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Laboratory Evaluation of the Noise and Durability Properties of Asphalt Surface Mixes

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Partnered Pavement Research Program (PPRC) Strategic Plan Element (SPE) 4.20:
Laboratory Evaluation of Durability and Noise Properties of Asphalt Surface Mixes

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Abstract:
This study made comparisons of the expected noise and durability performance of asphalt surface mixes based on laboratory testing only, and recommended a set of surface mixes for field test sections with improved surface performance properties. The study included a series of experiments to investigate the effects of several important mix variables identified in studies of field test sections, including nominal maximum aggregate size, aggregate gradation, binder type, additive, air-void content, and aggregate shape, on mix properties related to pavement surface performance. The study also included several other mix designs that had good or promising performance histories, and compared them with current Caltrans mixes in terms of laboratory test results. Specimens were prepared and tested in the laboratory. The performance indicators evaluated in the laboratory included durability, permeability, sound absorption, and friction. Durability included raveling, moisture damage, reflective cracking, and rutting. Friction included both macrotexture and microtexture levels. The study found that mixes with small aggregate sizes and either an asphalt rubber or polymer-modified binder, the Georgia 12.5-mm OGFC mix, and double-layer porous asphalts have good overall laboratory performance in terms of sound absorption, which is correlated with tire/pavement noise, and durability. However, performance evaluations in separate studies in the Netherlands indicated that the double-layer porous asphalt layers ravel faster than single-layer open-graded mixes. Therefore, this study recommends that the small aggregate size mixes with rubber and polymer binders, and the Georgia OGFC mix be further evaluated in field or HVS test sections.

Keywords: Asphalt surface mixes, Noise, Durability, Permeability, Friction, Open-graded friction course

Proposals for implementation:

Related documents:

- *Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphaltic Pavement Surface Types: First- and Second-Year Results,* by A. Ongel, J. Harvey, E. Kohler, Q. Lu, and B. Steven. February 2008. (UCPRC-RR-2007-03). Report prepared by UCPRC for the Caltrans Department of Research and Innovation.
- *Summary Report: Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphalt Pavement Surface Types: First- and Second-Year Results,* by A. Ongel, J.T. Harvey, E. Kohler, Q. Lu, B.D. Steven, and C.L. Monismith. August 2008. (UCPRC-SR-2008-01). Report prepared by UCPRC for the Caltrans Department of Research and Innovation.
- *Acoustical Absorption of Open-graded, Gap-graded, and Dense-graded Asphalt Pavements,* by A. Ongel and E. Kohler. July 2007. (UCPRC-TM-2007-13) Technical memorandum prepared by UCPRC for the Caltrans Department of Research and Innovation.
- *State of the Practice in 2006 for Open-Graded Asphalt Mix Design,* by A. Ongel, J. Harvey, and E. Kohler. December 2007. (UCPRC-TM-2008-07) Technical memorandum prepared by UCPRC for the Caltrans Department of Research and Innovation.
- *Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Three-Year Results,* by Q. Lu, E. Kohler, J. Harvey, and A. Ongel. January 2008. (UCPRC-RR-2009-01). Report prepared by UCPRC for the Caltrans Department of Research and Innovation.
- Work Plan for project 4.20, "Laboratory Evaluation of Noise and Durability Properties of Asphalt Surface Mixes"

Signatures:

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DISCLAIMER

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

PROJECT OBJECTIVES

The purpose of this study was to estimate the performance properties of a variety of asphalt surface mixes, in particular those that influence noise and durability; and to recommend a set of mixes for future field test sections. The study used direct comparisons and was conducted entirely in the laboratory.

The project had the following objectives:

1. To gather and summarize information that had become available since a 2004 UCPRC literature survey on this subject regarding types, design procedures, test methods, and performance of asphalt surface mixes from other states or countries, and to identify new mixes to evaluate.
2. To evaluate the properties and performance of selected mixes through laboratory testing and to determine a set of best asphalt surface mixes in terms of overall performance (i.e., sound absorption, durability, permeability, and friction).
3. To recommend improvements or innovations for the design, testing, and evaluation methods used with asphalt surface mixes.
4. To make recommendations for field test sections and HVS test sections based on the laboratory test results.

EXECUTIVE SUMMARY

Background

In the early 2000s, the California Department of Transportation (Caltrans) identified a need for research into the acoustics, friction, durability, and related performance properties of pavement surfaces on the state highway network. Consequently, in November 2004, the Caltrans Pavement Standards Team (PST) gave its approval to a research project to investigate the performance properties of asphalt surfaces, including the Department's open-graded mixes and select experimental mixes.

