content, and large maximum aggregate size (1.5 inch or larger) exhibit good rutting resistance. Based on such observations, he concluded that the use of larger maximum aggregate size (about two thirds of layer thickness) would be beneficial in reducing rutting propensity of mixtures subjected to high tire pressures.

A study by Button, Perdomo, and Lytton found nine possible causes of rutting, but stated that the aggregate characteristics were the primary material quality factor influencing rut susceptibility. Two other studies (31) more specifically addressed the type of fine aggregate used as the greatest influencing factor on stability. These studies indicated that properties of aggregates that were examined in the literature, two primary characteristics emerged: (1) gradation and (2) angularity that can reflect rutting significantly.

1.6.2 Binder.

A number of studies have indicated the importance of asphalt binders in contributing to rutting . Viscosity, asphalt content, and modification are some of the important factors

Mahboub and Little (1988) concluded that less viscous asphalts make the mixture less stiff and therefore, more susceptible to irrecoverable deformation, i.e. rutting. Several researchers tried to improve the rutting performance by using modifiers (polymers, microfillers, etc.) intended to increase the viscosity of the asphalt binder at high temperatures without adverse effect at low temperatures.

A study by Kamel, and. Miller (1994) indicates that asphalt content in excess of the optimum level may lead to problems like flushing, and insufficient air-voids space may yield a reduction in stability. On the other hand, asphalt contents below the optimum will jeopardize the long-term durability of the mixture and will produce a harsh mixture that complicates lay-down and construction operations. Another study, by Sebaaly et al (1997), indicates that asphalt content may be more important than gradation in determining performance. The authors of the Hot Mix Asphalt Materials, Mixture Design and Construction by NCAT states that probably the single largest contributor to rutting in HMA is excessive asphalt content (31).

Through SHRP program it has been recognized that one of the major factors affecting rutting potential is the performance-grading of asphalts. Establishing the importance of the performance-graded binders can be done by looking at two areas: performance grades (PG), and modified binders.

A study by University of Nevada-Reno compared HMA mixtures produced by using polymer-modified asphalt with unmodified asphalt. The polymer-modified asphalt resulted in significant reduction in the permanent deformation (rutting) of the HMA mixture tested in the study(31). Additional research by Kamel and Miller compared pavement performance of HMA containing conventional and engineered (modified) asphalts. The use of modifiers created higher grades of performance graded asphalts that provided rutting reductions of up to 50 percent and, an increase in pavement load-carrying capacity of more than 300 percent (34). The Wyoming transportation department concluded in a study that the susceptibility of HMA to rutting decreased as the high temperature grade increased for the performance graded binders as used in a field study on Interstate 80 (31).

1.6.3 Mixture Volumetric Properties and the Amount of Compaction Effort:

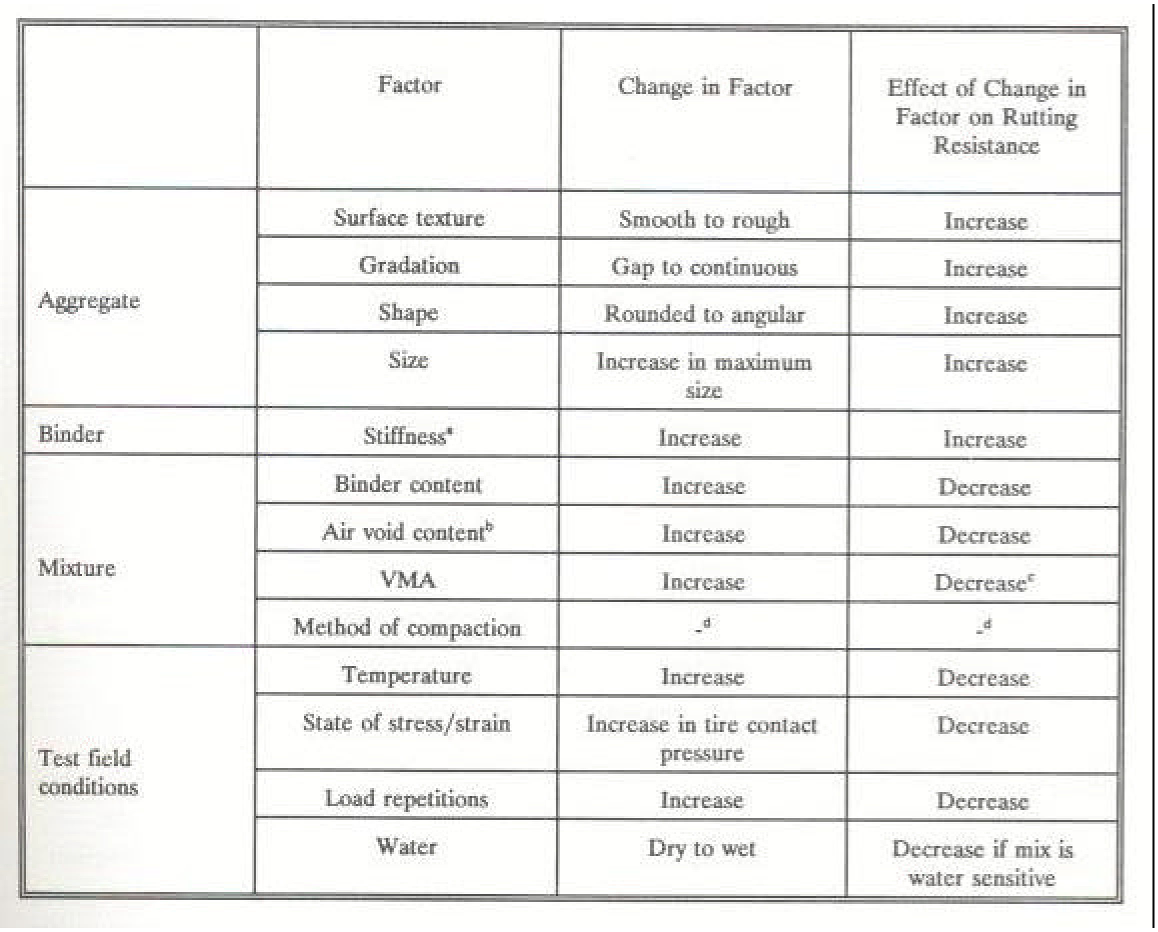
Volumetric properties of mixtures include voids in mineral aggregates (VMA) and total air voids. Cooper, Brown, and Pooley concluded that good resistance to permanent deformation requires low voids in the mineral aggregate (VMA) and that the desirable grading for minimum VMA can be determined using dry aggregate tests. However, they cautioned that the lowest theoretical VMA could be undesirable as it may not allow sufficient voids between the aggregate allowing enough binder to ensure satisfactory compaction without the mixture becoming overfilled(32). In the current mix design procedures a minimum value of VMA is required to ensure durability and sufficient particle coating.

Mahboub and Little suggested that the reduction in air voids as a result of increased asphalt content observed in their study indicates that void space is being filled with asphalt. As a result, the increase in asphalt content is equivalent to the introduction of lubricants between aggregate particles otherwise separated by a very tight network of air voids. This phenomenon causes the mixture with the higher asphalt content to be more susceptible to permanent deformation than a lower binder content.(32)

Linden and Van der Heide stressed the importance of proper compaction and concluded that degree of compaction is one of the main quality parameters of the placed mixture, especially for critical designs (those having low asphalt content intended to deliver a high resistance against permanent deformation). The well-designed, well-produced mixture performs better (better durability and mechanical properties) when it is well compacted. (32). Their study indicates that very high air voids due to low compaction could also result in rutting.

Changing the asphalt content of a HMA mixture can cause numorous problems. “An HMA pavement can ravel or crack if it is deficient in asphalt content by as little as 0.5 percent, whereas 0.5 percent excessive asphalt content can cause flushing and rutting”(31)..

Table 1 Factors affecting Rutting in Asphalt Pavement (32)



	Factor	Change in Factor	Effect of Change in Factor on Rutting Resistance[c]
Aggregate	Surface texture	Smooth to rough	Increase
	Gradation	Gap to continuous	Increase
	Shape	Rounded to angular	Increase
	Size	Increase in maximum size	Increase
Binder	Stiffness[a]	Increase	Increase
Mixture	Binder content	Increase	Decrease
	Air void content[b]	Increase	Decrease
	VMA	Increase	Decrease[c]
	Method of compaction	-[d]	-[d]
Test field conditions	Temperature	Increase	Decrease
	State of stress/strain	Increase in tire contact pressure	Decrease
	Load repetitions	Increase	Decrease
	Water	Dry to wet	Decrease if mix is water sensitive

1.6.4 Testing to evaluate resistance for rutting

One of the common methods to predict rutting is the use of Functional Equations based on laboratory test results. This requires extensive testing to determine the representative parameters. The development of predictive methods or models requires suitable techniques not only for calculating the response but to also realistically simulate it. The overall objective of material testing is to produce as closely as practical in situ pavement condition of the material. There are several tests developed to characterize the permanent deformation response of pavements. Some of the most widely used tests can be summarized in the following list (32,35).

- Uniaxial stress tests: unconfined cylindrical specimens in creep, repeated, or dynamic loading
- Triaxial stress tests: confined cylindrical specimens in creep, repeated, or dynamic loading.
- Diametral tests: briquet specimens in creep, repeated loading.
- Wheel track tests: slab specimens or actual pavement cross sections, tests using repeated passes of a loaded wheel

Although many studies indicate that the triaxial stress test offer the best simulation to field conditions, it is known that the most practical is the uniaxial test. This test was also chosen by the most recent study (NCHRP-465) for selecting a simple performance test for asphalt mixtures (35). Therefore, for the purpose of this study the specimens will be tested using the uniaxial testing procedure as described in the NCHRP 465 report (35).

1.6.4.1 Uniaxial test

Through a recent study conducted for the National Cooperative Highway Research Program (NCHRP), Arizona State University has formulated a laboratory test method for permanent deformation of asphalt mixes (31). Figure 1.13 shows a schematic of the test setup. A cylindrical sample approximately 100 mm in diameter and 150 mm in height, is subjected to a haversine axial load. Load is applied for a duration of 0.1 second, and then has a rest time of 0.9 second. A confining pressure could also be applied during the test. The cumulative axial and radial strains are measured using LVDT's and recorded during the test (35). This test should be conducted in a temperature controlled chamber to be able to test at voarious temperatures.

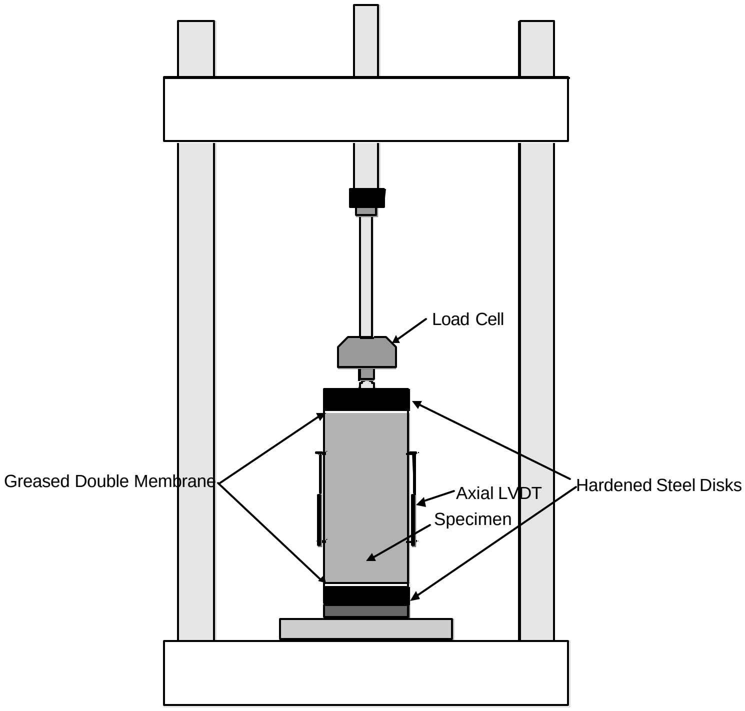


Figure 1.13 Schematic of the Permanent Deformation Test Setup (24)

Rutting is a creep failure, which means that it is time dependent. Therefore, the modulus is equivalent to the deviator stress over the total strain. For Visco-elastic materials, compliance was used rather than the modulus. Compliance is the reciprocal of the modulus. *D(t)= 1/E(t)* The main reason for using the compliance is that it allows for the separation of different strain components ($?_e$, $?_p$, $?_{ve}$, …) at constant stress levels. Therefore, the time dependent strain ?(t) can simply expressed by(35):

$$\begin{aligned} ?(t) &= s_d*(1/E(t)) = s_d*D(t) \\ &= s_d(D_e+D_p+D_{ve}+D_{vp}) \qquad \text{Equation [12]} \end{aligned}$$

Three zones generally define the cumulative permanent strain curve: primary, secondary, and tertiary. *Primary zone*: permanent deformation accumulates rapidly. *Secondary zone*: the rate decreases reaching a constant rate of deformation throughout the zone. *Tertiary zone*: the rate of deformation increases again and permanent deformation accumulates rapidly. The starting point (cycle number) at which

$$e_p = aN^b \qquad \text{Equation [13]}$$

The tertiary flow starts is referred to as the “flow number.” The results obtained from the test are typically presented in a log-log chart showing the cumulative permanent strain versus the number of cycles as shown in the following curve, and analyzed using the power law model(36):

Using the linear portion of the chart, the permanent deformation parameters *a* and *b* are derived. The parameter *a* represents the permanent strain at N = 1, and *b* represents the rate of change in the permanent strain as a function of change in loading cycles. Another chart, plotting the rate of change in permanent strain versus the loading cycles, Figure 18, is used to determine the “flow number”. This is identified as the point where minimum slope occurs, and indicates the cycle number at which tertiary flow begins.

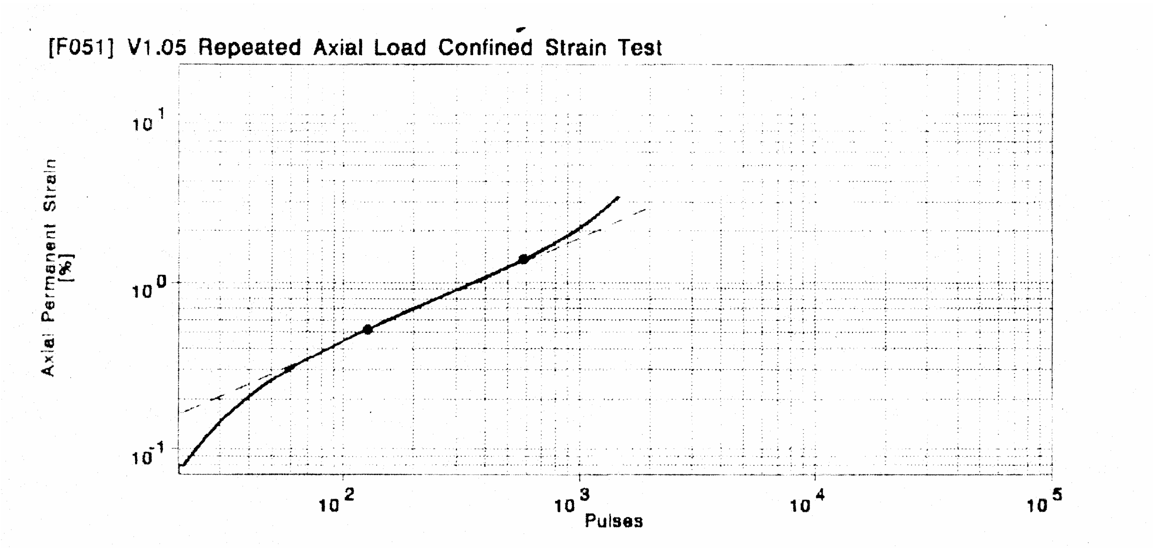


Figure 1.14 Cumulative Permanent Strain Versus Number of Loading Cycles

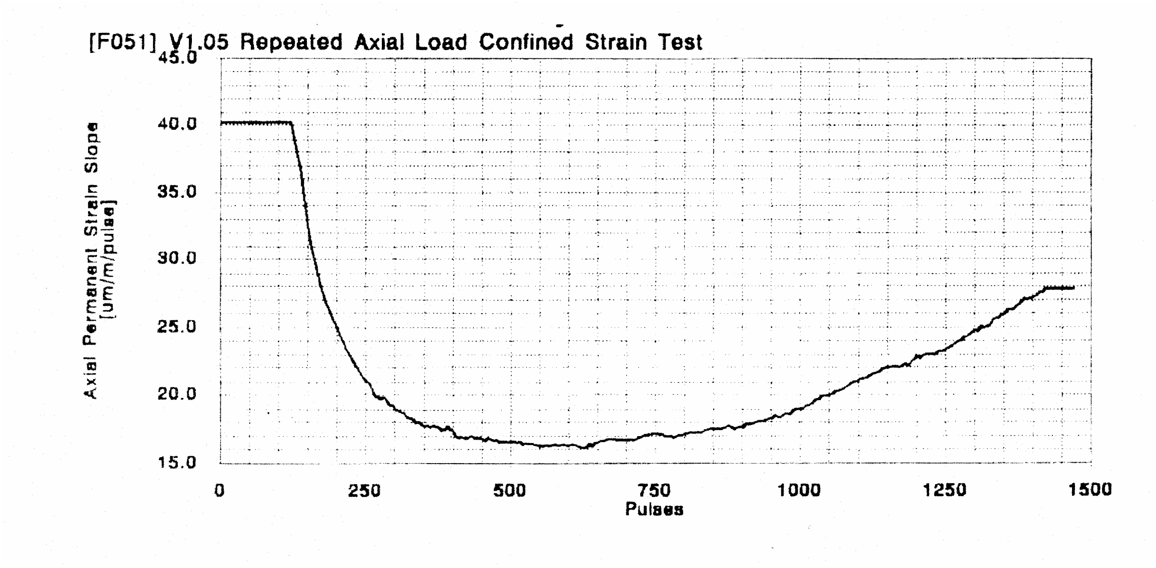


Figure 1.15 Axial Permanent Strain Rate Versus Number of Loading Cycles

The flow number and the rate of deformation are expected to reflect the mechanical stability of the mixture. However, the flow number represents a fundamental property of the mixture that can be used in correlating the mechanical stability of the mixture to various volumetric properties. Furthermore, traffic indices that are calculated from the SGC, which are a good representation of the volumetric-performance related properties, can be related to the flow number. Both then can provide a characterizing procedure for the asphalt mixtures.

In this study no confining pressure will be used. The temperature and load level was selected after significant testing and evaluation of the performance of mixtures produced with Wisconsin aggregates. The details of testing conditions are explained in chapter three.

1.7 Chapter One Summary:

The following points summarize the main findings from the literature review for the this Project:

- Current Superpave mix design procedure considers volumetric properties only, while it is known that it is the mixture's mechanical properties that directly relate to the performance of asphalt pavements. Although volumetric properties play a major role in defining mechanical properties, they are not sufficient to ensure or predict good performance.

- Since the mechanical properties of asphalt mixtures are at least as important as their volumetrics, it is necessary to measure these properties in designing pavements to evaluate their stability in construction and under traffic.
- The pressure distrebuter analyzer (PDA) is an accessory to the Superpave gyratory compactor (SGC), and developed by the University of Wisconsin Asphalt Research Group is a simple tool for measuring the mechanical stability of asphalt mixtures. Its use in this project could provide a simple option to measuring mechanical stability.
- Methods for interpreting testing data from the SGC with PDA have been proposed for evaluating the workability during construction and rutting resistance under traffic of asphalt mixtures. These methods should be evaluated in this study.
- Further testing using SGC with PDA with carefully selected and controled variables is necessary for the purpose of establishing a standard as a supplement to incorporate mechanical stability measurements into the current Superpave mix volumetric design procedure. In addition, the test method should be standardized.
- The laboratory rutting test developed at Arizona State University provides a direct measure of the rutting resistance of asphalt mixture and should be used in establishing the validity of the PDA in measuring resistance to rutting.
- Field and/or laboratory studies are necessary to validate the interpretation of mechanical stability measurements from SGC with PDA and the supplementary standard for full-scale implementation.

Chapter Two

Research Methodology

2.1 Hypothesis

Based on the literature review presented in the previous chapter, it has been concluded that the Superpave gyratory compactor could possibly be used to measure an indicator of the resistance of asphalt mixtures to rutting deformation. This finding also suggests that compaction properties measured by the SGC appear related to the stiffness and rutting resistance of asphalt mixtures measured in the laboratory and in the field (31). However, the concept is very broad and lacks details regarding what should be measured, what criterion should be used for acceptance of mixtures, and how the other characteristics of a mix interfere with the properties of compacting mixtures.

The main hypothesis of this research is that the stability of an asphalt mixture can be predicted from compaction parameters measured or estimated using the Superpave gyratory compactor.

2.2 Controlled Variables

There are a number of factors that are known to affect mixture resistance to rutting. Aggregate source and aggregate gradation are expected to influence the changes in the performance of the mix. Asphalt content and asphalt properties could have an significant effect on the performance of asphalt mixtures. Several studies suggest that a change of 0.50 percent of asphalt content will result in raveling or cracking if it is deficient in asphalt content, or can cause flushing and rutting if it has excessive asphalt content (Anderson et al,Epps and Hand, 2000, Sebaaly, Ridolfi Dan, Gangavarama nd Epps, 1997, and Kandhal, and Cross, 1993).

Since the objective of this research is to evaluate the relationship between the mixture stability and measurements of compaction by the SGC, it is necessary to include in the experimental design the factors that have been shown to affect rutting. These include asphalt content, aggregate gradation, and aggregate source. It is also necessary to study the possible interaction of these properties on the stability of mixtures. The following levels of these variables were included in the experimental testing program:

1. Aggregate Source: Four different sources of aggregates were chosen for testing from four major asphalt contractors in Wisconsin. For the purposes of this research, they are referred to as sources W, X, Y, and Z.

2. Blend Gradation: Two types of blends were tested for each source:

    a. S-shaped blend
    b. fine blend.

    The general gradation curves for each of these blends are shown in Figure 2.1. The specific gradation tables are shown in Chapter 3.

3. Asphalt Binder Content (AC): Three asphalt contents were included for each aggregate blend. These levels include optimum (producing 4% air voids at N_{des}), optimum + 0.5%, and optimum – 0.5%. All mixes were tested at their individual optimum asphalt content (instead of constant asphalt content for all mixes). This was done in order to simulate actual mixture properties used in the field.

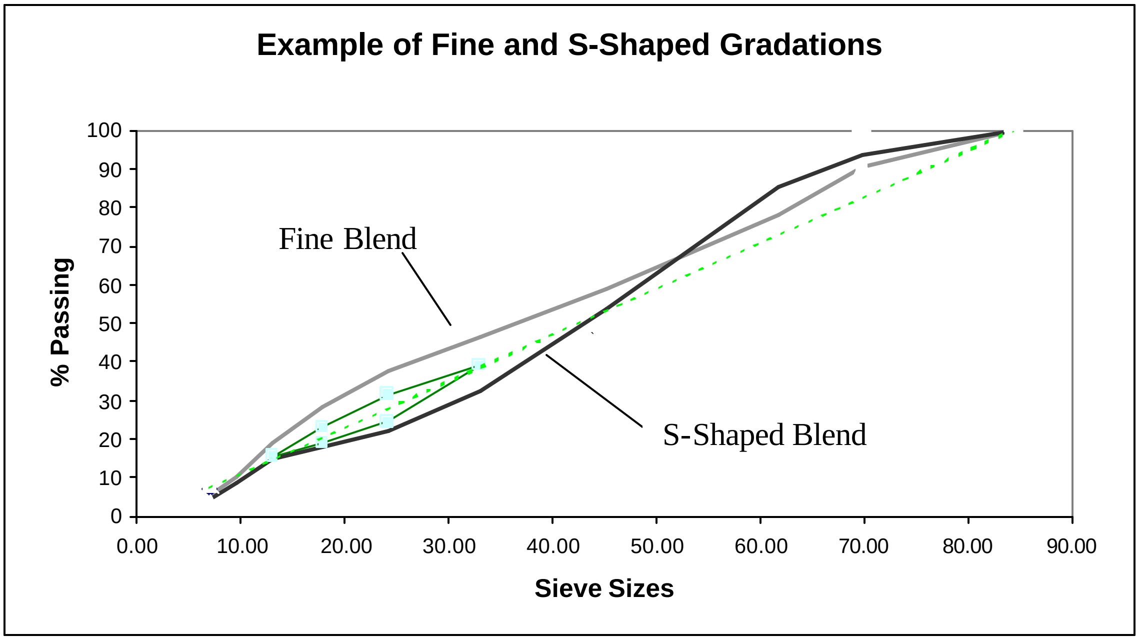


Figure 2.1 Examples of Fine and S-Shaped Aggregate Blends

Only a single performance grade asphalt (PG58-28) was used in the study. This grade of asphalt is the most common asphalt grade used in the state of Wisconsin.

2.3 Response Variables

Two main types of tests were used in this study to measure densification characteristics of mixtures and the resistance to permanent deformation. The Superpave gyratory compactor was used for measuring densification of the mixtures as well as shear resistance during the densification process. The densification is measured at relatively high temperatures resembling compaction temperatures, generally in the range of 125 – 140 C. The resistance of mixtures to permanent deformation (rutting) was evaluated using the newly developed simple performance test which consists of a uniaxial compression test system under repeated creep. The results of this test is used to estimate the rutting rate and the flow number under a uni-axial compression repeated creep test. The details of these measurements are explained in the sections below.

2.3.1 Densification Characteristics

In earlier work, the Asphalt Research Group at the University of Wisconsin-Madison introduced new concepts regarding interpretation of data obtained from the Superpave Gyratory Compactor (SGC). The primary contribution of the previous studies was the introduction of the concept of dividing the compaction curve into two sections, one representing construction compaction and the other representing traffic densification (10).

It is generally accepted that when pavement is being constructed in the field, a paver screed would apply a certain preliminary compaction effort to the pavement before rollers are used to apply further compaction. This initial compaction effort is simulated by the compaction effort applied by the SGC during the first 8 gyrations (prior to reaching $N_{initial}$). Contractors are required to reduce the air voids further using rollers until the pavement has reached approximately 92% G_{mm} (8% air voids). At this point, the road is opened to traffic. Traffic increases densification of the pavement over its service life until the pavement reaches 98% G_{mm} (2% air voids), which is considered the terminal density. At this point, the pavement could be prone to rapid accumulation of rutting.

The new concept proposes that the compaction curve produced by the SGC be divided at 92% G_{mm}. The compactions that occur in the SGC between N_{ini} and 92% G_{mm} and again between 92% G_{mm} and 98% G_{mm} are considered to be representations of the construction compaction and traffic densification, respectively. The research group introduced two energy indices, the construction energy index (CEI) and the traffic densification index (TEI). The CEI correlates with the construction side of the curve (N_{init} to 92% G_{mm}), and the TEI correlates with the traffic side of the curve (92 to 98% G_{mm}). The indices are found by integrating the area under the curve between any two points (i.e. 92%G_{mm} through 98% G_{mm}). The area is thought to represent the energy required for the gyratory to reduce the air voids of the mixture between those two points. Figure 2.2 illustrates the two areas under consideration.

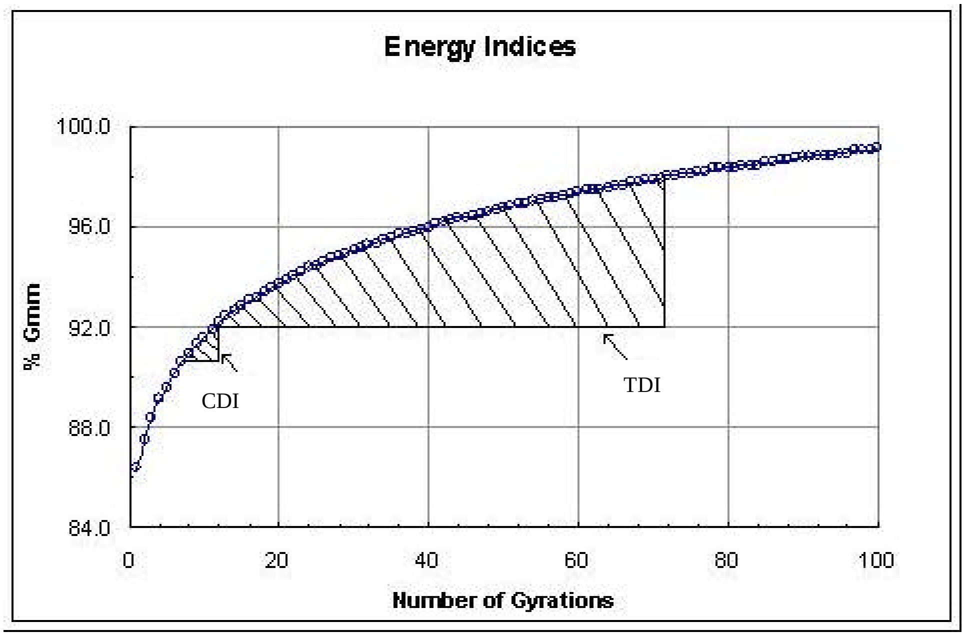


Figure 2.2 Energy Indices as proposed by Bahia et al., 1998 (10).

Mixes with higher CDI values are expected to require a great deal of energy to densify during construction. Lower CDI values are therefore desirable because fewer roller passes will be required. Once traffic is on the pavement, it is desirable for the pavement to require a lot of energy (high traffic volume) to densify. High TDI values are therefore desirable. The ideal pavement would be easy to densify further during construction (low CDI) and hard to compact under traffic (high TDI).

Although the densification of the mixture is an important measure of performance, the resistance to distortion is also considered important and possibly more relevant to rutting under traffic. Since the CEI and TEI are derived from densification (volume change) only, they could be considered incomplete in representing the resistance of mixtures to distortion under traffic. Another method of measurement is required that could directly quantify the shear resistance of mixtures. The pressure distributor analyzer (PDA), which was developed by the same asphalt group in an effort to measure and evaluate the resistance of the mixture to distortion, was used as that method of measurements. (20). The GLPA is placed in the gyratory compactor mold and provides a load measure that is recorded simultaneously with deflection. The vertical load and the eccentricity of that load are measured using 3 load cells placed at the edge of the plate. The measurements are used to calculate the resistive effort (w) as a function of the number of gyrations.

2.3.2 Resistive Effort (w)

In this research project**,** the GLPA is used to determine the resistive effort of the mixes. This method for analyzing resistive effort data using a technique similar to the energy indices proposed by Bahia et al. for use on the compaction data was first introduced and used by Delage (2000). As shown in Figure 1.9, the resistive effort curve is divided at 92% G_{mm} into a construction side and a traffic side. Under 92% G_{mm}, it is desirable for the mix to have a low resistive effort as it will enable ease of compaction by the contractor. Above 92% G_{mm}, it is desirable for the resistive effort of the mix to be high. The high level of resistive effort is an indicator of high resistance of mixture to distortion under traffic, which will reduce rutting.

To quantify the resistive efforts above and below 92% G_{mm}, the area under the resistive effort curve between N_{init} and 92% G_{mm} is calculated and termed the compaction force index (CFI), and the area between 92% and 98% G_{mm} is calculated and termed the traffic force index (TFI). It is also suggested that the construction energy index (CDI) relating to the compaction curve be renamed the construction densification index (TDI). In this way, the CDI and TDI will relate to the densification curve, and the CFI and TFI will relate to the resistive effort curve. Figure 2.3 illustrates the four energy indices used as response variables in this research.

2.3.3 Volumetric Data

Superpave volumetric mix design sets a specific target air void levels for HMA at different compaction levels. At N_{init}, the % G_{mm} is supposed to be equal to or lower than 89%. This is meant to insure that the HMA structure is not failing rapidly under load at the beginning of compaction efforts. At N_{des}, the % G_{mm} is expected to be at 96%. All superpave mixes are designed primarily to meet this 4% air voids criteria. At N_{max}, the % G_{mm} is supposed to be less than 98%. For the purpose of this research, the %G_{mm} at N_{init}, %G_{mm} at N_{des}, and %G_{mm} at N_{max} are considered as response variables and used in the analysis.

Superpave mix design parameter also set minimum limits on the voids in the mineral aggregate (VMA) allowed for mixes (as evaluated by compacting to $N_{des)}$. VMA limits are based on the nominal maximum aggregate size used in the mix. VMA is another response variable studied in this research.

2.3.4 Resistance to Permanent Deformation

The permanent deformation resistance of mixtures was measured using the proposed simple performance test, as suggested by NSCHRP 9-19, which includes a uni-axial compression repeated creep test. Two main parameters were obtained from this test. The first is the flow number (Fn), defined as the point (number of cycles) at which the mixture starts to flow rapidly by going into tertiary flow. It presents a fundamental property of the mixture that reflects the true stability of the mixture. The second parameter is the permanent deformation rate. This property shows the behavior of the mixture during what is called the secondary creep zone. As shown in Figure 2.3, in this zone the rate of permanent strain accumulation is relatively constant, which allows characterizing the asphalt mixture with a single parameter related to the rate of rutting.

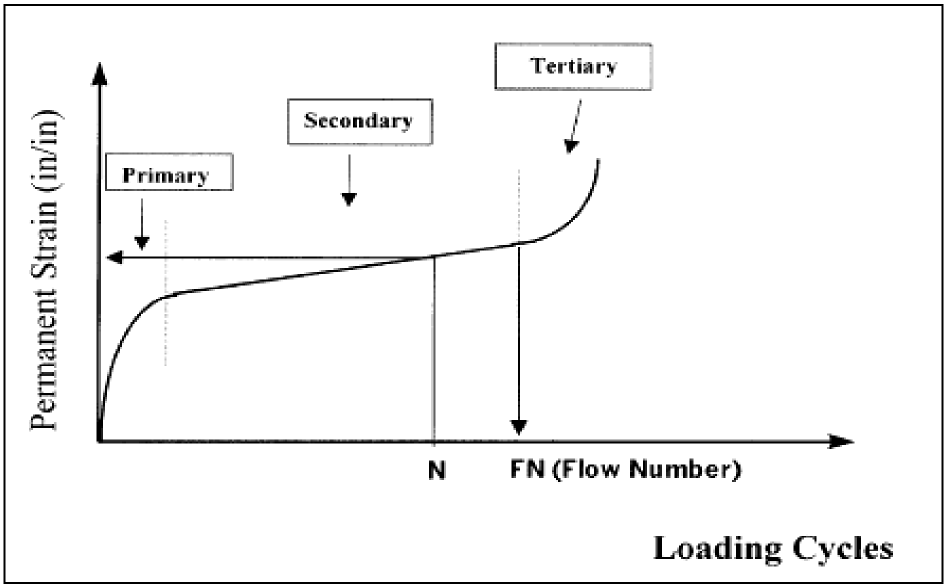


Figure 2.3 : Stages of creep deformation after the NCHRP-465 report , 2002.

Chapter Three

Experimental Design and Testing Methods

In this chapter the details of materials used and sample preparation of the asphalt mixtures are presented. Also the specific conditions used in testing are explained.