PPRC SPE 4.16 included two years of field measurements, and focused on the measurement of material properties and field performance of various asphalt surface mixes currently in use on California highways, as well as on some new materials and thicknesses placed in experimental sections. The two-year project was followed by third-, fourth-, and fifth-year projects—PPRC SPE numbers 4.19, 4.27, and 4.29, respectively. Pavements with the following asphalt surface mixes were included in the PPRC SPE 4.16, 4.19, 4.27, and 4.29 projects:

- Dense-graded asphalt concrete (DGAC), since renamed *hot-mix asphalt* (HMA)
- Open-graded friction course (OGFC), with conventional and polymer-modified binders
- Rubberized hot-mix asphalt—open graded (RHMA-O)
- Rubberized hot-mix asphalt—gap graded (RHMA-G)
- Oregon F-mix, with conventional and rubberized binders

Statistical analyses were performed to investigate the correlation between mix design variables, environmental variables (climate and traffic), age, and pavement performance (noise, friction, durability, permeability, and roughness). These studies of field mixes provide the first comprehensive evaluation of the performance of Caltrans standard surface mixes and experimental mixes. However, as with most field studies they were constrained by the availability of asphalt surface mix types in the field as well as some uncontrollable traffic and climate factors specific to the physical locations of the existing field mixes. Therefore, complete full or balanced factorial design for statistical analysis was impossible. For example, without historical project records, it was impossible to distinguish in the field between mixes with conventional asphalt binder and those with polymer-modified binder. In another example, the nominal maximum aggregate size (NMAS) and thickness effects could not be fully evaluated, as these variables have different specifications for different mix types. It was determined from these results that a laboratory experimental study was needed to investigate variables that could not be completely evaluated in the field study and to further optimize mix design for noise reduction and durability improvement.

Purpose and Objectives

The purpose of this study was to evaluate the performance of a variety of asphalt surface mixes, and in particular their noise and durability properties; to make recommendations regarding design of current mixes; and to formulate a recommended set of mixes for future test sections. The study was conducted entirely in the laboratory.

The laboratory experiment design of this project (PPRC SPE 4.20) was based on the results of the field study, but permitted a factorial design that considered the variables that could not be fully evaluated in the field, such as binder type and nominal maximum aggregate size. To provide a link to the field study results, current Caltrans mixes were included in the laboratory experiment. Some new mixes included in the experiment were optimizations of Caltrans mixes currently in use but with changes to them made based on the results of the field study. In addition, a review of surface mix performance from some other state DOTs and from the Netherlands and Denmark identified several promising mixes that were also included in the laboratory experiment design.

The objectives of this project are to:

1. To gather and summarize the information that had become available since a 2004 UCPRC literature survey on this subject regarding types, design procedures, test methods, and performance of asphalt surface mixes from other states or countries, and to identify new mixes to evaluate.
2. To evaluate the properties and performance of selected mixes through laboratory testing and to determine a set of best asphalt surface mixes in terms of overall performance (i.e., sound absorption, durability, permeability, and friction).
3. To recommend improvements or innovations for the design, testing, and evaluation methods used with asphalt surface mixes.
4. To make recommendations for field and HVS test sections based on the laboratory test results.

This report summarizes the work completed under project PPRC SPE 4.20, including the following:

- A literature review of current practice and recent and ongoing research in other states and countries on asphalt surface mixes (Chapter 2),
- Selection of materials and test methods (Chapter 3),
- Experimental design (Chapter 4),
- Test results and analysis (Chapter 5),
- Conclusions (Chapter 6), and
- Recommendations for noise-reducing mix designs and candidate mixes for field and possible HVS test sections (Chapter 7).

Appendices provide details of the mix designs and test results.

Literature Survey

A literature survey was performed to evaluate current practice, and recently completed research in other states and countries on asphalt surface mixes that are durable, noise-reducing, and safe. The focus of the literature survey was on research reported since the previous UCPRC literature survey on this subject performed in 2004

All of the studies reviewed for the literature survey showed that porous asphalt concrete pavement surfaces provide significant noise reduction benefits in addition to reduced splash and improved skid resistance, with benefits diminishing after a few years as the surfaces age. Several studies indicated that smaller aggregate sizes and greater thickness tend to provide more significant noise reduction. The literature survey also updated information regarding the durability of porous asphalt mixes and the effects of mix design, traffic, and the ambient environment. The results confirmed that different types of mixes might be suitable for different locations, and provided information regarding the performance of double-layered porous asphalt courses and small size aggregate mixes used in Europe. The literature survey also showed that the laboratory tests to be included in the experiment design for this project would be adequate to provide an indication of future field performance.

Experiments

This study designed a series of experiments to investigate the effects of several potentially important mix variables, including nominal maximum aggregate size (NMAS), aggregate gradation, binder type, additive, air-void content, and aggregate shape, on mix properties related to pavement surface performance. Specimens were fabricated and tested in the laboratory. The performance measures evaluated in the laboratory included durability, permeability, sound absorption, and friction.

The following mix designs, which showed promising performance for other agencies in the literature survey, were also included:

- Georgia OGFC mix,
- Arizona rubberized open-graded asphalt mix with high binder content,
- European double-layer porous asphalt (DLPA) mix, and
- Danish SMA mixes with small NMAS

A total of 22 mixtures were included in this study, including one dense-graded asphalt mixture, two stone mastic asphalt mixtures, and nineteen open-graded (porous) asphalt mixtures.

Results and Conclusions

The following are the primary conclusions regarding mix design for noise reduction and durability improvement:

- Reducing the NMAS of open-graded mixes from 9.5 (3/8 in.) or 12.5 mm (1/2 in.) to smaller sizes (e.g., 4.75 mm [No. 4 sieve]), together with the use of asphalt rubber or polymer-modified binders, can significantly reduce raveling potential and therefore reduce tire/pavement noise generated by the tire vibration phenomenon when a wheel passes over a raveled pavement surface.
- The tradeoff with regard to the first conclusion (i.e., reducing the NMAS) is that the reduction in aggregate size causes some reduction in the permeability and sound absorption capabilities of a mix, as well as the friction. It appears that the reduction in friction can be compensated for by use of asphalt rubber binder, although the reason for this effect is not clear, or by introduction of some oversized aggregates into the mix.
- Using polymer-modified or asphalt rubber binders in open-graded mixes may reduce the mix permeability, but it increases acoustic absorption. Using asphalt rubber binder also improves mix resistance to moisture damage/premature failure, raveling, rutting, and reflective cracking.
- Hydrated lime, added in lime slurry form, did not improve the resistance of an open-graded mix to moisture/premature failure, as evaluated by the TSR test or HWTD test. The potential benefit of hydrated lime in OGFC mixes was largely undetected in this laboratory study.
- It was difficult to compact an open-graded asphalt mix to an air-void content level of 15 percent or lower for the gradations included in this study. However, reducing air-void content by 2 or 3 percent from 20 percent can increase mix durability in terms of raveling and reflective cracking without significantly affecting permeability and overall acoustic absorption.

Additional conclusions are presented in the report regarding the inclusion of oversized aggregates in the 4.75-mm NMAS open-graded mix, the effects of aggregate shape on acoustic performance, and other effects of aggregate shape and surface texture identified from producing the same mixes with different aggregate sources. Conclusions are also presented in the report regarding the laboratory performance of the Arizona rubberized OGFC mix with high-binder content, the double-layer porous asphalt mix, and the Georgia 12.5-mm OGFC mix. Finally, conclusions are presented in the report regarding performance evaluation and test procedures, including laboratory permeability testing, acoustic absorption testing, use of the tensile strength ratio (TSR) test for evaluating the moisture sensitivity of OGFC mixes, use of the standard RSST-CH test for open-graded mixes, and use of the British Pendulum Tester (BPT) and Dynamic Friction Tester (DFR) for measuring friction.

Recommendations

Based on this study's findings and conclusions, two series of recommendations are given.

The first set of recommendations provides details for mix design and for including performance-related tests in the Caltrans mix design procedures for open-graded mixes. Mix design recommendations are made regarding aggregate size selection, use of hydrated lime, and binder type selection. Recommendations are made regarding laboratory tests for draindown, optimum binder content selection considering permeability, acoustic absorption, raveling moisture damage, friction, and reflective cracking. It is recommended that the tests be included in a comprehensive framework based on the results of recent work on open-graded mix design by the National Center for Asphalt Technology (NCAT). It is recommended that these recommendations be implemented after completion of additional work on laboratory tests for open-graded mix design currently underway at the UCPRC for Caltrans.

The second set of recommendations is a list of mixes for further evaluation in the field or on HVS test sections:

- Three rubberized or polymer-modified 4.75-mm NMAS mixes (AR475, AR475P, and P475), one Georgia OGFC mix (G125), and two double-layer porous asphalts (DL, and DL with the top mix E8 replaced with mix AR475P) were initially recommended for long-term performance evaluation in field test sections. However, performance evaluations to date in the Netherlands indicate that the double-layer porous asphalt layers ravel faster than single-layer open-graded mixes. Therefore this study recommends comparing the Georgia OGFC mix and the small aggregate size mixes with rubber and polymer binders against current Caltrans mixes produced using the same aggregates in the test sections. Further, it is recommended that additional evaluation of the double-layer porous asphalt be postponed in California for several years until more performance information is available from Europe.
- Mixes with small aggregate sizes and asphalt rubber or polymer-modified binder (e.g., AR475, AR475P, and P475) are recommended for evaluation in HVS test sections for their resistance to reflective cracking.
- Hydrated lime can be added into the above mixes to evaluate its effect on mix durability in the field.
- Control mixes consisting of current Caltrans mix designs should be included in any HVS or field experiments.

CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**Convert From**	**Multiply By**	**Convert To**	**Symbol**
LENGTH				
in.	Inches	25.4	millimeters	mm
ft	Feet	0.305	meters	m
AREA				
in.^{2}	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
VOLUME				
ft^3	cubic feet	0.028	cubic meters	m^3
MASS				
lb	Pounds	0.454	kilograms	kg
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	C
FORCE and PRESSURE or STRESS				
lbf	Poundforce	4.45	newtons	N
lbf/in.^{2}	poundforce/square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**Convert From**	**Multiply By**	**Convert To**	**Symbol**
LENGTH				
mm	Millimeters	0.039	inches	in.
m	Meters	3.28	feet	ft
AREA				
mm^2	square millimeters	0.0016	square inches	in.^{2}
m^2	square meters	10.764	square feet	ft^2
VOLUME				
m^3	cubic meters	35.314	cubic feet	ft^3
MASS				
kg	Kilograms	2.202	pounds	lb
TEMPERATURE (exact degrees)				
C	Celsius	1.8C+32	Fahrenheit	F
FORCE and PRESSURE or STRESS				
N	Newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce/square inch	lbf/in.^{2}

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (revised March 2003).