3.1 Preparation of Aggregate Blends:

Four aggregate sources (A, B, C, D) were selected for this research. The sources are known to be commonly used for pavement construction in the state of Wisconsin. For three of these sources (B, C, and D) contractors provided two mix designs per source. The fourth contractor provided five mix designs using different Job Mix Formula (JMF) gradations and sources. The main reason for using mixes provided by the contractors is to make sure that the outcome of the research is more relevant to actual practice in the field. The mix design JMF was followed in preparation of the samples.

Due to limitation of aggregates available, a partial factorial design was used as shown in Table 3.1. For contractor A's mixtures, two replicate specimens were prepared, and compacted using three different asphalt contents; optimum, optimum plus 0.5% and optimum minus 0.5%. For the other three contractors (B, C, and D) two replicate specimens were prepared and compacted using the optimum asphalt content only.

Table 3.1 Asphalt content for different mixes

Contractor	Design No.	Type	PG	NM Size (mm)	Gradation Type	Optimum AC	AC Tested		
							Opt-05%	Opt	Opt+0.5 %
A	01	E-30	58-28	19.0	F	4.3	X	X	X
	02	E-10	58-28	19.0	F	4.6	X	X	X
	03	E-10	58-28	19.0	F	4.5	X	X	X
	04	E-3	58-28	19.0	S	5.1	X	X	X
	05	E-3	58-28	12.5	S	4.6	X	X	X
B	01	E-1	58-28	12.5	S	6.2		X	
	02	E-10	64-28	12.5	F	5.8		X	
C	01	E-3	58-28	12.5	F	5.5		X	
	02	E-3	58-28	19.0	F	5.0		X	
D	01	E-3	58-28	12.5	F	5.3		X	
	02	E-3	58-28	19.0	F	5.3		X	

The aggregate JMF gradations for all mixes provided by the contractors are as shown in Figures 3.1 through 3.4, for sources A, B, C, and D, respectively.

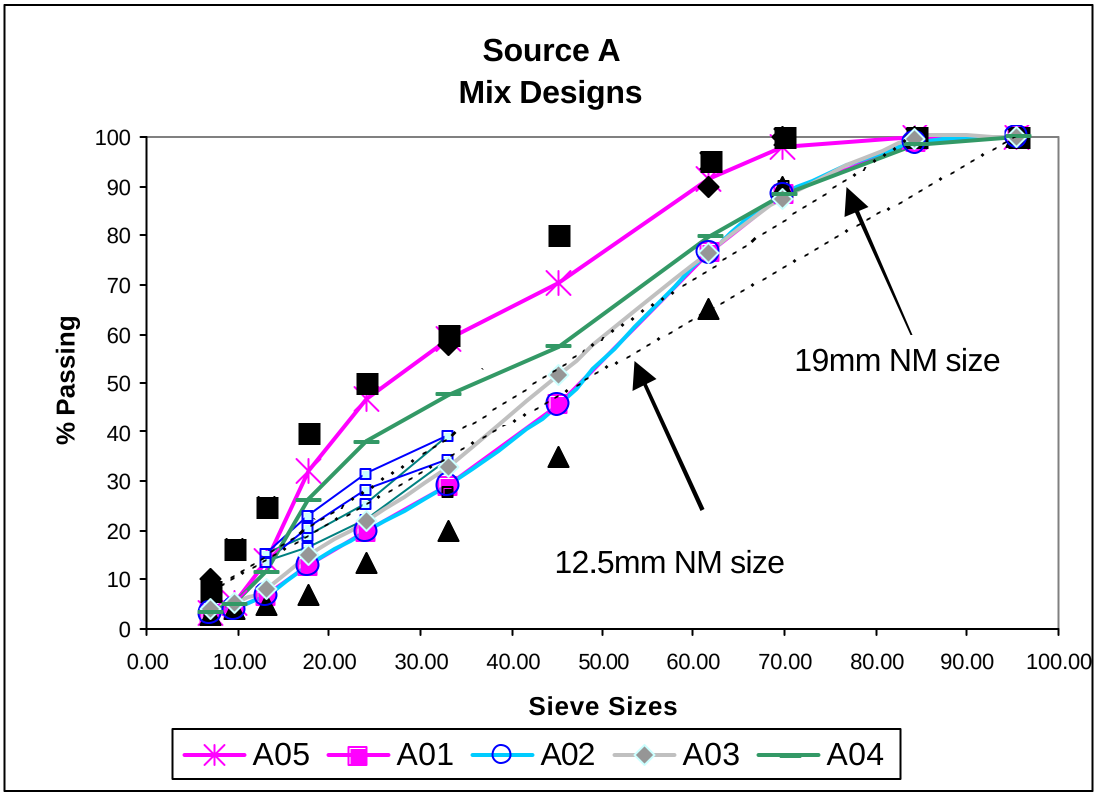


Figure 3.1 Mix designs for source A

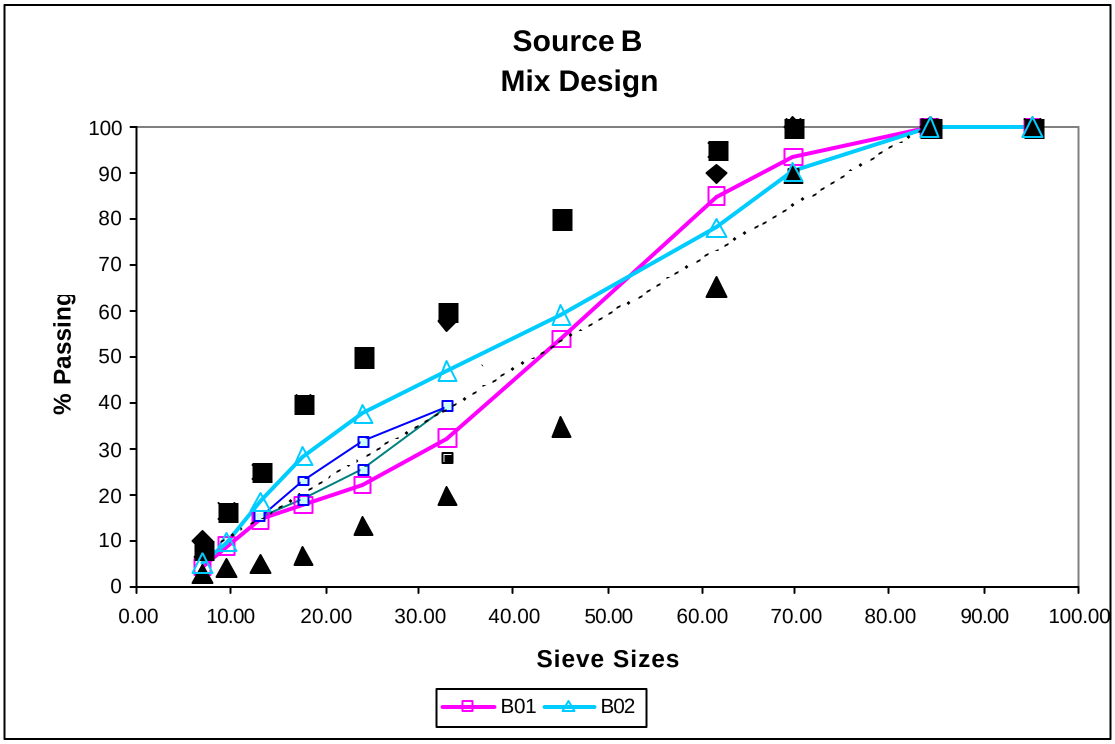


Figure 3.2: Mix designs for mix B

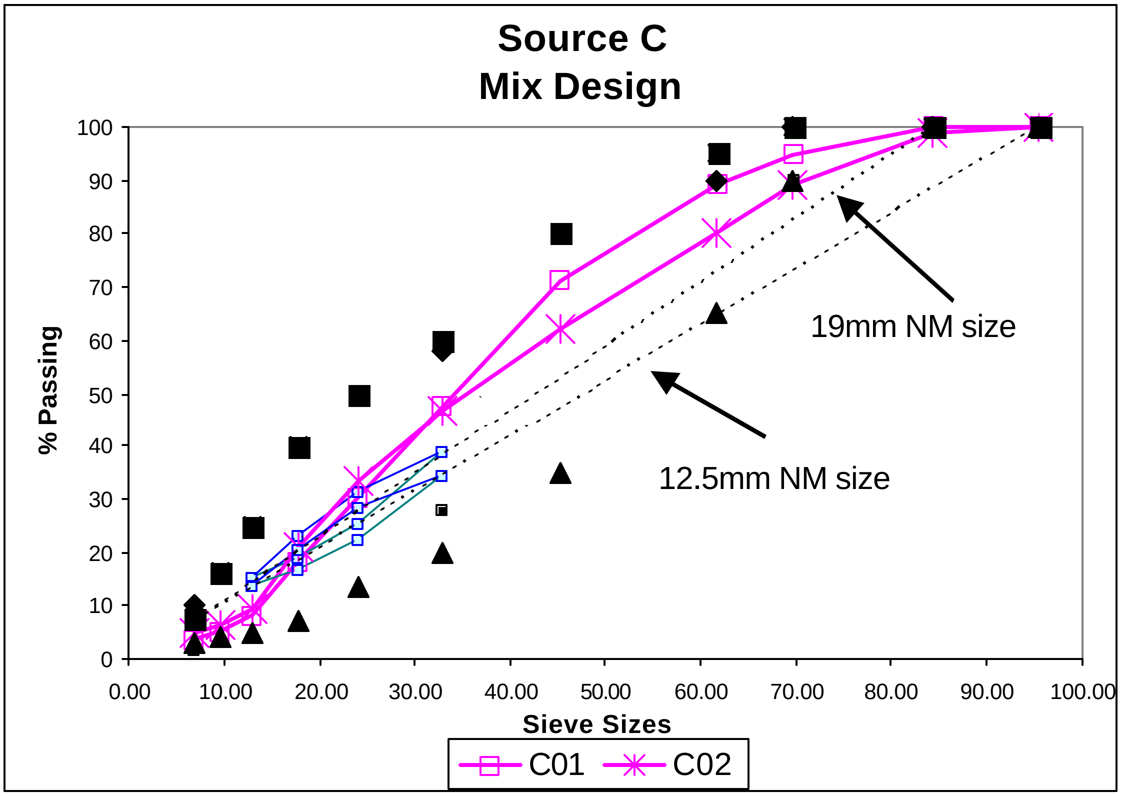


Figure 3.3: Mix designs for mix C

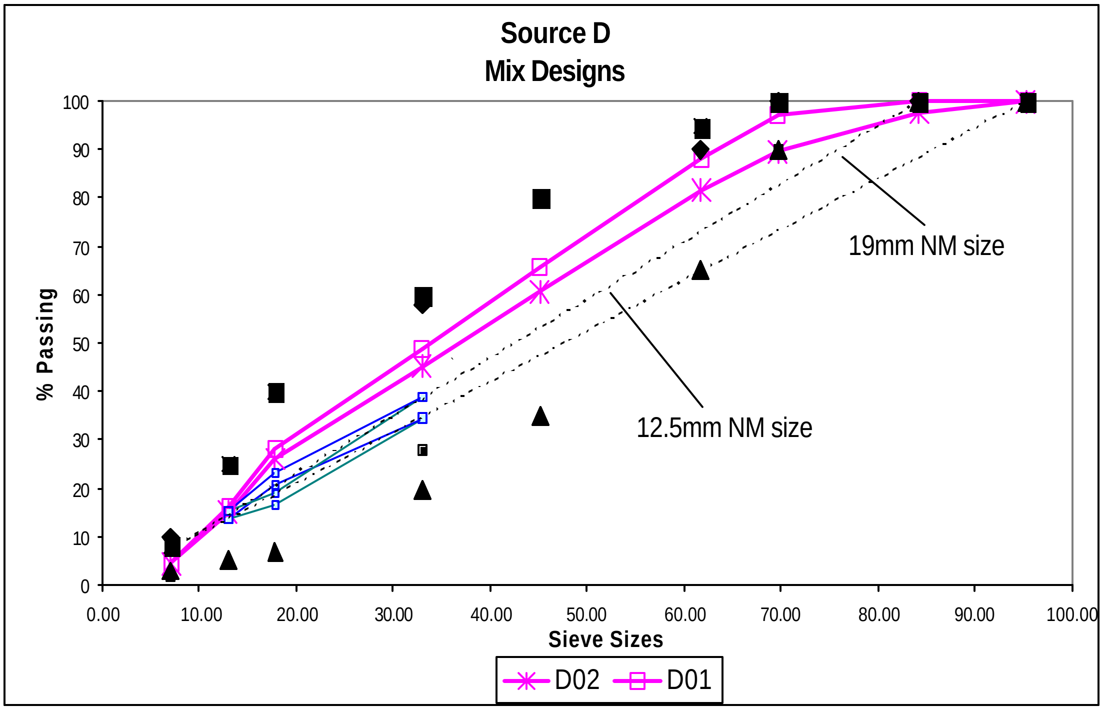


Figure 3.4: Mix designs for mix D

The types of aggregate used in each mix design are shown in the following table. This table also shows the associated component blend percentages used for each mix.

Table 3.2 Aggregate Blends for mixes

Source	Type	Mix Design #	PG Binder	S or F	Opt. AC	Blend Design	Quantity (%)
SourceA	19.0 mm Superpave E30 (Gravel)	01	64-22	F	4.3	7/8" Chip	10
						5/8" Stone	15
						3/8" Chip	30
						1/4" Minus Man. Sand	25
						Washed Nat. Sand	20
	19.0 mm Superpave E10 (Gravel)	02	58-28	F	4.6	7/8" Chip	10
						5/8" Stone	15
						3/8" Chip	30
						1/4" Minus Man. Sand	25
						Washed Nat. Sand	20
	19.0 mm E10 Superpave (Gravel)	03	58-28	F	4.5	Cr. RAP	15
						7/8" x 5/8" H.F. Stone	10
						5/8" x 1/2" H.F. Stone	15
						3/8" x 1/4" H.F. Stone	20
						1/4" Minus Man. Sand	30
						Screened Nat. Sand	10
	19.0 mm Superpave E3 (Gravel)	04	58-28	S	5.1	7/8" Chip	10
						5/8" Chip	15
						3/8" Chip	15
						Washed Nat. Sand	20
						Screened Nat. Sand	40
	12.5 mm E3 Superpave (Gravel)	05	58-28	S	4.6	5/8" Chip	15
						3/8" Chip	15
						Washed Nat. Sand	5
						Screened Nat. Sand	65
SourceB	12.5 mm E10 Superpave	01	64-28	S	6.2	3/8" Chip	30
						1/8" Man Sand	25
						3/4" Conc. Stone	20
						1/2" Bit Stone	25
	12.5 mm E1 Superpave	02	58-28	F	5.8	3/4" Limestone	40
						3/8 Washed Chips	11
						Man. Sand	22
						Nat. Sand	27
Source C	12.5 mm E3 Superpave	01	58-28	F	5.5	3/4" Stone	13
						3/8" Stone	15
						Man. Sand	42
						Nat. Sand	25
						Dust	5
	19.0 mm E3 Superpave	02	58-28	F	5	3/4" Stone	10
						1/2" Stone	9
						3/8" Stone	10
						Dust	10
						Nat. Sand	61
SourceD	12.5 mm E3 Superpave (Gravel)	01	58-28	F	5.3	5/8" Rock	8
						5/8" Single Agg.	14
						5/16" Nat. Sand	13
						1/4" Man. Sand	45
						5/8" Recycle	20
	19.0 mm E3 Superpave (Gravel)	02	58-28	F	5.3	1" Rock	11
						5/8" Rock	4
						5/8" Single Agg.	10
						5/16" Nat. Sand	12
						1/4" Man. Sand	43
						5/8" Recycle	20

From the previous table it is clear that a mix of natural and manufactured aggregates is used in preparation of the samples. For contractor A (mix number 3) and contractor D, the mixes contained recycled asphaltic pavement (RAP) aggregates. The mixes listed were actually used or proposed for use in actual pavements in Wisconsin.

3.2 Mixture Volumetric Properties

Calculating the volumetric properties requires accurate determination of the maximum specific gravity (G_{mm}) values. For this reason, two G_{mm} (rice) samples were tested at each asphalt content used (according to AASHTO T209. The calculations of the bulk specific gravity (G_{mb}) values were based on testing specimens compacted to N_{des} gyrations (according to AASHTO T166). This was done to increase accuracy because there is no extrapolation or correction necessary to determine the G_{mb} at N_{des}, versus back calculating using data from the specimen compacted to 600 gyrations(This selected compactive effort is discussed in details in section 3.3).

The volumetric properties of the asphalt mixes were investigated for compliance with superpave mixture design requirements. These requirements include an air void content parameter check at different compaction levels. These levels start with the initial compaction level (6 to 9 gyrations) and referred to as N_{ini}. The second compaction level is called the design compaction level, N_{des}, and it varies between 40-125 gyrations. The third level is called the maximum compaction level, N_{max}, and it varies between 60 and 205 gyrations. These three compaction levels are selected to simulate the efforts of the compaction process in the field, the intermediate pavement service conditions, and the ultimate pavement service conditions, respectively. The number of gyrations selected for the mixture design varies depending on the traffic ESALs level expected to be applied on the pavement a 20 years design life. The higher the traffic level, the higher the number of gyrations.

In addition to the Gmm and Gmb values, another volumetric property was calculated and evaluated for the mixes in this study. It is the voids in mineral aggregates (VMA). VMA is the sum of volume of air voids and effective binder in compacted specimen. It represents the space between the uncoated aggregates. Minimum VMA requirements are based on the nominal maximum size of aggregate used. The results collected for the mixtures tested in this study are summarized in section 4.1.

3.3 Mixture Densification Resistance Testing

As discussed in chapter 2, response variables measured with the use of the gyratory compactor included densification indices and resistive force indices.