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LIST OF ABBREVIATIONS USED IN THE TEXT

AIMS	Aggregate imaging system
ABR	Approximate bitumen ratio
ADOT	Arizona Department of Transportation
BPN	British Pendulum Number
BPT	British Pendulum Tester
CTM	Circular Texture Meter
CPX	Close-proximity method
CPB	Controlled pass-by
DLPA	Double-layer porous asphalt
DFT	Dynamic Friction Tester
PEM	European mix design
GDOT	Georgia Department of Transportation
EC	Granular expanded clay
HWTD	Hamburg wheel tracking device
HMA	Hot-mix asphalt
MPD	Mean profile depth
NCAT	National Center for Asphalt Technology
NMAS	Nominal maximum aggregate size
OBSI	Onboard sound intensity
OGFC	Open-graded friction course
OBC	Optimum binder content
PM	Photocatalytic cement mortar
PMAC	Polymer-modified asphalt cement
PFC	Porous friction course
AR	Rubber-modified asphalt binder
SSCR	Slurry seal with crumb rubber
SPB	Statistical pass-by
SMA	Stone mastic asphalt, stone matrix asphalt, or Splitt mastix asphalt
SBS	Styrene-butadiene-styrene
TSR	Tensile strength ratio
TTI	Texas Transportation Institute

1 INTRODUCTION

1.1 Project Background

In the early 2000s, the California Department of Transportation (Caltrans) identified a need for research into the acoustics, friction, durability, and related performance properties of the state highway network's pavement surfaces. In November 2004, the Caltrans Pavement Standards Team (PST) gave its approval to a research project to investigate the performance properties of asphalt surfaces, including the Department's open-graded mixes and select experimental mixes. That investigation was included as Strategic Plan Element (SPE) 4.16 in the Partnered Pavement Research Center (PPRC) contract, and the research had as its objectives evaluation of the mixes' durability and their comparative effectiveness in increasing safety and reducing noise, determination of the pavement characteristics that affect the tire/pavement noise, and evaluation of the correlation between laboratory sound absorption and tire/pavement sound intensity in the field.

PPRC SPE 4.16 included two years of field measurements, and focused on the measurement of material properties and field performance of various asphalt surface mixes currently in use on California highways in a range of climate and traffic-level applications, and on some new materials and thicknesses placed in experimental sections. Mixes included in the partial factorial experiment included in the study are listed below:

- Dense-graded asphalt concrete (DGAC), since renamed *hot-mix asphalt* (HMA)
- Open-graded friction course (OGFC), with conventional and polymer modified binders
- Rubberized hot-mix asphalt—open graded (RHMA-O)
- Rubberized hot-mix asphalt—gap graded (RHMA-G)
- Oregon F-mix, with conventional and rubberized binders

Experimental mixes included in at least one test section in PPRC SPE 4.16 included:

- Rubber-modified asphalt concrete, gap-graded, dry process (RUMAC-GG)
- Gap-graded rubberized asphalt concrete, terminal blend (Type G-MB)
- Dense-graded rubberized asphalt concrete, terminal blend (Type D-MB)
- European gap-graded asphalt concrete (EU-GG)
- Bonded wearing course (BWC)

Statistical analyses were performed to investigate the correlation between mix design variables (aggregate gradation, mix type, binder type), environmental variables (climate and traffic), age, and pavement performance (noise, friction, durability, permeability, and roughness). The final report for PPRC SPE 4.16 *(1)* contains recommended open-graded mix designs to reduce noise and improve durability, and specifies which experimental mixes showed promise over those currently in use. The results have been updated with third, fourth, and fifth years of field measurements of noise, ride quality, macrotexture and permeability as part of PPRC SPE 4.19 *(2)*, 4.27, and 4.29 (reports currently being prepared), respectively.

These studies of field mixes provide the first comprehensive evaluation of the performance of Caltrans standard surface mixes and experimental mixes. However, as with most field studies they were constrained by the availability of asphalt surface mix types in the field as well as some uncontrollable traffic and climate factors specific to the physical locations of the existing field mixes. Therefore, complete full or balanced factorial design for statistical analysis was impossible. For example, without historical project records showing binder types used during construction, it was impossible to distinguish in the field between mixes with conventional asphalt binder and those with polymer-modified binder. In another example of this, nominal maximum aggregate size (NMAS) and thickness effects could not be fully evaluated, as these variables have different specifications for different mix types. Specifically, current Caltrans open-graded mixes have NMAS of 9.5 mm and 12.5 mm while those of dense- and gap-graded mixes have NMAS of 12.5 mm and 19 mm. Furthermore, open-graded mixes are placed in thin layers while RAC-G and DGAC mixes are usually placed in thicker lifts, with RAC-G mixes usually placed in thicknesses that are approximately half those of DGAC mixes. Therefore, the possibilities for considering NMAS and thickness effects in the field section experiment were constrained by the mix types in place in the field at the time the experiment was performed.

The laboratory experiment design of this project (PPRC SPE 4.20) followed the results of the field study, but permitted a factorial design that considered the variables that could not be considered in the field experiment. The laboratory experiment covered a wider variety of material types than was possible in the field experiment. In addition, the laboratory experiment included new mix designs and mix types based on the field research results and on the experience of other agencies.

This laboratory study was intended to screen the new mix types by comparing them with the mixes whose field performance was measured, and it was undertaken as a first step before the construction of field test sections and, if warranted, Heavy Vehicle Simulator (HVS) test sections for further verification and calibration.

1.2 Project Purpose and Objectives

The purpose of this study was to evaluate the performance, particularly the noise and durability properties, of a variety of asphalt surface mixes, and to formulate a recommended set of mixes for future test sections. The study was conducted entirely in the laboratory.