The Energy indices calculated from densification curves included CDI (area under the densification curve 92%Gmm to 98%Gmm), and TDI (area under the densification curve 92%Gmm to 98%Gmm). The Resistive force indices were calculated from the eccentricity plots generated using the GLPA. These include CFI (area under the resistive effort curve from the cycle number corresponding to 89%Gmm to cycle number corresponding to 92%Gmm), and TFI (area under the resistive effort curve from the cycle number corresponding to 92%Gmm to cycle number corresponding to 98%Gmm).

The CDI and CFI were calculated from specimens compacted to N_{des} (100 gyrations). Since the TDI and TFI require that the mixture reaches 98 % Gmm, they could not be determined from compactions made to $N_{des.}$ It was necessary to compact to a number of gyrations that would result in % Gmm above 98 % to guarantee that TDI and TFI could be determined. This meant that the samples should be compacted to no less than 300 gyrations and to no less that 98% G_{mm}. For this reason, the decision was made to compact specimens to 600 gyrations. The results are shown and discussed in section 4.2 of Chapter 4.

3.4 Samples Preparation and Testing of Mixture for Resistance of Permanent Deformation (Rutting)

In a recent study sponsored by the National Cooperative Highway Research Program (NCHRP 9-19 project), Arizona State University has formulated a laboratory test method for permanent deformation. The air void percentage recommended by the NCHRP 9-19 when the testing for permanent deformation is 7 %. The recommended dimensions for the rutting samples are 6 inches (150 mm) high by 4 inches (100mm) in diameter. Using the information gathered from volumetric testing of the mixtures, the number of gyrations needed to achieve 7% air voids for each mixture was determined.

The laboratory specimens are produced using the SGC. Since the standard size of a sample produced by the gyratory compactor is 6 inches in diameter, coring of the samples to achieve the needed sample diameter was required. The sample is then trimmed from the top and the bottom to achieve the desired height. After obtaining the required standard sample, the percentage of air voids is measured to make sure that it meets the 7% requirement. A final preparation step is needed before starting the testing for permanent deformation. This is to attach four plastic pads, two at opposite side of the sample. These pads are needed to mount the vertical LVDT's on the sample.

Figure 1.13 shows a schematic of the test setup. The cylindrical sample is subjected to a haversine axial repeated load. This load is applied for a duration of 0.1 second, and then has a rest time of 0.9 second. The cumulative axial and radial strains are measured using LVDT's and recorded during the test. The results obtained from the test are typically presented in a log-log chart showing the cumulative permanent strain versus the number of cycles as shown in the example in Figure 1.14, and analyzed using the following power law model:

$$e_p = aN^b \qquad [3.1]$$

Using the linear portion of the plotted results, the permanent deformation parameters *a* and *b* are derived. The parameter *a* represents the permanent strain at N = 1, and *b* represents the rate of change in the permanent strain as a function of change in loading cycles. Another chart, plotting the rate of change in permanent strain versus the loading cycles, Figure 1.15, is used to determine the "flow number". This is identified as the point where minimum slope occurs, and indicates the cycle number at which tertiary flow begins.

For the purpose of this study the flow number and the rate of permanent deformation (b) were calculated to be used in addressing the pavements performances as a function of rutting resistance.

Chapter Four

Results Analysis and Discussion

In this chapter the results of volumetric properties for the mixtures are compared and discussed. This is followed by the analysis of the densification and resistive force indices. The third section covers the results of mixture resistance to permanent deformation. The fourth section includes the testing of the hypothesis that the densification indices are related to the permanent deformation resistance measures. The last section includes the proposal of mixture acceptance criteria to ensure acceptable resistance to permanent deformation under traffic loading.

4.1 Results of Volumetric Properties

The following charts show a summary of volumetric properties measured for the mixtures under investigation. The summary includes % Gmm at Nini (Figure 4.1), % Gmm at Ndes (Figure 4.2), and % Gmm at Nmax (Figure 4.3). It also includes the VMA at Ndes (Figure 4.4).

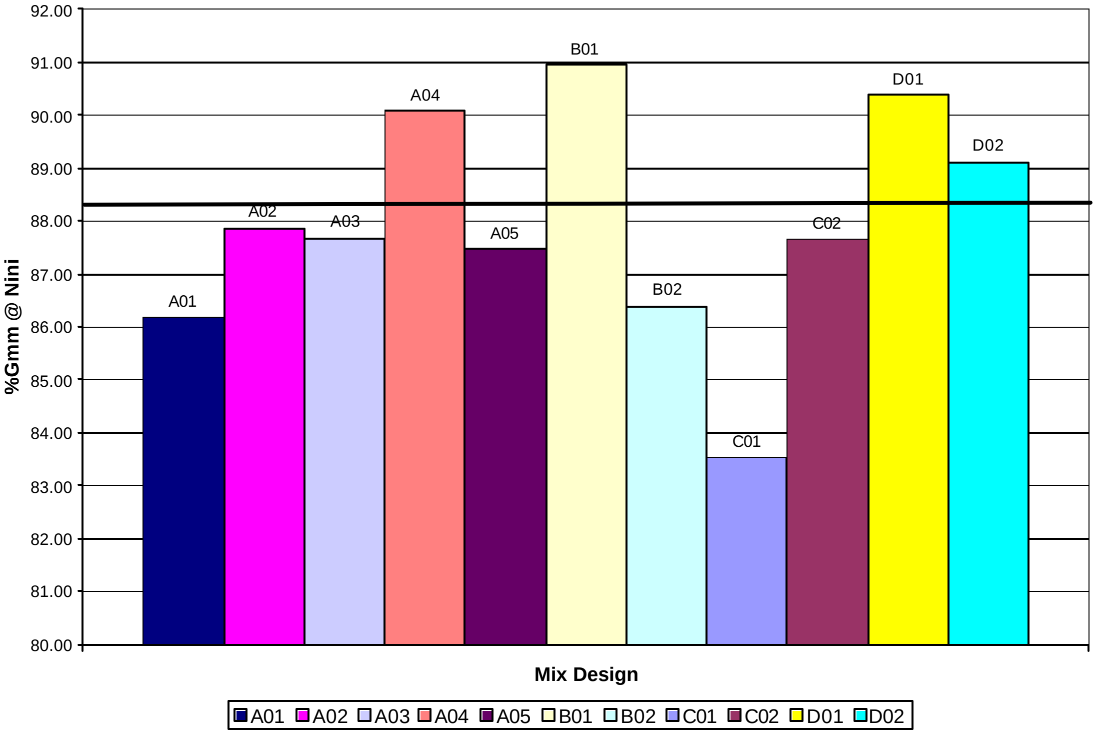


Figure 4.1 Average %Gmm at N_{ini} for all mixes

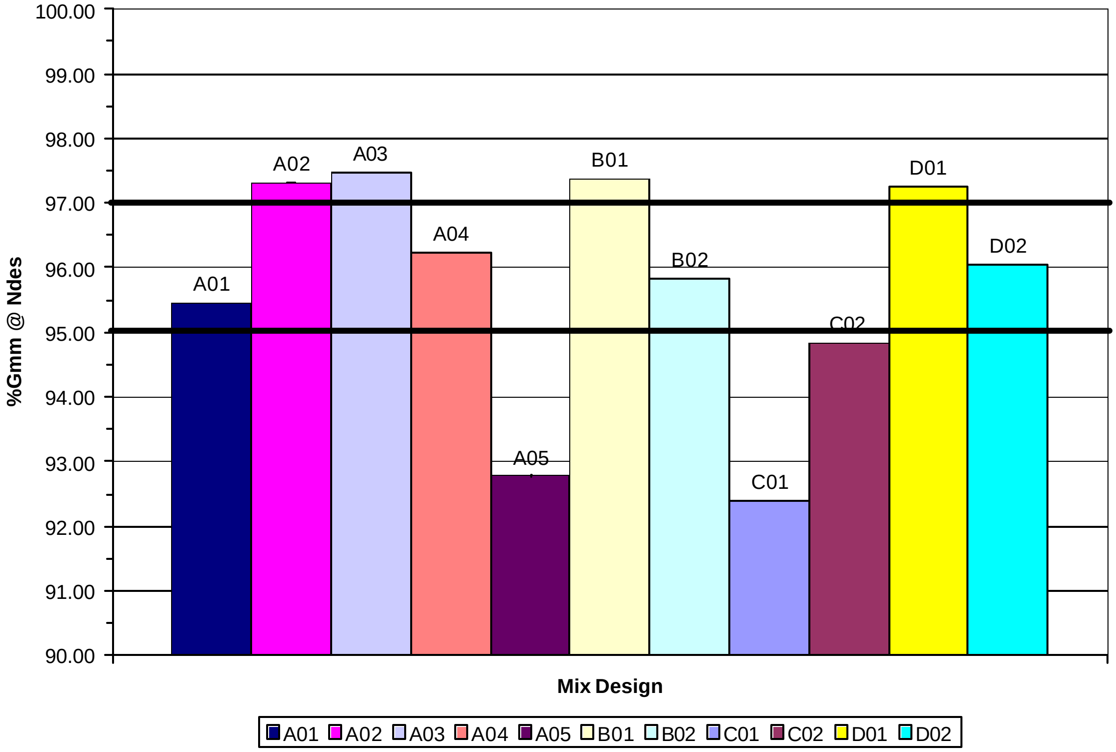


Figure 4.2 Average %Gmm at N_{des} for all mixes

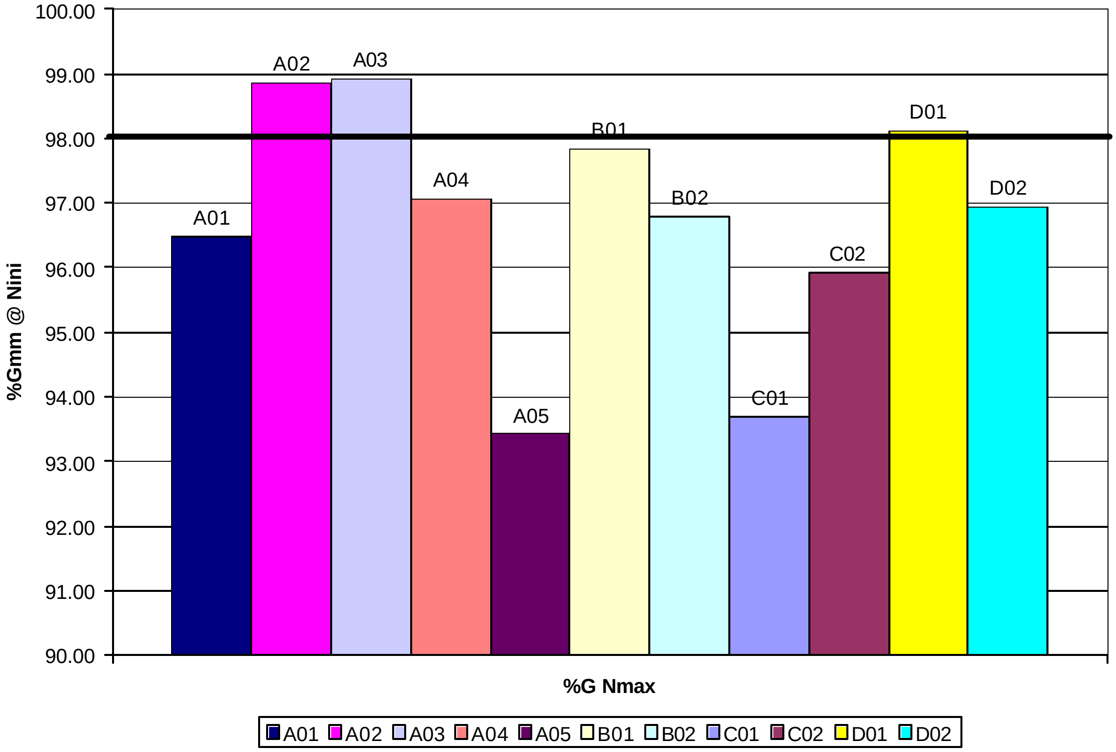


Figure 4.3 Average %Gmb at N_{max} for all mixes

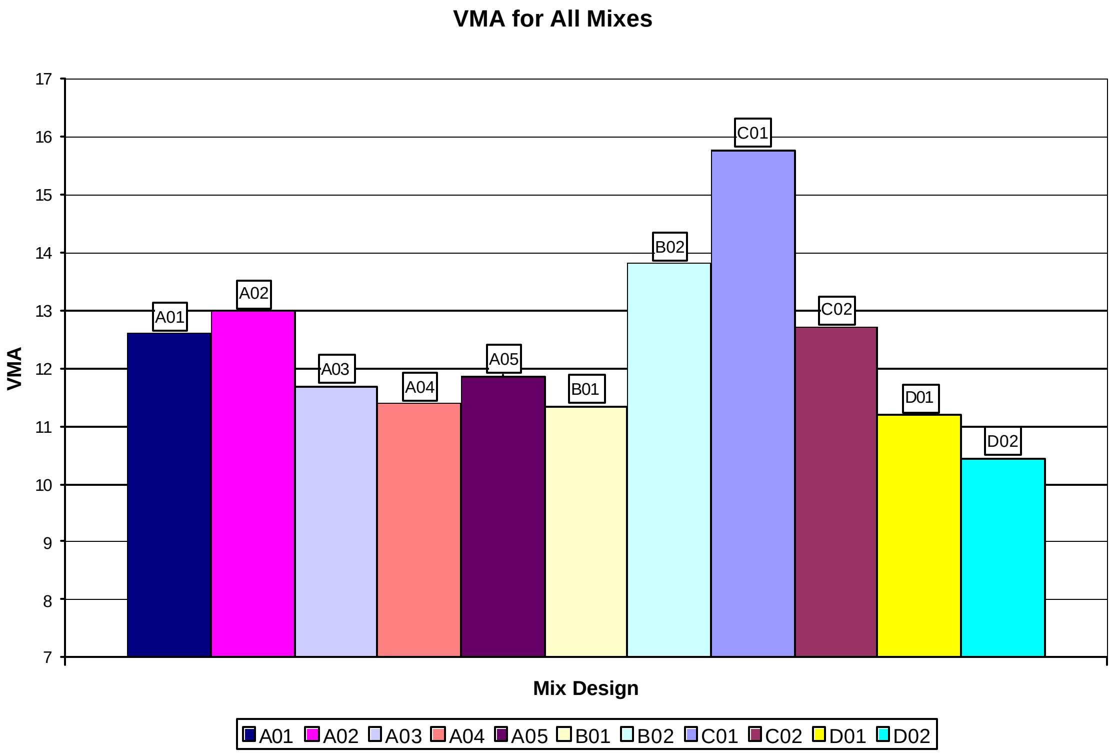


Figure 4.4 Average VMA for all mixes

From the data in shown in Figures 4.1 through 4.3, it is clear that some of the mixtures do not meet the volumetric requirements as stated by the Superpave specifications used by the Wisconsin DOT. It is however important to remember that, for the purpose of this research, it was not necessary that all mixtures meet the requirements. The purpose was the evaluation of mixture performance, as measured by the resistance to permanent deformation, rather than the volumetric properties. The performance is compared to the densification characteristics, as measured by the GLPA in the SGC, to test the hypothesis that densification measures derived from the SGC testing could be used as a surrogate to measuring the permanent deformation (rutting) resistance for a wide range of volumetric properties, aggregate types, and asphalt contents. The next section covers the comparison.

4.2 Results of the Densification and Resistive Force Indices

As indicated in chapter 3, four measures were used to estimate the mixtures resistance to densification. They include two measures of densification derived from the volumetric properties; the Construction Densification Index, CDI, the Traffic Densification Index, TDI. The other two measures; derived from measuring the shearing resistance of mixtures during gyrating using the GLPA device, include the Compaction Force Index, CFI, and the Traffic Force Index, TFI. The following charts (Figure 4.6 through Figure 4.7) show the average values of these four measures for the mixtures tested.

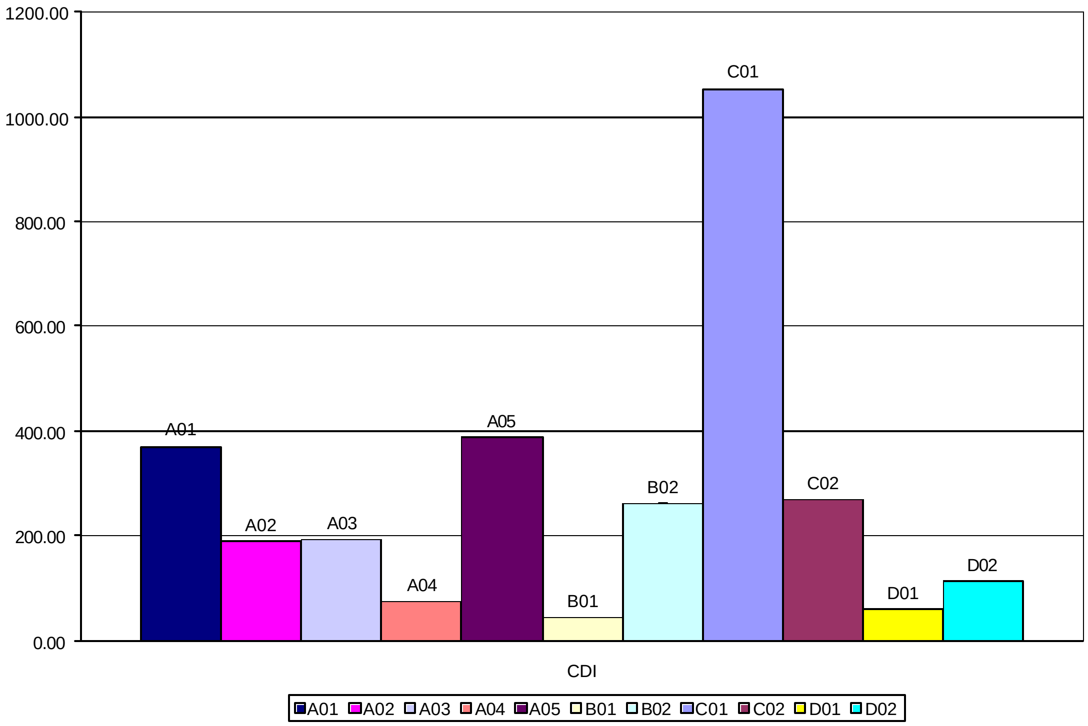


Figure 4.6: Average CDI values for all mixes

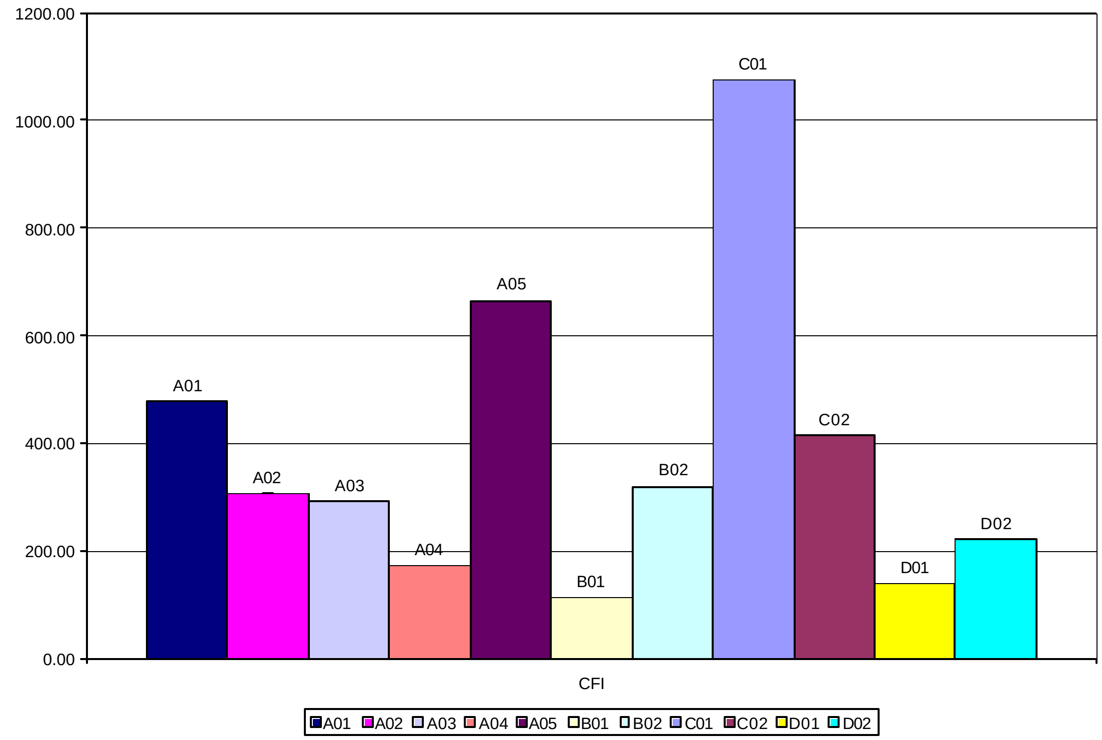


Figure 4.7: Average CFI values for all mixes

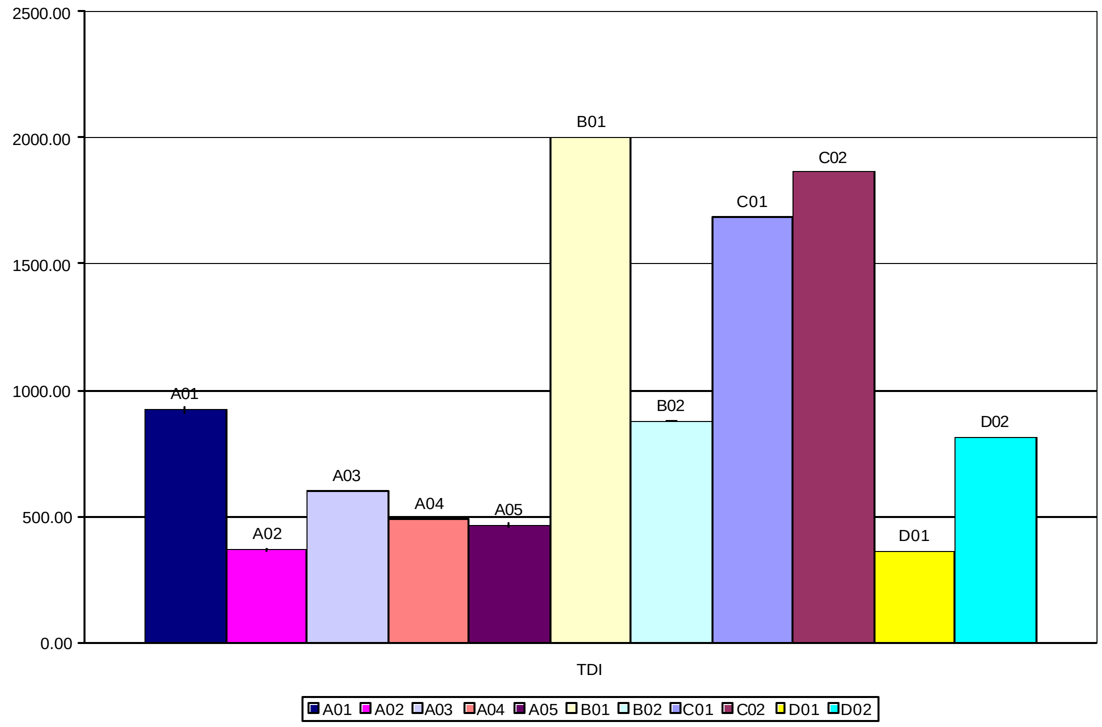


Figure 4.8: Average TDI values for all mixes

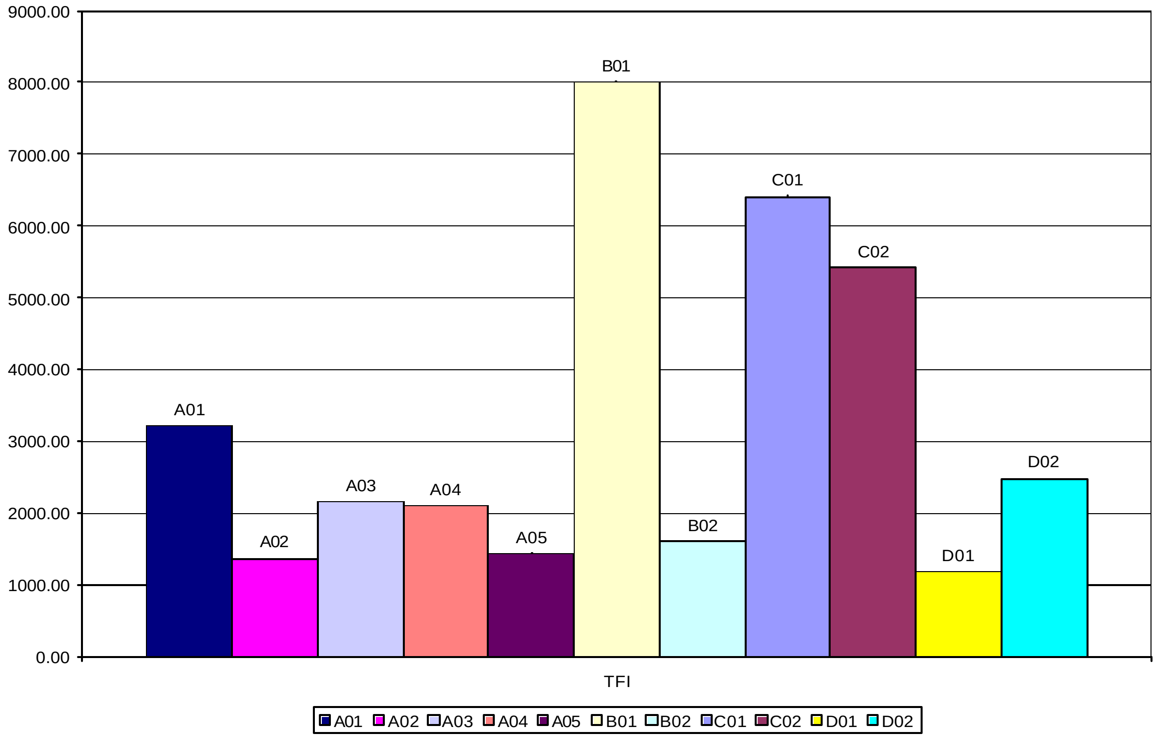


Figure 4.9: Average TFI values for all mixes

It is clear from the data presented that there is a significant variation in densification behavior of the mixtures selected. For example the CDI values vary between 50 units and 1000 units, which is a 20 fold difference. This wide difference is also confirmed by the CFI values which ranges between 100 and more than 1000 units. This similarity in differences indicates that the frictional resistance of the aggregates and the type of skeleton produced by the various gradations and sources plays a major role in achieving the 92 % Gmm density level targeted by most contractors during construction. Figures 4.8 and 4.9 depict the measures related top performance under traffic (92% Gmm to 98 % Gmm). Although the range is narrower, the values of the TDI varies between 500 and 2000 and the TFI between 125 to 8000, a significant difference that lead to believe that these mixtures will have different performance under traffic in the field.

4.3 Flow number and rate of deformation

This study included measuring the rutting resistance of mixtures at standard pavement temperatures typically known for Wisconsin summer environment. The measurements were used to compare the densification properties of the asphalt mixture measured by the SuperPave gyratory compactor with the mixtures' resistance to permanent deformation measured using the un-axial repeated creep test in the lab. The densification properties of the mixtures are described by the traffic indices (TFI, TEI), and they were covered in details in the previous section. The resistance of the mixtures to rutting is described by the rate of deformation of the mixture till failure, and the flow number, which is viewed as the point of failure in the repeated creep test.

In order to generate a fair correlation between these two properties, the challenge is to develop an effective procedure for determining the rate of deformation and the flow number from the repeated creep test results.

In the creep test the material undergoes three stages of deformation (Figure 2.4). In the initial or the primary stage, the strain rate is relatively high and decreasing with time or loading cycles. In the secondary stage, the permanent strain accumulated per cycle is constant with loading cycles. This is the stage that we are interested in as the rate of permanent deformation used in this study is determined as the constant rate within the secondary creep stage. The third stage is called the "tertiary creep stage," which is the portion at which the strain rate increases rapidly with loading time or loading cycles. The flow number is the point at which the material shows the transition from the secondary stage to the tertiary stage (NCHRP-465, 2002). However, it is difficult to quantify this point objectively and automatically. Therefore, in this study the research team had to work on developing a method for determining the flow number based on a fixed criterion.

The rate of deformation was the key variable used in determining the flow number. First a plot was generated showing the rate of deformation versus the number of cycles. There are several methods for calculating the deformation rate. To avoid interference from experimental noise, a moving average was used. Based on several trials, the moving average of every consecutive fifty points was used, as shown in Figure 4.10. The rate of deformation used in this plot is a moving average of every fifty points.

To normalize the moving average rate, it was divided by the minimum value estimated for all the test data. Therefore, when plotting the normalized rates against the number of cycles, the minimum point equals to the value of one, as shown in Figure 4.11. The reason for the normalization is the need for a better and clear definition of the point at which the flow number is estimated. To determine the flow number it was decided that it is defined as the number of cycle at which the rate of permanent deformation is doubled, in other words, it is the number of cycles at which the normalized rate value is equal to two. This means that the flow number is chosen to be the point at which the rate of deformation doubles compared to the minimum rate of deformation achieved throughout the test period. Figure 4.11 shows the flow number for one of the tested mixtures.

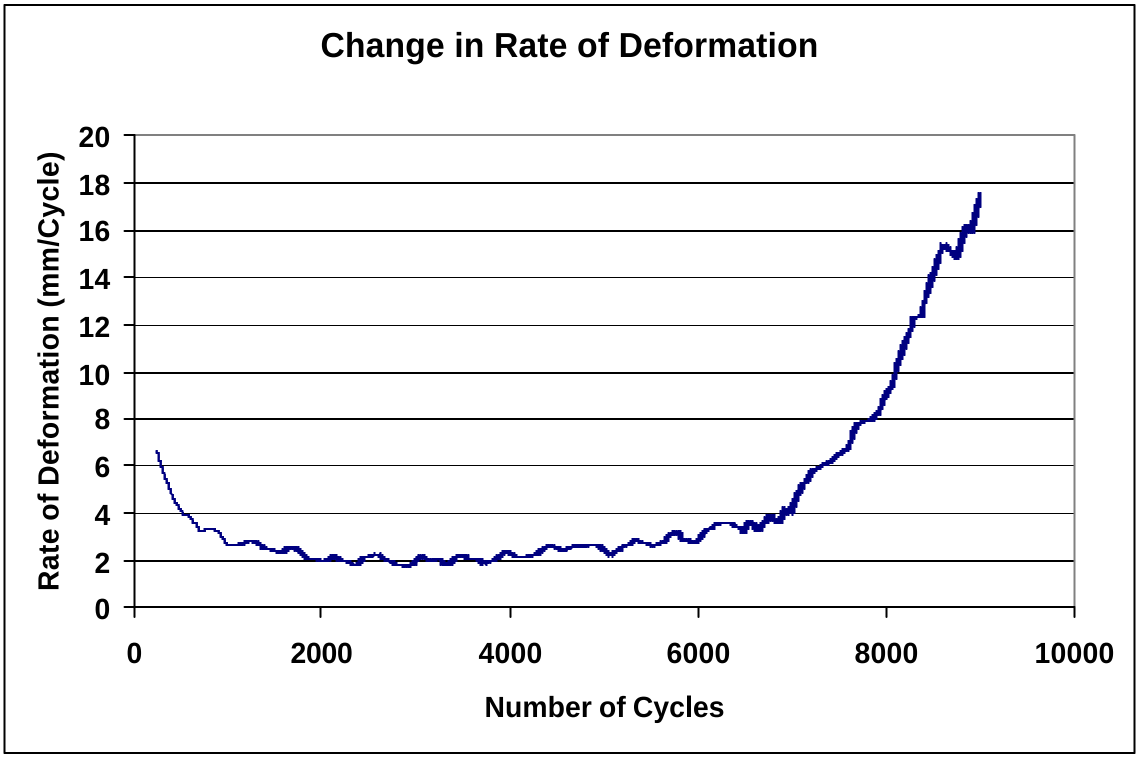


Figure 4.10: Change of rate of deformation with respect to cycle number

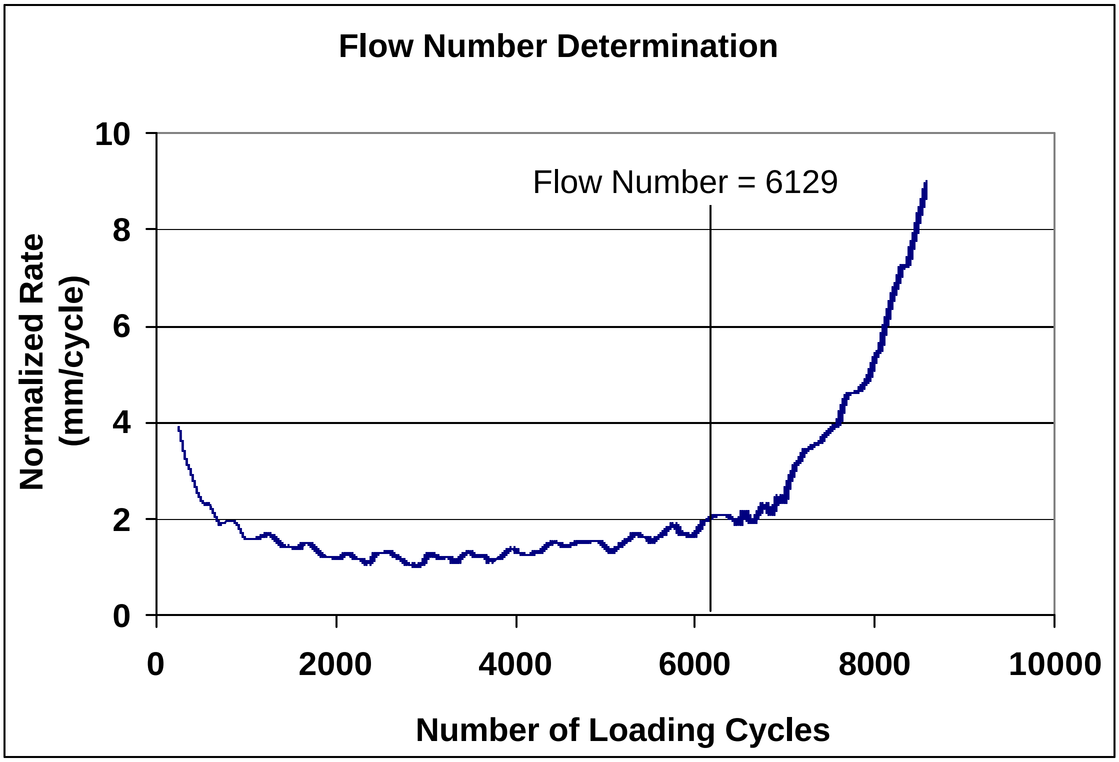


Figure 4.11: Determination of flow number

4.4 Results and Analysis of Rutting Testing

As explained in Chapter 3, several mixtures were produced using different asphalt contents and gradations. This is to insure that the study covers as wide a range of mixture properties as possible. The minimum asphalt content used was 3.8% and the maximum asphalt content used was 6.2%. The gradation varies between course, fine and a combination of both. A total of eleven mixture designs were used in this study from four different sources. Five of these mixes were compacted at three different asphalt contents; optimum, optimum plus 0.5%, and optimum minus 0.5%. Table 4.1 shows the mixes used, their flow number, the normalized rate of deformation, and densification indices.