The objectives of this project are to:

1. To gather and summarize the information that had become available since a 2004 UCPRC literature survey on this subject regarding types, design procedures, test methods, and performance of asphalt surface mixes from other states or countries, and to identify new mixes to evaluate.
2. To evaluate the properties and performance of selected mixes through laboratory testing and to determine a set of best asphalt surface mixes in terms of overall performance (i.e., sound absorption, durability, permeability, and friction).
3. To recommend improvements or innovations for the design, testing, and evaluation methods used with asphalt surface mixes.
4. To make recommendations for field test sections based on the laboratory test results and for HVS test sections, if warranted by lab test results.

1.3 Organization of This Report

Chapter 2 of this report presents a literature review of current practice, and recent and ongoing research in other states and countries on asphalt surface mixes. The report also presents selection of materials and test methods (Chapter 3), experimental design (Chapter 4), and test results and analysis (Chapter 5), followed by conclusions (Chapter 6) and recommendations for noise-reducing mix designs and candidate mixes for field and possible HVS test sections (Chapter 7).

2 LITERATURE REVIEW

2.1 Introduction

A literature survey was performed to evaluate current practice, and recently completed research in other states and countries on asphalt surface mixes that are durable, noise-reducing, and safe. The focus of the literature survey was on research reported since the previous UCPRC literature survey on this subject performed in 2004 *(1, 3)*. The main objective of the literature survey was to investigate:

- Types of asphalt surface mixes used in the United States and in other countries that appear to offer superior performance with respect to noise, permeability, and durability in climate regions similar to those in California;
- Design philosophies and methods for asphalt surface mixes in use including information about air-void content, layer thickness, and layer structure;
- Laboratory test methods and criteria for durability, permeability, friction, and acoustical properties;
- Construction techniques, including mixing and compaction procedures and special construction equipment; and
- Performance of asphalt surface mixes, including identification of any published performance data with respect to long-term noise, durability, friction, and permeability. The focus was on relating that information to California climates and traffic and on identifying potential candidate mixes from other states or countries that should be further evaluated in California.

Note: Many of the studies cited in the literature survey covered both asphalt and concrete surfaces, but only the results pertaining to asphalt surface materials are discussed in this report. It is common that a material has different names in different states or countries. The original terms used by the cited reports/papers are used in this literature survey, and not “translated” into their California equivalents.

2.2 Field Measurement of Traffic Noise

A number of studies investigating the noise characteristics of different pavement surface materials were reported in the literature. Since the measurement technologies and test conditions varied from one study to another, direct comparisons of measured noise levels of different materials across these studies were not feasible. Therefore, the noise reduction performance of these materials is summarized in terms of the comparisons within each study.

Road noise measurements reviewed in the literature survey used one or more of the following four methods:

- Statistical pass-by (SPB),
- Controlled pass-by (CPB),
- Close-proximity method (CPX),
- Onboard sound intensity (OBSI).

Detailed technical descriptions of these noise measurement methods, including their advantages and drawbacks compared to other methods, are presented in each report or paper reviewed and are not included in this report.

2.2.1 Dense-Graded HMA and SMA on NCAT Track

The National Center for Asphalt Technology (NCAT) performed a road noise study on the NCAT test track *(4)*. The NCAT test track consisted of 46 sections with dense-graded hot-mix asphalt (HMA) and stone matrix asphalt (SMA). Road noise measurement was performed using the close-proximity method (CPX) at a speed of 72 km/h (45 mph). Additionally, the pavement surface texture of these sections was measured with the Circular Texture Meter (CTM), and aggregate gradation and air voids of the mixes were also measured. The study's conclusions included:

- Recorded noise levels ranged from 91.3 dB (A-weighted) to 94.8 dB(A) for dense-graded HMAs, and from 96.3 dB(A) to 100.6 dB(A) for SMA mixes.
- No apparent correlation was found between HMA-surfaced pavement noise levels and the Mean Particle Depth values of these pavements (note that this parameter is typically referred to as Mean Profile Depth in other references), or between HMA pavement noise levels and the measured air voids.
- Good correlation was found between HMA surface noise levels and the fineness moduli measured for the aggregate gradations in these HMA mixes, indicating smaller aggregate particle sizes can reduce noise levels.

2.2.1 2003 Colorado Study by NCAT

In October 2003, NCAT performed a road noise study on 18 selected highway sections for the Colorado Department of Transportation. Twelve of these sections were asphalt surfaced, including SMA, Superpave-designed HMA, open-graded friction course (OGFC), and Nova Chip. Noise measurement was performed using the CPX method at a speed of 96 km/h (60 mph). The average measured noise levels were 95.3 dB(A), 95.7 dB(A), 96.5 dB(A), 97.0 dB(A), and 101.0 dB(A) for OGFC, HMA with Superpave grading SX, SMA, Nova Chip, and HMA with Superpave Grading S, respectively. The sections of HMA mix with Superpave grading S, which had the highest noise levels among the sections tested, were significantly older than the others. However, whether the noise level difference between these and the other test sections was due to pavement age could not be determined with the data provided. *(5)*