The flow number and normalized rate of rutting is used to indicate the rutting performance of mixtures as measured using the un-axial repeated creep test. This test is used to simulate the field rutting of pavement. This test is used as an indicator for the field performance of the mixtures. The construction and the traffic indices (CDI, TDI, CFI, and TFI) were calculated using the data gathered from the SGC.

The objective of the study is to try to use the indices estimated from the SGC to evaluate mixes with respect to their rutting performance. If the indices proof to be a good surrogate to the rutting testing, they could be used to support the Superpave volumetric mixture design procedure.

In the rutting test the mixtures are subjected to thousands of loading cycles (10000 Max) while recording the cumulative permanent deformation as a function of these cycles. A haversine pulse load consisting of a 0.1 sec and 0.9 sec rest time is applied for the test duration. (SHRP-A/IR-91-104, 1991)

As mentioned in the Chapter 3 the traffic force index is the area under the compaction curve from the 92% density till 98% density. To make sure that the mixes achieve such a high density, the mixes were compacted for 600 gyrations. Some of the mixtures were very strong that they did not reach the 98% density, even after 600 gyrations. In these cases extrapolation was used to estimate the number of cycles at 600 gyrations. There were some outliers in the data set which were identified due to complete collapse of the mixture during compaction and the loss of asphalt from the mold. Also there were samples that did not show reasonable rutting behavior that were removed from the data set before the correlations.

Table 4.1: Summary of data

Sample	FN	Rate	AC	Average CEI	Average TEI	Average CFI	Average TFI
A0101	6143.0	0.95	3.8	758.94	2217.80	914.01	7504.23
A0102	5280.0	0.97					
A0103	6751.0	0.93					
A0105	2407.0	2.29	4.3	413.7	921.6	529.1	3224.2
A0106	2575.0	2.28					
A0201	1545.0	8.13	4.1	351.1	814.4	496.9	3103.5
A0202	2015.0	7.28					
A0305	2263.0	7.60	4.5	191.80	271.92	292.79	1153.98
A0402	1486.0	11.00	4.6	97.1	570.0	95.6	2132.2
A0403	743.0	28.78					
A0404	1086.0	16.30					
A0405	450.0	61.70	5.1	76	490	170	2103
A0406	420.0	96.00					
A0501	901.0	12.90	4.1	302.35	752.00	491.34	1789.00
A0502	1060.0	12.93					
A0503	900.0	16.83					
A0505	445.0	45.00	4.6	393.67	463.68	688.75	1441.58
A0506	413.0	48.00					
B0101	6055.0	1.50	6.2	180.87	1935.61	491.34	7789.00
B0102	9000.0	0.70					
B0202	1157.0	8.16	5.8	376.08	876.69	422.01	1610.19
B0203	3361.0	5.50					
B0204	2013.0	7.77					
C0101	4188.0	1.40	5.5	1047.26	1687.92	1129.95	6410.50
C0202	1200.0	30.82	5.0	255.95	117.95	416.24	925.16
C0203	770.0	31.42					
D0101	1240.0	23.87	5.3	63.77	362.42	141.11	1181.18
D0102	980.0	32.00					
D0103	991.0	27.00					
D0104	3106	6.80					
D0105	2776	8.00					
D0201	1053.0	13.25	5.3	97.4	812.8	201.8	2480.9
D0202	1430.0	13.22					
D0203	2034.0	11.42					

The main result of the rutting test is the flow number, which is commonly derived from the typical power-law model recommended for representing rutting. The model, defined in the following equation, includes an initial strain factor, e_{p1}, and a slope factor, S (NCHRP-459,2001)

$$e_p = e_{p1}N^S \qquad \text{(Equation 4.1)}$$

Where, e_p is the total accumulated permanent strain and N is the number of cycles.

Having this relationship in mind, the measured rate of accumulation of permanent deformation (S) was used to evaluate the repeatability and the consistency of the measurements achieved by the test. Figure 4.12 depicts a bar chart for the rate of deformation for some of the mixes used in this study.

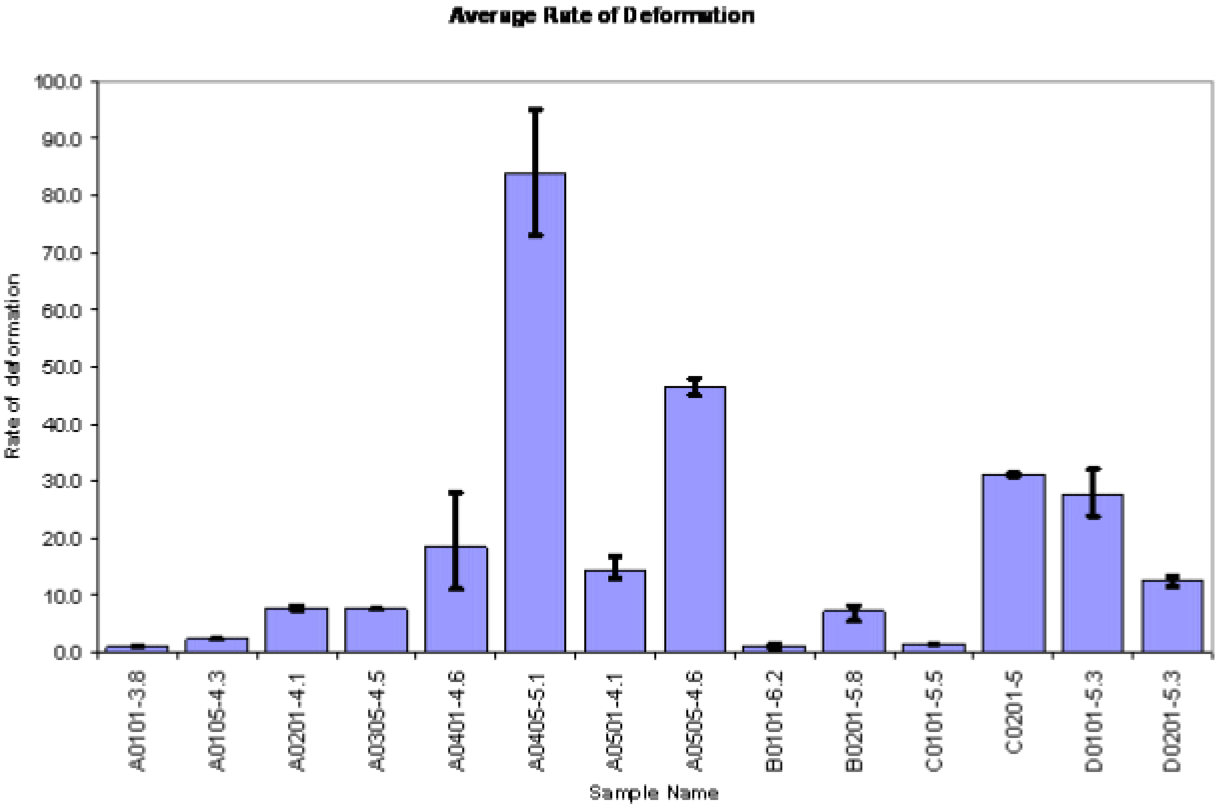


Figure 4.12: Repeatability of measured rutting rate

Beside the name of each sample the asphalt content is shown. It is clear that for a given mixture the values for the rate of deformation are very repeatable, which indicates that this test is distinguishing between the mixes and showing reliability in evaluating the behavior of different mixes with different types of aggregates or gradations. It is also clear that the test is sensitive to asphalt content.

To evaluate the possible inter-correlation of the derived response parameters, the flow number and the rate of deformation both are plotted versus each other. Since the flow number is a function of the total permanent strain accumulated to failure, the relationship of the flow number to the rate of permanent deformation should a power relation as indicated in the previous equation (equation 4.1)

From the data shown in Figure 4.13, it is clear that the two values obtained form testing the samples using the uniaxial creep loading machine are acceptably consistent according to the relationship stated earlier.

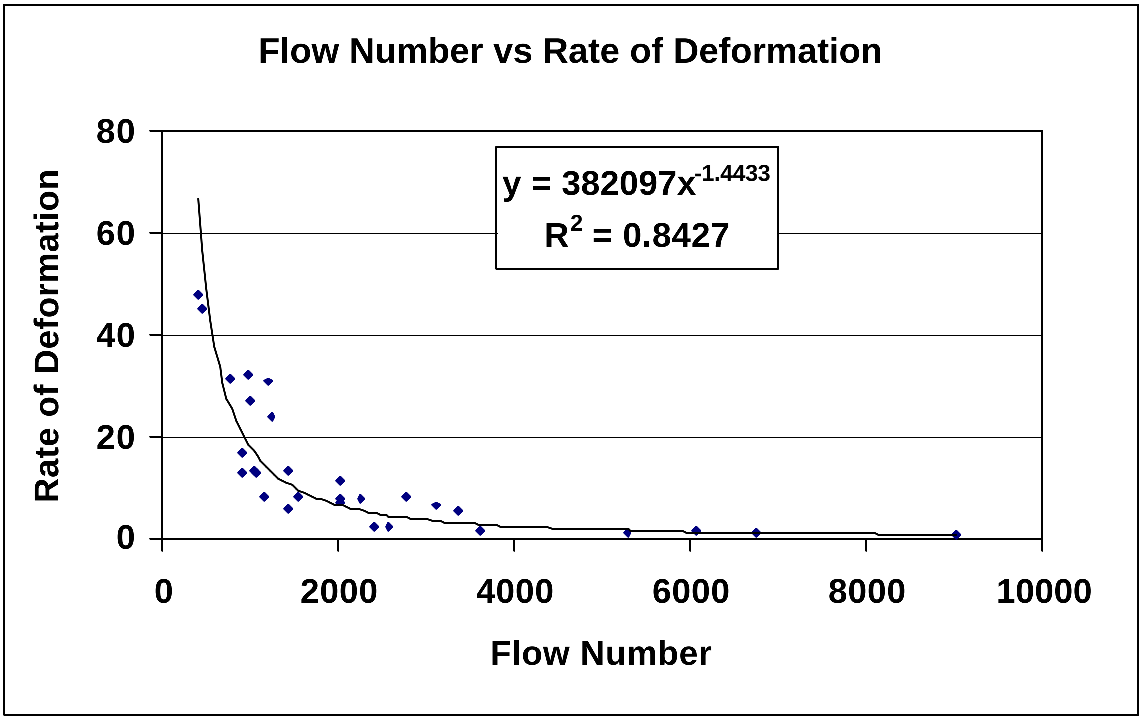


Figure 4.13: Flow number vs. the rate of deformation to the consistency of the test in producing results

To determine the significance of the densification indices in terms of defining resistance of mixtures to rutting, two stages of analyses were conducted. In the first stage statistical analysis was used to try to correlate the critical densification indices to the asphalt mixture characteristics such as asphalt content and the gradation. Figure 4.14 shows an example of this analysis for the TFI value. As can be seen, the adjusted correlation coefficient (Adjusted R ^2) is above 83 % which indicates that this measure is a true indicator of mixture composition and volumetric properties. Similar high R^2 values were found for the other indices. The complete results of the statistical analysis could be found in Appendix A.

SUMMARY OUTPUT

TFI

Regression Statistics	
Multiple R	0.928592201
R Square	0.862283476
Adjusted R Square	0.831679805
Standard Error	1003.235853
Observations	34

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	6	170150749.3	28358458.22	28.17581757	2.03161E-10
Residual	27	27175018.79	1006482.177		
Total	33	197325768.1			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
(Gradation)	-947.9746612	1402.666033	-0.675837754	0.504891713	-3826.005705	1930.056382	-3826.005705	1930.056382
(ESALS)	0.022243252	0.00443914	5.010712382	2.95915E-05	0.013134896	0.031351608	0.013134896	0.031351608
(AC*GRAD)	2642.96862	382.3452063	6.912519307	1.98825E-07	1858.461584	3427.475657	1858.461584	3427.475657
(AC*ESAL)	-0.003267157	0.000776734	-4.20627834	0.000255919	-0.004860882	-0.001673433	-0.004860882	-0.001673433
(GRAD*ESAL)	-0.006623492	0.001383918	-4.786042926	5.41292E-05	-0.009463056	-0.003783928	-0.009463056	-0.003783928
(AC*GRAD*ESAL)	0.000905842	0.000239182	3.787252273	0.000774869	0.000415082	0.001396603	0.000415082	0.001396603

Figure 4.14: Result of regression analysis when comparing the TFI with the mixture type and volumetric properties

The second stage of the analysis involved correlation between the traffic indices and the mixtures rutting indicators, which include the flow number and the normalized rate of deformation.

Figure 4.15 show the relationship between the Traffic Force Index (TFI) to the normalized rate of accumulation of permanent deformation. Figure 4.16 shows the relationship of the same index with the flow number.

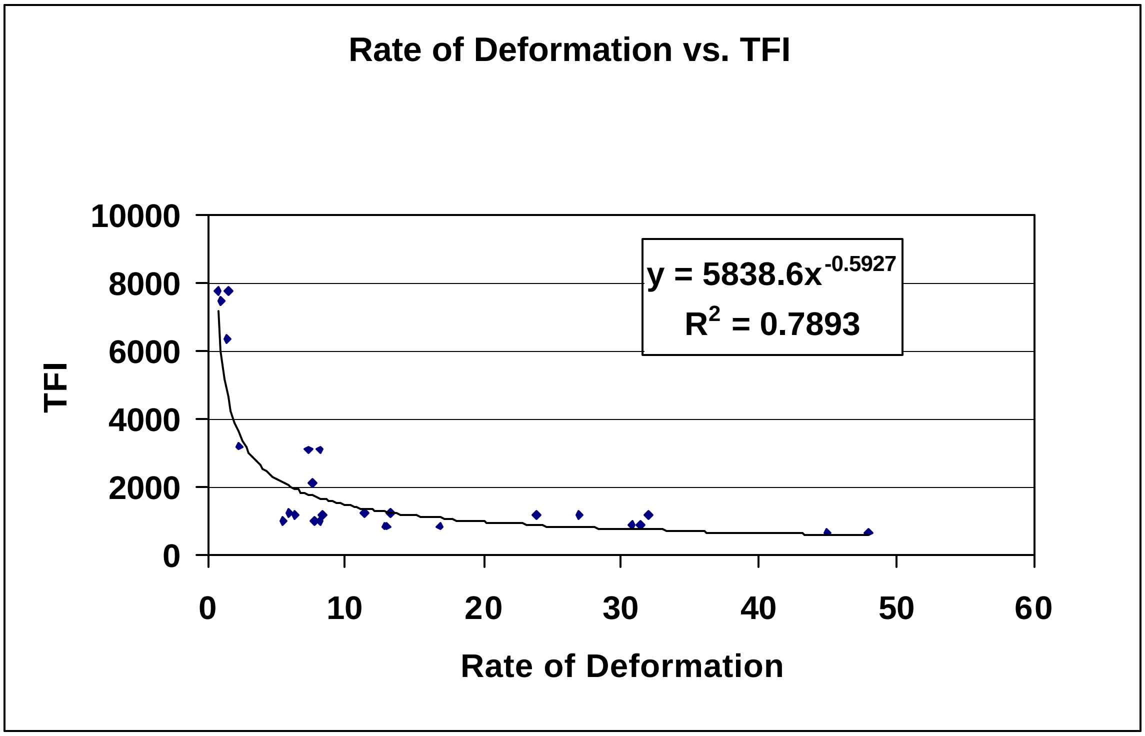


Fig. 4.15: Relationship between the rate of deformation and traffic force index

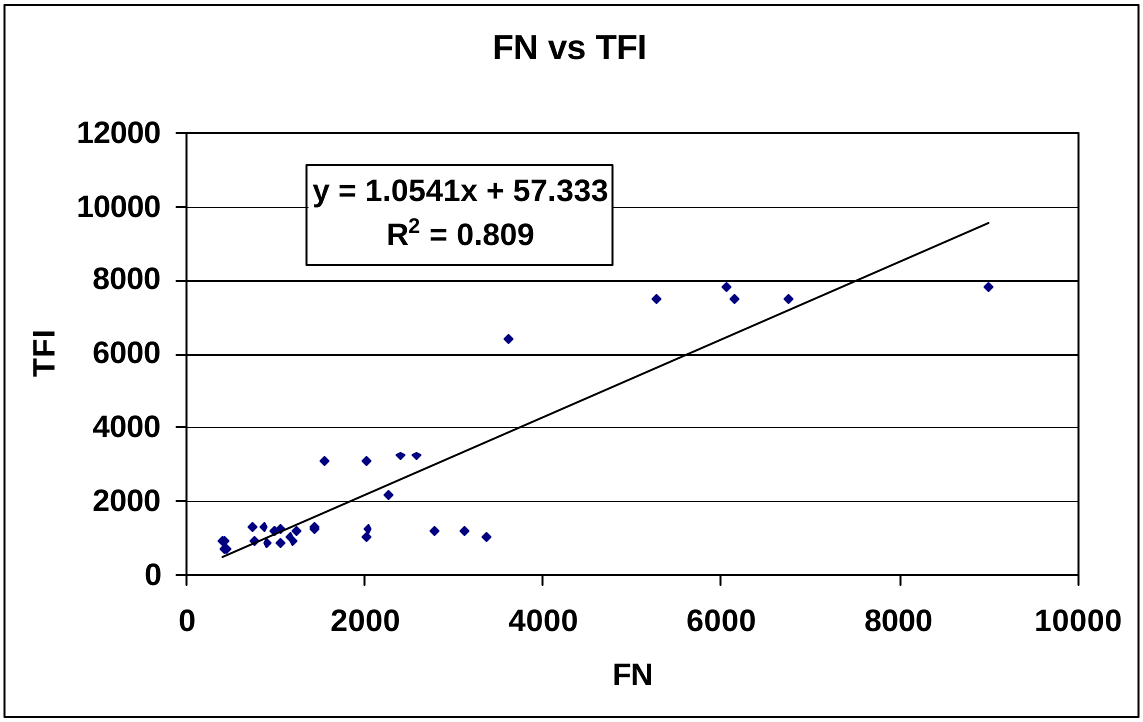


Figure 4.16: Relationship between the flow number and the TFI

The traffic index (TFI) is assumed to represent the energy needed to reach the terminal permanent strain condition at 98 % Gmm. Based on equation 4.1 relating the strain rate to the total accumulated strain, the rate of deformation should show a power relation with the terminal permanent strain. This type of trend is shown in Figure 4.16. Using a power-law fit the data in the figure shows a fair correlation between TFI and the normalized strain rate. The correlations coefficient is approximately 79 %, which signifies a strong correlation.

For the Flow Number (FN), based on equation 4.1, since the TFI is related to the failure strain and the number of cycles, the relationship between the FN and the TFI should be a linear one. Such a linear relationship is confirmed in Figure 4.16, which shows that the correlation coefficient is at 80 %, which is even higher than the one obtained from the rate of deformation.

This high correlation however is the results of the wide range of the data points and there appears to be much more scatter in the data compared to the deformation rate shown in Figure 4.16. This scatter of data points, although affects the credibility of the correlation factor for the FN, it still depicts a very strong trend.

Although the relation of TFI with the rate of deformation seems to be the more reliable, as it consists of wider range of data points and it possesses a strong correlation factor, the flow number should be the main parameter that should be used in developing a criterion for mixture stability. This is because the flow number is a fundamental material property that reflects mixture critical behavior in terms of proximity to instability under traffic loading. The rate of deformation is a local property of the material that depends on the secondary creep condition of the material and the testing conditions.

4.5 Developing a Mixture Stability Criterion

In addition to finding a strong relationship between TFI and mixture rutting, a second step is needed to convert this relationship to control limits for the control of mixture stability. These limits should take into account the traffic volume (ESAL's) as it is the governing factor in selecting mixture parameters in a typical mixture design.

Since the mixtures included in this study covered a range of mixtures designed for different traffic levels, it is logical to use the design ESAL designations to try to derive an initial criterion. Figure 4.17 shows the relationship between the mixture ESAL designation and the TFI value. as shown for a given TFI value there can be multiple ESAL values. This is because in the current practice of mixture design only the volumetric properties are used and no mechanical stability measure is targeted. The governing decision when designing is mainly based on volumetric properties.

However, the data in the figure show a definite trend indicating that the higher the ESAL level on the mixture the higher is the FN number.

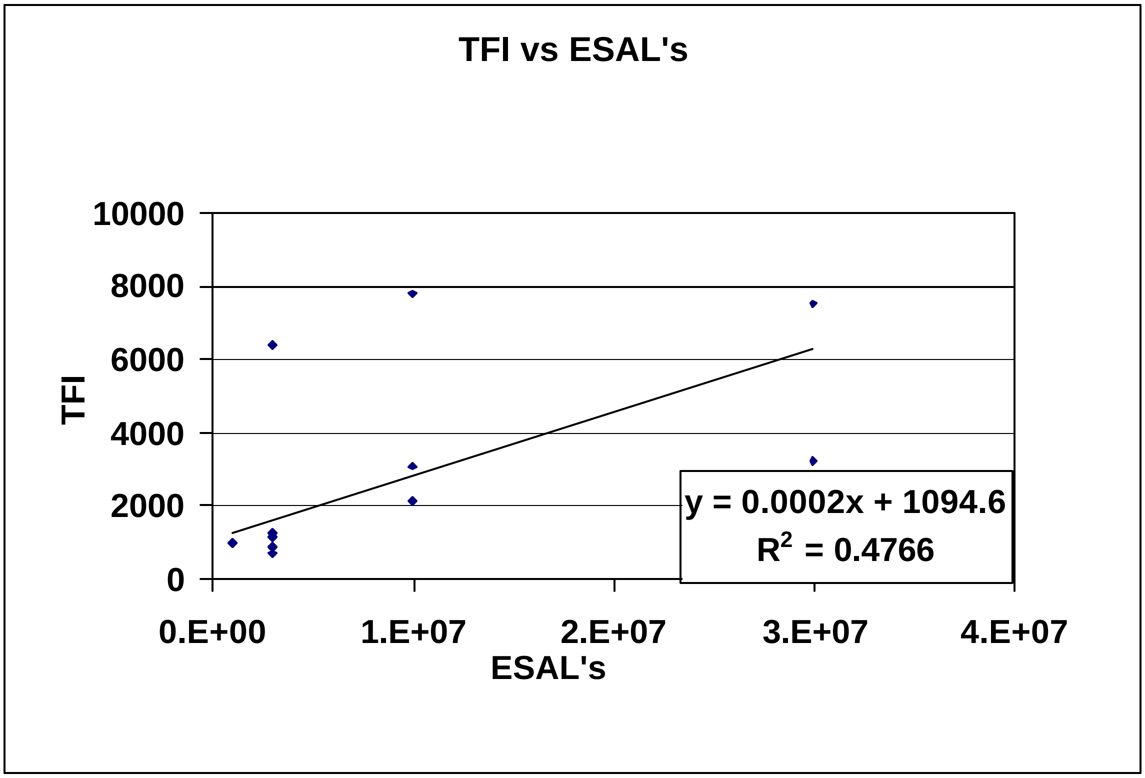


Figure 4.17: TFI vs. the ESAL's

To be on the safe side it is logical to use the minimum values of the ESALs for each TFI value as the guide for deriving the limits for the design criterion. The graph shown in Figure 4.18 shows the relationship between the TFI and the minimum ESAL values.

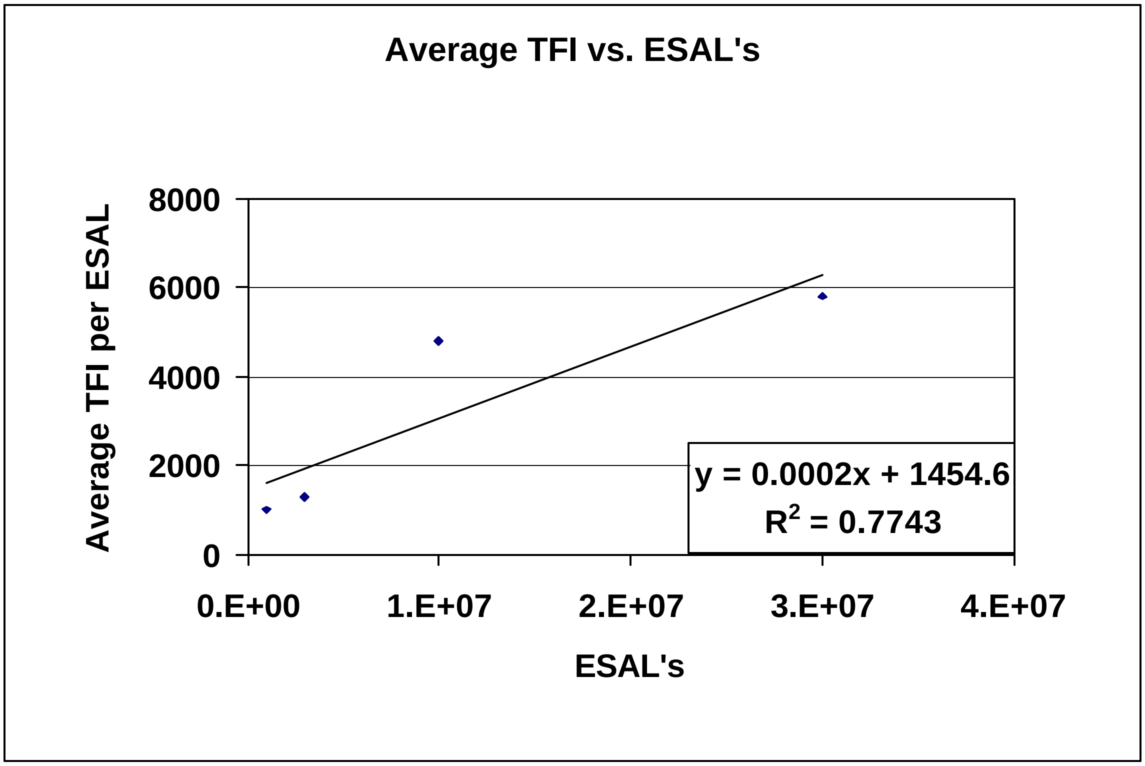


Figure 4.18: Min TFI per ESAL vs. ESAL

Using the equation of the trend line, the proposed limits can be estimated and are shown Table 4.2. This table can be used as a basis for modifying the mixture design procedure to include the TFI values as a surrogate to the mixture stability value. In other words it is a measure of the performance of the mixture that can be used in the mixture design in addition to its volumetric properties.

Table 4.2: TFI minimum values.

ESAL	Min TFI
1.00E+06	750
3.00E+06	1000
1.00E+07	2000
3.00E+07	4500

4.6 Simplified Analysis

In the previous section the stability criterion was developed based on the TFI which requires a special accessory device (PDA) to be mounted in the SGC for measuring the shear resistance of the mixtures. Although the use of the device is a more accurate way to determine the shear resistance, the cost of the device, and the complexity of calculating the shear resistance may deter users from using it in determining the stability of the asphalt mixtures.

Therefore, a simplified method to evaluate the mixtures without the use of an additional device is of more interest with respect to the users of the SGC. The proposed simplified method is based on using the densification data generated by the SGC by measuring the change in height of specimen with gyrations. This data is used to generate the common compaction curves already used in different HMA labs to determine the density of the mixes at selected gyrations. As explained in chapter one, compaction curves can be used to determine the Traffic Densification Index (TDI). This index is proposed to be used as a substitute to the TFI in evaluating the stability of the mixtures if the GLPA is not used or is not available. This idea is not a new idea. In fact in a previous study focused on fine aggregate angularity and binder grades, the concept of using the TDI for measuring mixture stability was introduced.(31)

Before using the TDI as a surrogate for the TFI, it should be validated that it correlates with the TFI. From the data generated for the purpose of this study the plot shown in Figure 4.19 is generated to compare the TDI values with the TFI values for various mixtures. Two different regression equations were used to show the strong correlation between the two indices. Figure 4.20 shows the relationship between the two indices, the regression equations used, and the coefficient of determination (R^2).

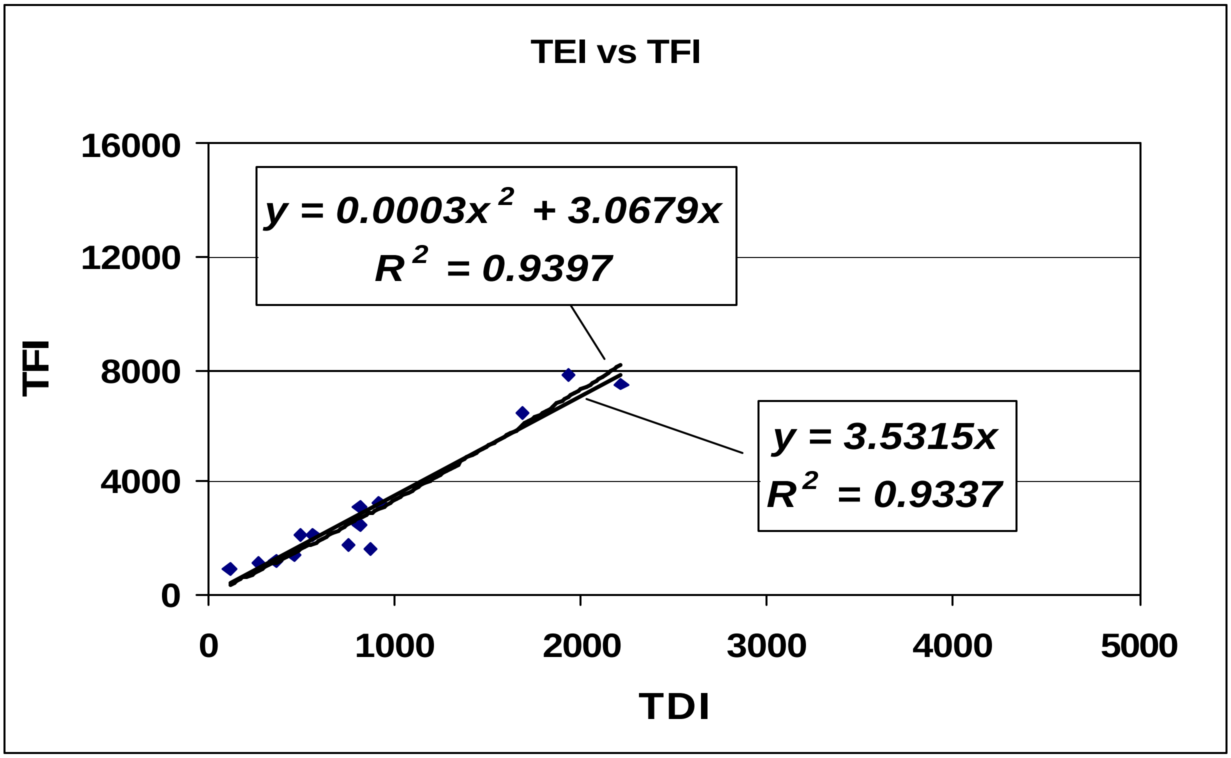


Figure 4.19: Comparison between the TDI and the TFI

As shown in the Figure 4.19, there is a very strong relationship between the two indices. The two regression equations used show high coefficient of determination. However, one can argue that this relationship can be project specific.

A similar plot was published in a previous report number WHRP 03-04 for a study sponsored by Wisconsin DOT. In that study more data points were used that were generated using many different mixtures. The final plot published in that study is reproduced in Figure 4.20.

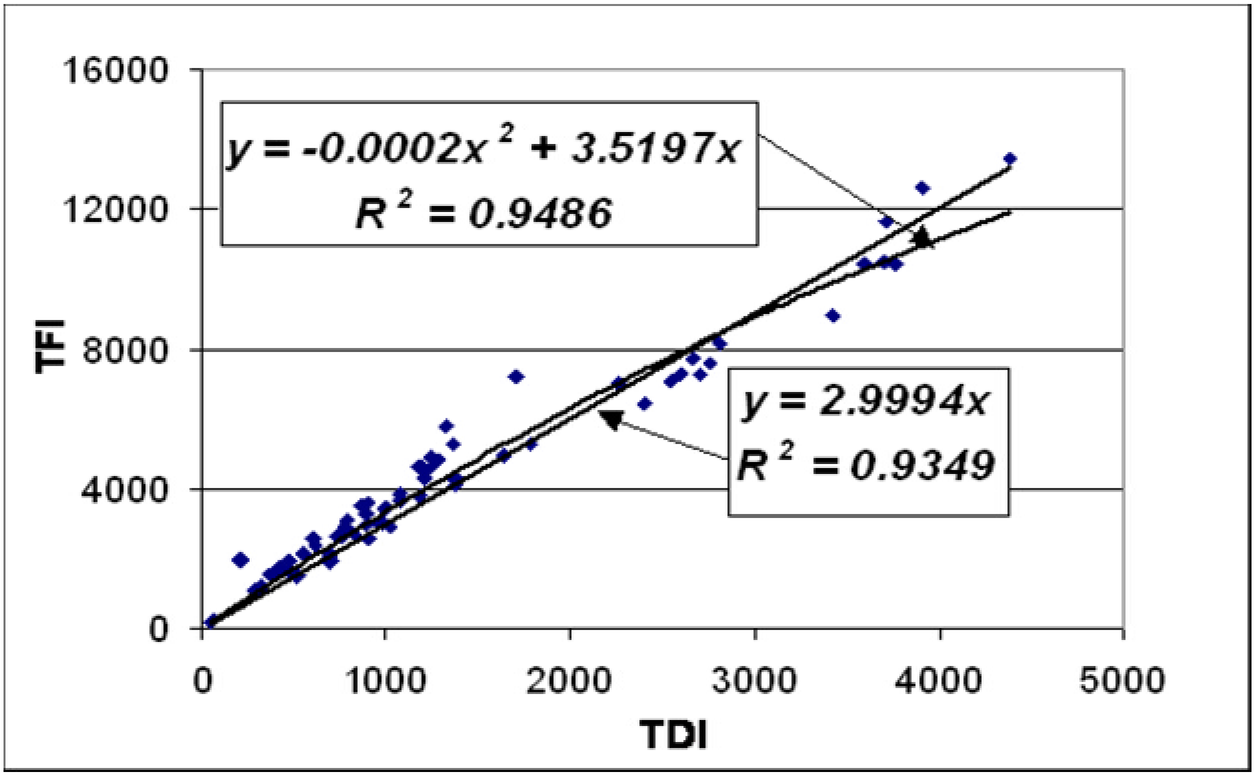


Figure 4.20: Correlation between TDI and TFI using different data set. (Reproduced from report number WHRP 03-04, October 203)

Examining Figure 4.19 and Figure 4.20, it is clear that TDI correlates very well with TFI. Furthermore, looking at the linear regression equation in the two plots it shows that the slope of the line in each is very close to the other (3.53 vs. 2.99). Neglecting the quadratic coefficient since it is very close to zero in both plots leaves us with the first order coefficient. In both plots these coefficients are again very close in value (3.0679 vs. 3.5197). It can only be concluded that the TDI correlates linearly very well with the TFI. Therefore, for the sake of simplicity, it can be assumed that, in case the GLPA is not used, the TDI can be used successfully to evaluate mixture stability and resistance to rutting as a surrogate to the TFI.