2.2.3 2005 Colorado Study by NCAT

Following its 2003 study, the NCAT team performed road noise measurement with the CPX method on Colorado DOT highways in 2004 and 2005. Nineteen sections (13 asphalt and 6 concrete [PCC]) were selected, only partly overlapping with the 2003 study. The report concluded that noise levels for the asphalt-surfaced pavements (including OGFC, SMA, Nova Chip, Superpave dense-graded) generally increased during this three-year period, but noise levels on a number of sections were observed to have significantly decreased. The small sample size and large measurement variation made the drawing of definitive conclusions regarding the evolution of noise performance of different pavement surface materials very difficult. *(6)*

2.2.4 Pooled Results of NCAT Studies in Ten States

As of 2005, NCAT had tested 244 pavement sections in 10 states, which included 210 sections surfaced with various asphalt materials. The pooled data indicated that the average noise levels were 93 dB(A), 97 dB(A), 97 dB(A), and 96 dB(A) for the fine open-graded mixes, coarse open-graded mixes, dense-graded mixes, and SMA mixes, respectively. Open-graded hot-mix asphalt (HMA) mixes with small aggregate sizes appeared to provide superior noise reduction performance compared to other types of the asphalt surfaces. Due to the "snapshot" nature of these studies, no definitive evaluation of the evolution of noise reduction performance with respect to time could be made. *(4, 5, 6, 7)*

(Note: The NCAT reports mostly presented data and generally did not have clear conclusions. The above conclusions were mostly based on interpretation of their results, and therefore might be different from the conclusions in these reports.)

2.2.5 WSDOT Study on an I-5 Section

The Washington State Department of Transportation built an experimental section on Interstate 5 in 2006 to investigate the potential benefits of OGFC in reducing road noise. Two OGFC sections were built with a rubber-modified asphalt binder (OGFC-AR) and a styrene-butadiene-styrene–polymer asphalt binder (OGFC-SBS), respectively, with a control section with 1/2 inch maximum aggregate size dense-graded HMA constructed nearby. Void ratios of the OGFC mixes were not reported. Noise levels were measured with the OBSI method immediately after construction, and measurement continued for a year on a monthly basis. The newly constructed OGFC-AR and OGFC-SBS sections were found to be 2.8 and 3.8 dB(A) quieter than the control sections, respectively. One year later, the differences dropped to 1.5 and 3.3 dB(A), respectively. However, noise measured between the wheelpaths was found to remain largely unchanged in the first year after construction, indicating that traffic, especially studded tire wear had a significant negative effect on the noise-reduction performance of OGFC mixes. The sections paved with OGFC mixes were also observed to have less splash and spray than the control sections, and the difference in rut depth between these sections was small *(8).*

2.2.6 I-80 Davis OGAC Pavement Noise Study

A long-term traffic noise monitoring program on an open-graded asphalt concrete (OGAC) overlay was conducted by the Illingworth & Rodkin, Inc., for Caltrans on Interstate 80 near Davis. The road was repaved in 1998, and the evolution of its performance in noise reduction has been monitored continuously (three times per year) since then. The construction consisted of removal of the existing AC and placement of a new dense-graded (DGAC) that was 60 mm (0.20 ft) thick, followed by an open-graded (OGAC) overlay that was 25 mm (0.08 ft) thick. No new control DGAC sections were placed. Traffic noise was measured with the statistical pass-by (SPB) method at different distances from the roadway, as well as with the OBSI method. The noise level measured on the original road was used as the baseline for comparison. It was found that the OGAC surface provided about 6 dB(A) of noise reduction during the first four years and then a steady 4.5 to 5.0 dB(A) reduction over the last three years. Since a comparison between performance of the OGAC overlay and a control DGAC surface of the same age under similar conditions was not feasible, it is not possible to quantify how much of the noise was from the improved smoothness and how much from the noise absorption of the OGAC. The data did show a minor deterioration of the noise reduction performance of the OGAC *(9).*

2.2.7 A 2003 Study in Indiana

This study compared early performance of three pavement surface types including porous friction course (PFC), SMA, and conventional DGAC. All three test sections were constructed in summer 2003, and similar aggregate and asphalt sources were used for the three materials. The maximum aggregate sizes for all three mixes were 12.5 mm (1/2 in.). The void ratios were 23.1 percent, 4.0 percent, and 4.0 percent for the PFC, SMA, and DGAC, respectively, as indicated in the mix design. Road noise was measured by both the CPX method and the controlled pass-by (CPB) method. The noise levels measured on the PFC surface were 4 to 6 dB(A) lower than those of the other two surface types. The PFC surface showed the best skid resistance among the three mixes, and the DGAC the worst. The PFC surface also showed superior splash-reducing and spray–reducing performance (by subjective observation) than the SMA surface. The PFC mixes were subjected to the frequency sweep test in the Superpave Shear tester at 40°C. The PFC mix showed low (188 MPa at 10 Hz and 97 MPa at 1 Hz on average) and variable shear modulus. Shear moduli of the other mix types were not measured. How the low stiffness would affect the mechanical and acoustic performance of the road is unknown since the study did not include follow-up monitoring on the sections *(10).*

2.2.8 The Japanese CERI for Cold Region

The study consisted of a five-year field monitoring program on five of Japan’s national highways. The results showed that the benefits of both permeability and noise reduction of open-graded porous asphalt diminished in two years at sites with severe winter conditions and snow removal activities. Noise levels measured with OBSI-type equipment (detailed configurations different from the OBSI equipment developed and used in California) increased from 89 dB to 96 dB after the initial construction. Porous mixes also showed slightly higher rut depths: 12 mm compared to 10 mm for dense-graded mixes *(11).*

2.2.9 *Trial of Different Materials on an Urban Italian Street*

Santagata et al. *(12)* reported a comparison study of the noise-reducing performance of different paving materials applied on a busy urban street. Five materials, namely (1) dense-graded HMA (SBS modified binder) with the addition of granular expanded clay (EC), (2) slurry seal with crumb rubber (SSCR), (3) splitt mastix asphalt (SMA, equivalent to stone matrix asphalt), (4) OGFC, and (5) OGFC partially filled with photocatalytic cement mortar (PM), were used as an overlay on a street. SPB noise measurement was performed. Only the OGFC mix showed significant noise reduction (4 to 5 dB[A]) compared to the original road surface with dense-graded asphalt concrete. However, this benefit diminished after eighteen months of service and the road showed some signs of raveling. The air-void content of the OGFC mix was 19.9 percent, the binder was SBS modified, and the maximum aggregate size was 16 mm *(12)*.

2.3 Characteristics of Open-Graded Mixes Other Than Noise

2.3.1 *WSDOT Experience*

A WSDOT in-house report dated 1995 was included as an appendix in a 2008 WSDOT report *(8)*. It summarized WSDOT's early experience with the "open-graded asphalt seal coat" (Class D asphalt overlay). This type of material was basically a chip seal aggregate mixed with a relatively high asphalt content. It was applied as an overlay in the 1970s with a thickness of 18 mm (0.059 ft) regardless of the traffic conditions on pavement that was structurally sound but showing surface distresses. This type of mix was significantly different from the open-graded asphalt mixes currently used in paving practice, and noise reduction was not a consideration in the time it was applied. The main failure modes were raveling and delamination, and the service life was shorter than the design life of eight years in areas with high traffic volume. The failure was also accelerated by the use of studded tires by vehicles in Washington. The benefits in reducing spray were observed to last only two years. Certain regions reported satisfactory performance of the Class D mixes, implying that construction quality and ambient environment might be important factors in determining the durability of this type of mix.

2.3.2 *Oregon Experience*

Huddleston et al. *(13)* summarized the Oregon DOT's experience with open-graded asphalt concrete mixes. As of 1991, Oregon had approximately 400 km centerline highways paved with OGAC that were mostly constructed in the 1980s. The maximum aggregate size of these mixes was 19 mm to 25 mm (3/4 to 1 in.), and the layer thickness was 38 mm to 50 mm (0.12 to 0.16 ft). Typical void ratios after five to six years of service were from 10 to 13 percent. It was a common practice to add 1 percent portland cement as a mineral filler to stiffen the mix during transportation and laydown. Ten OGAC sections and seven dense-graded asphalt concrete (DGAC) sections were surveyed in this study, and the OGAC sections were found to have performed satisfactorily. The OGAC pavement surfaces were found to have lower hydroplaning potential and less water splash and spray than dense-graded asphalt concrete surfaces do. Road noise was measured with a rather ad-hoc method, and no significant difference was identified between OGAC and DGAC sections in noise levels. This might be partially attributed to the large aggregate sizes used and the relatively low void ratio *(13)*.

Another more recent study was performed in Oregon to investigate the effects of de-icer application on the skid resistance of OGAC pavement surfaces. The study concluded that the application of de-icer does not reduce surface skid resistance significantly. The same report also mentioned that approximately 21 percent of all highways in the state of Oregon are paved with OGAC *(14)*.

A UCPRC researcher's first-hand qualitative observations of these mixes on Interstate 5 between Eugene and Ashland between 2006 and 2008 indicated that many sections are now nearly as noisy as transversely tined PCC, with conversation at less than shouting volume nearly impossible within a vehicle.

2.4 Potential Improvement to Mix/Structure Design and Construction

A number of measures to improve the current practice for design and construction of quiet and permeable pavement were proposed in the literature.

A study by the University of Florida proposed use of a thick polymer-modified tack coat to bond open-graded friction courses. The study found that introduction of this thick tack coat could increase rutting and cracking resistance without adverse changes to friction and noise characteristics *(15)*.

The Japanese CERI study proposed increasing the void ratios of open-graded asphalt concrete from 17 percent to 20 percent to 23 percent to retard the permeability and noise absorption capability loss due to clogging. A "high-durability" modified binder was used for the high void ratio mixes. Monitoring results on trial sections showed that the high void ratio mixes can maintain permeability and noise-reduction capability longer than conventional open-graded mixes. However, no result beyond the initial eight months of monitoring was available *(16)*.

2.5 European Experience

In 2004, a quiet pavement scan team was organized by the Federal Highway Administration and visited a number of European countries including Denmark, France, Italy, the Netherlands, and the United Kingdom to learn of these countries' experience with quiet pavements *(17, 18)*. Subjects scanned by the team included road noise policy, pavement design, noise analysis, construction, maintenance, and related research. Findings relevant to this UCPRC study include:

- The noise reduction benefits provided by porous asphalt mixes usually last only a few years primarily due to clogging, which is highly dependent on environmental and traffic conditions. However, the materials can withstand traffic for a number of additional years after the noise reduction benefits are lost. A discussion of the literature regarding the clogging phenomenon is included in Reference *(1)*, and it has been recognized through the results presented there and through recent collaboration with the Danish Road Institute that differences in rainfall patterns between California (six to eight months with no rain) and northern Europe (year-round rainfall) probably result in different rates of clogging between the two regions.