Using the TDI requires only the use of the SGC as is the practice today, thus minimizes the need to purchase new equipment or go through additional calculation techniques to determine the TFI.

In order to be able to generate recommended values of the TDI for every traffic level similar to the TFI recommended values mentioned earlier, the data from figures

4.19 and 4.20 are combined together. This was done to increase the number of data points used for higher level of confidence and to make correlation independent of project or mixture type. Figure 4.21 shows the combined data points and the regression equations used.

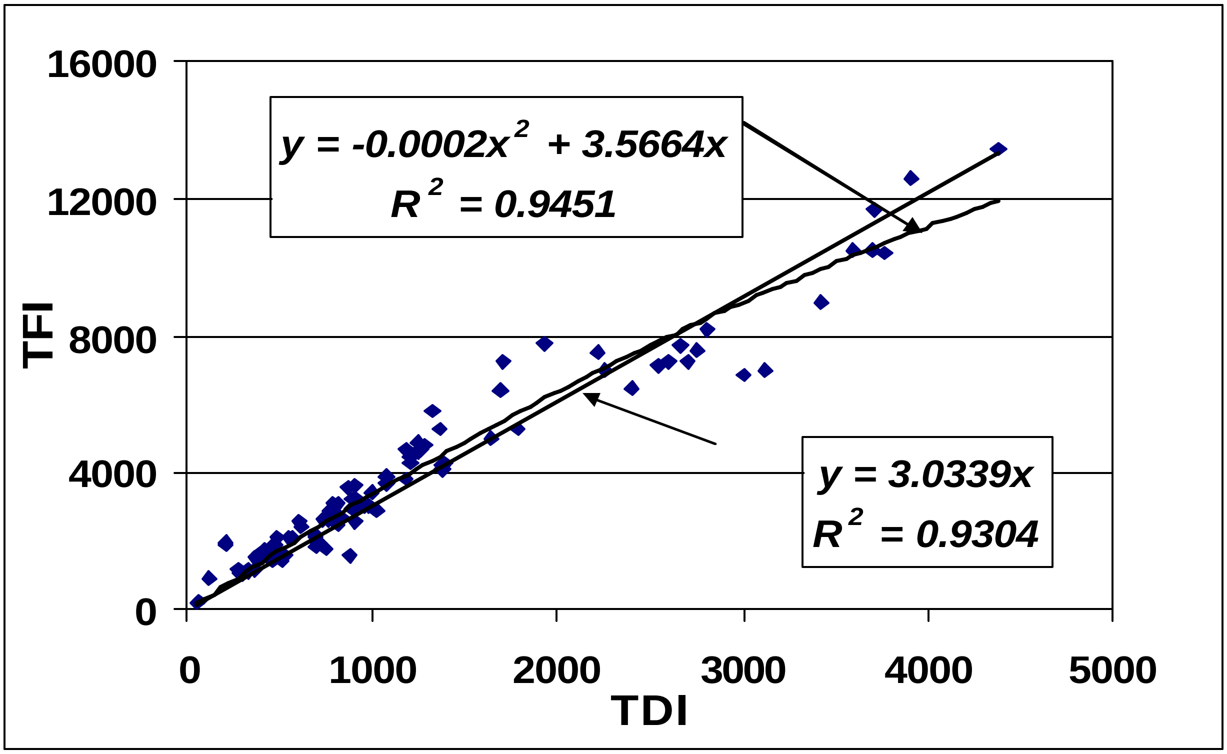


Figure 4.21: Combined data for the relationship between the TDI and the TFI

From the previous graph, it can be concluded that the TFI is approximately three times the TDI. Using this relation the recommended values for the TDI can be generated using the TFI values stated in table 4.2. table 4.3 shows both the TFI and the TDI recommended values for different traffic levels.

Table 4.3 TDI minimum values

ESAL	MinTDI	MinTFI
1.00E+06	750	250
3.00E+06	1000	300
1.00E+07	2000	600
3.00E+07	4500	1500

There is no doubt that the values shown in table 4.3 are tentative values that need to be validated. This project, although used actual rutting testing, did not cover field validation which should be the next step.

Chapter Five

Summary of Findings and Conclusion

5.1 Summary of Findings

This study was funded by the Wisconsin department of transportation to develop better mechanical stability criteria for asphalt mixes from measurements collected by the Superpave Gyratory Compactor (SGC). The SGC was used to calculate the Traffic Force Index (TFI), and the Traffic Densification Index (TDI) as the proposed mechanical stability parameters. To measure the TFI a special device to measure force distribution (called the Pressure Distribution Analyzer, PDA) is needed during compaction to determine the mixture resistance to compaction. In order to validate these parameters, the results from the SGC were compared to the results of a performance test of mixtures. In this study this performance test was chosen to be the uni-axial repeated creep test recommended as the simple performance test by NCHRP 9-19 project (22, 35). The output of the performance test is the flow number (FN), which indicates the mixture tertiary creep failure, and the creep rate which is a measure of resistance of a mixture to accumulation of permanent strain.

Based on the analysis of results for the mixtures, the correlation between the TFI and the creep rate yielded a coefficient of determination of approximately 81% which indicates a significant relationship between mixture resistance to permanent deformation and the TFI. Therefore, it is found that the TFI can be used as an indication of mixture mechanical stability. It can be used as a basis to recommend minimum limits of TFI to ensure acceptable performance of mixture for each traffic level. A tentative set of limits are recommended as a starting point to expand the mixture design process for asphalt mixtures to include, in addition to the volumetric properties used today, an indication of the mechanical stability of asphalt mixtures.

The study has also considered the possibility of not using the PDA. A good correlation was found between the Traffic Densification Index, which is a measure derived from the rate of change in height of specimen between 92 % Gmm and 98 % Gmm, and the TFI. The high correlation (R^2 = 93%) found agrees with a previous study done using similar but different aggregate sources used in building Wisconsin pavements. The agreement in results is very encouraging and lead to more confidence in using the densification curves as measured today to derive a simple and practical parameter to amend the volumetric mixture design. A tentative set of limits for the (TDI) are also proposed to compliment the existing mixture design criteria.

Taking into account the different asphalt contents, gradations, and sources used in this study, have the strong correlations mentioned earlier indicate that the concept of using the SGC as a performance prediction tool is not a property specific approach. On the contrary these results prove that this approach is more of a universal mechanical stability prediction tool that can be used for all mixtures.

It is however critical to indicate that the results presented in this report are based on using two different gradation types for aggregates collected from four different sources commonly used in Wisconsin. The optimum asphalt contents used varied from 4.3% to 6.2%. The study of this limited sample size is primarily intended to create a tentative criterion that will need to be examined by practitioners from industry and from DOT before it can be implemented.

5.2 Recommendations

The following are the major recommendations of this research study:

1) The results indicate a significant correlation between the traffic indices obtain by using the SGC and the mixtures resistance to permanent deformation indicated by the flow number (FN) and the rate of rutting. Therefore, the SGC is recommended to be used as a tool for mixtures mechanical stability prediction.

2) The results show that the strong correlation between the traffic indices and the FN is not property specific, meaning that the relationship is not based on asphalt content, gradation, source, or any other property that differentiate a mixture form the other. On the contrary the correlation is only based on the mechanical stability of the mixtures and their resistance to permanent deformation. Therefore, it is recommended that the traffic indices limits proposed to be used as guidance for all mixtures regardless for their properties.

5.3 Conclusion

The following are the major conclusions of this research study:

1) The SGC results show very promising indications that it can be used as a mechanical stability tool for mixtures. According to the results mentioned earlier, the traffic indices (TFI, and TDI), measured from the SGC, correlate very strongly to the mixture resistance to permanent deformation

2) These strong correlations to the mixtures' resistance to permanent deformation is observed regardless of the mixtures' gradations, asphalt content, or source.

3) The mixtures performance prediction can be estimated by two methods. The first is by using the GLPA. This method helps in calculating the Traffic Force Index (TFI). The second method is by using the densification curve produced by plotting the %Gmm verses number of SGC gyrations. The second method, thus, does not require any additional equipment for predicting the mixture performance.

4) Instead of using a new equipment to measure the performance of asphalt mixtures under simulated rutting conditions, the SGC is already being used for compactions and can be used as performance test as well.

5.4 Suggestion for Future Research

For future research, we believe that conducting similar evaluations of mixtures' performance while varying the asphalt binder grade, and using wider gradation range will support the mentioned conclusions. In addition, for the purpose of this study all the mixtures were tested at one temperature which is corresponding to the high design pavement temperature in Wisconsin. More testing is suggested to be conducted on mixtures design for different temperature regions (higher or lower).

References

1. Asphalt Institute. Performance Graded Asphalt, Binder Specification and Testing. Superpave Series No. 1 (SP-1), 1995.
2. Asphalt Institute. Superpave Mix Design. Superpave Series No. 2 (SP-2), 1996.
3. Roberts, Freddy L., Kandhal, Prithvi S., Brown, E. Ray, Lee, Dah-Yinn, and Kennedy, Thomas W. Hot Mix Asphalt Materials, Mixture Design and Construction, Second Edition. NAPA Research and Education Foundation, 1996.
4. State of Wisconsin Department of Transportation. Supplement Specifications amending the 1996 Edition of the Standard Specifications for Highway and Structure Construction, 2000 Edition. July 2000.
5. Sousa, Jorge B., Way, George, Harvey, John T., and Hines, Michael. Comparison of Mixture Design Concepts. Transportation Research Record, 1492. TRB, National Research Council, Washington, D.C., pp. 151-160, 1995.
6. Anderson, R. Michael, and McGennis, Robert B. A Look at the Superpave Level I Mixture Design Process. Infrastructure: New Materials and Methods of Repair, Proceedings of the Third Materials Engineering Conference. American Society of Civil Engineers, New York, NY, pp. 880-887, 1994.
7. Sigurjonsson, Sigujon, and Ruth, Byron E. Use of Gyratory Testing Machine to Evaluate Shear Resistance of Asphalt Paving Mixture. Transportation Research Record 1259, TRB, National Research Council, Washington, D.C., pp. 63-78, 1990.
8. Hopman, P.C., Valkering, C.P., and van der Heide, J.P.J. Mixtures and Five Procedures: Search for a Performance-Related Mixture Design Procedure.

(Towards a Performance-Related Asphalt Mix Design Procedure.) Asphalt Paving Technology, Journal of the Association of Asphalt Paving Technologists, Vol. 61, pp. 188-216, 1992.

9. Ruth, B.E., Shen, X, and Wang, L.H. Gyratory Evaluation of Aggregate Blends to Determine their Effect on Shear Resistance and Sensitivity to Asphalt Concrete. Effects of Aggregate and Mineral Fillers on Asphalt Mixture Performance, ASTM 1147, Meininger, Richard C., ed, Ann Arbor, MI, p. 252, 1992.

10. Bahia, Hussain U., Friemel Timothy P., Peterson, Pehr A., Russell, Jeffery S., and Poehnelt, Brian. Optimization of Constructibility and Resistance to Traffic: A New Design Approach for HMA Using the Superpave Compactor. Asphalt Paving Technology, Journal of the Association of Asphalt Paving Technologists, Vol. 67, pp. 189-232, 1998.

11. Francken, L. Editor. Bituminous Binders and Mixtures. State of the Art and Interlaboratory Tests on Mechanical Behaviour and Mixture Design. RILEM Report 17. Report of the RILEM Technical Committee 152-PBM Performance of Bituminous Materials. E & FN Spon, London and New York, 1998.

12. Janoo, Vincent C. Quantification of Shape, Angularity, and Surface Texture of Base Course Material. US Army Corps of Engineers Cold regions Research and Engineering Laboratory Special Report 98-1, January 1998.

13. Masad, Eyad, Muhuthan, B., Shashidhar, Naga, and Harman, Thomas. Quantifying Laboratory Compaction Effects on the Internal Structure of Asphalt

Concrete. Transportation Research Record 1681, TRB, National Research Council, Washington, D.C., pp. 179-185, 1999.

14. Mallick, Rajib B. Use of Superpave Gyratory Compactor to Characterize Hot-Mixture Asphalt. Transportation Research Record No. 1681, TRB, National Research Council, Washington, D.C., pp. 86-96, 1999.

15. Brown, E. Ray, Buchanan, M. Shane. Consideration of N_{design} Compaction Matrix and Evaluation of Gyratory Compaction Requirements. Asphalt Paving Technology, Journal of the Association of Asphalt Paving Technologists, Vol. 68, pp. 153-191, 1999.

16. Haddock, John, Pan, Changlin, Feng, Aiwen, and White, Thomas D. Effect of Gradation on Asphalt Mixture Performance. Transportation Research Record No. 1681, TRB, National Research Council, Washington, D.C., pp. 59-68, 1999.

17. Kose, Sadi, Guler, Murat, Bahia, Hussain U., and Masad, Eyad. Distribution of Strains within Binders in HMA Using Imaging and Finite Element Techniques. Presented at the 79th Annual Meeting of the Transportation Research Board, Paper No. 00-1391, Washington, D.C., January 2000.

18. Bahia, H.U., Hanson, D.I., Zeng, M., Zhai, H., Khatri, M.A., and Anderson, M.R. Final Report, Project NCHRP 9-10, Superpave Protocols for Modified Asphalt Binders. Prepared for the National Cooperative Highway Research Program, Transportation Research Board, National Research Council, December 2000.

19. Delage, Kenneth P. The Effect of Fine Aggregate Angularity on Hot Mixture Asphalt Performance. Master Degree Thesis, Department of Civil and Environmental Engineering, University of Wisconsin-Madison, November 2000.

20. Guler, Murat, Bahia, Hussain U., Bosscher, Peter J., and Plesha, Michael E. Development of a Device for Measuring Shear Resistance of HMA in the Gyratory Compactor. Presented at the meeting of the Transportation Research Board, Paper No. 00-1318, Washington, D.C., January 2000.

21. Hot Mix Asphalt Visions: 2000 and beyond, National Asphalt Pavement Association (NAPA), 2000.

22. Sousa, Jorge B., Craus, Joseph, and Monismith, Carl L. Summary Report on Permanent Deformation in Asphalt Concrete. SHRP-A/IR-91-104, Washington, D.C., 1991.

23. Mitchell, James K. Fundamentals of Soil Behavior, 2nd Edition. John Wiley & Sons, Inc, New York · Chichester · Brisbane · Toronto · Singapore, 1993.

24. NCHRP 9-19 Superpave Models Draft Test Method W2. Standard Test Method for Simple Performance Test for Permanent Deformation.

25. Witczak, M.W. Superpave Support and Performance Models Management. Simple Performance Test: Test Results and Recommendations. NCHRP 9-19 Interim Task C Report for Project Deliverable Subtask C.3. Tempe, AZ, November 2000.

26. S. Dessouky, E. Masad, and F. Bayomy, Prediction of Hot Mix Asphalt Stability Using the Superpave Gyratory Compactor", Journal of Materials in Civil Engineering, ASCE, (2002) in review.

27. F. Bayomy, E. Masad, and S. Dessoukey, "Development and Performance Prediction of Idaho Superpave Mixes," Interim Report of ITD-NIATT Project

KLK464, National Institute for Advanced Transportation Technology, University of Idaho, Moscow, Idaho, July (2002).

28. Bahia, Hussain, Masad, Eyad, Staktson, Anthony, Dessouky, Samer, and Bayomy Fouad. Simplistic Mixture Design Using The SGC and The DSR. AAPT, 2003

29. A. Stakston, and H, Bahia, " Using the Gyratory Compactor to Design Asphalt Mixtures for Optimum Constructibility and Traffic Resistance," Draft final report submitted for the Wisconsin Department of Transportation July 2002.

30. Kandhal, P. S. Parker Jr, F. Aggregate Tests Related to Asphalt Concrete Performance in Pavements. NCRP Report 405 National Academy Press Auburn, AL 1998.

31. Stakston, Anthony D. The Effect of Fine Aggregate Angularity, Asphalt Content and Performance Graded Asphalts on Hot Mix Asphalt Performance in a Laboratory Study. Masters Thesis. University of Wisconsin Madison 2002

32. Sousa, Jorge B. Craus, Joseph. Monismith, Carl L. Summary Reposr on Permanent Deformation in Asphalt Concrete. SHRP-A/IR-91-104, Strategic Highway Research Program 1991.

33. Sebaaly, Peter E., Ridolfii Dan, Gangavaram, Raja S., and Epps, Jon A. "Selecting Most desirable Hot-Mix Asphalt Mixtures" Transportation Research Record 1590. Transportation Research Board, Washington D.C 1997

34. N. I. Kamel, L. J. Miller. Comparative performance of pavement Mixes Containing Conventional and Engineered Asphalts. Transportation Research Record 1454. Transportation Research Board, Washington D.C 1994

35. M.W. Witczak, K. Kaloush. T. Pellinen, M. El-Basyouny, and H. V. Quintus. Simple Performance Test For Superpave Mix Design. NCHRP Report 465. National Academy Press 2002.

36. H. U. Bahia, D. I. Hanson, M. Zeng, H. Zhai, M. A. Khatri, R. M. Anderson. Characterization of Modified Asphalt Binders in Superpave Mix Design. NCHRP Report 459. National Academy Press 2001.

37. Y. H. Huang, “Pavement Analysis and Design”. Prentice Hall, 1993

38. Kaloush, K. and Witczak, M.W., “Tertiary Flow Characteristics of Asphalt Mixtures”. *Journal of the Association of Asphalt Paving Technologists*, Volume 71, St. Paul, MN, March 2002, pp248-280.