- The main failure mode of porous asphalt mixes is raveling, which can be accelerated by vehicle braking, accelerating, and turning, as well as hot temperature.
- Some countries use pressured water and vacuuming to clean clogging in porous pavement materials, but the effectiveness of such methods is under debate.
- Maintenance of porous pavements is a concern where severe winter weather is common. The cost of de-icing porous pavements could be significantly higher than that for de-icing conventional pavement surfaces.
- The scanning tour identified three types of quiet pavement surfaces that have promise for providing long-lasting noise-reduction benefits: (1) thin-surfaced, negatively textured, gap-graded asphalt mixes, (2) single- and double-layer highly porous asphalt mixes, and (3) exposed aggregate concrete pavements. The first two pavement types were positively identified as providing noise benefits compared with current open-graded mixes, and much of their report focused on design, construction, maintenance and noise results for those pavement types. Regarding the third type, exposed aggregate concrete (EAC) pavements, the scanning tour stated that this type of pavement "should be researched further and considered when constructing new concrete pavements." The only results shown in the scanning tour report *(17)* were from the UK, and stated that EAC could reduce noise by about 3 dBA compared with their typical concrete surface, but that porous asphalt concrete was found to be more cost-effective in the UK on both concrete and asphalt pavements. The EAC used in the UK had aggregate sizes between 6 and 10 mm (0.24 and 0.39 in.) or between 8 and 14 mm (0.32 and 0.55 in.), which are smaller than maximum size aggregates typically used in concrete mixes in California. Most of the UK comparisons for EAC were with a noisy asphalt mix used there called Hot Rolled Asphalt, which has a great deal of positive texture and is noisy. Research sections with EAC in the Netherlands with similar aggregate gradations to those used in the UK indicated that the EAC was louder for passenger cars but quieter for trucks, compared with dense-graded asphalt. Whether the promise of these surfaces identified by the tour holds true for their use in California remains to be determined.

More recent field evaluations of durability have been conducted in the Netherlands regarding porous asphalt concrete (PAC). These studies indicate that:

- The average lifetime of single-layer porous asphalt concrete (PAC) is about 11 years, while double-layer porous asphalt concrete has a lifetime of about 8 years. The problem with these very open wearing courses is their relatively short lifetime because of raveling *(19)*.
- The lifetime of PAC in the Netherlands, typically controlled by raveling, shows a large variation. It is believed that the construction process controls the variability. A study to determine to what extent the development of raveling is determined by the composition of the mixture as laid and factors like traffic and climate indicated that bitumen contents lower than 4 percent should not be accepted and siliceous river gravel should not be used. It was also found that although the double-layer PAC offers a better reduction in traffic noise than the conventional single-layer PAC, problems may arise with the permeability because of a low void content in the interface between the top and bottom layers *(20)*.

2.6 Correlation of Acoustical Impedance, Permeability, and Macrotexture with On-Board Sound Intensity

The correlation of acoustical impedance, permeability, and macrotexture, and on-board sound intensity (OBSI) was investigated as part of PPRC SPE 4.16 *(1, 21, 22)*. These three laboratory test parameters were used in this study as indicators of the noise reduction potential in the field for different mixes.

Tire/pavement noise generation and sound absorption are different phenomena, and tire/pavement noise measured by OBSI should not be affected by the sound absorption properties of the pavement surface. However, both are affected by the permeability of the pavement surface: tire/pavement noise primarily by reduction of the air pumping mechanism, and sound absorption by the passage of sound waves into the surface and the resulting attenuation and scattering of the sound energy.

In the 4.16 study, the purpose of comparing tire/pavement noise (sound intensity) in the field and sound absorption in the laboratory was to determine if there were statistical correlations that would indicate whether sound absorption could be used to inexpensively screen mixes in the laboratory without having to build full-scale test sections and subject them to field measurements. It was found that the noise levels of dense- and gap-graded mixes decrease with increasing absorption, although no correlation was found between the overall A-weighted sound intensity measured in the field and absorption measured in the laboratory for open-graded mixes. However, the extent of correlation between sound intensity (noise) measured in the field and laboratory absorption values was found to depend on frequency.

Noise levels around 500 Hz are governed by tire vibrations; therefore, absorption has no effect on the noise levels for any mix type. At frequencies above 630 Hz, absorption reduces the noise levels caused by air pumping for dense- and gap-graded mixes, and there are clear trends relating noise to absorption.

Tire vibrations may cause significant noise levels for open-graded mixes with high macrotexture (as represented by mean profile depth [MPD]) values at lower frequencies (less than 1,000 Hz), and there is no trend between noise and absorption. The noise-reducing effect of absorption begins to be seen at 1,000 Hz for open-graded mixes, if macrotexture is also considered, as shown in Figure 2.1 from References *(1)*, *(21)*, and *(22)*. The noise-reducing effects of absorption can be clearly seen at frequencies above 1,000 Hz for open-graded mixes, as shown in Figure 2.2 from References *(1)*, *(2)* and *(22)* for 1,600 Hz. Air-pumping noise governs noise generation at frequencies above 1,000 Hz, confirming the earlier findings of other researchers, as increasing absorption is correlated with noise levels regardless of the macrotexture values. This trend is stronger for higher frequencies.

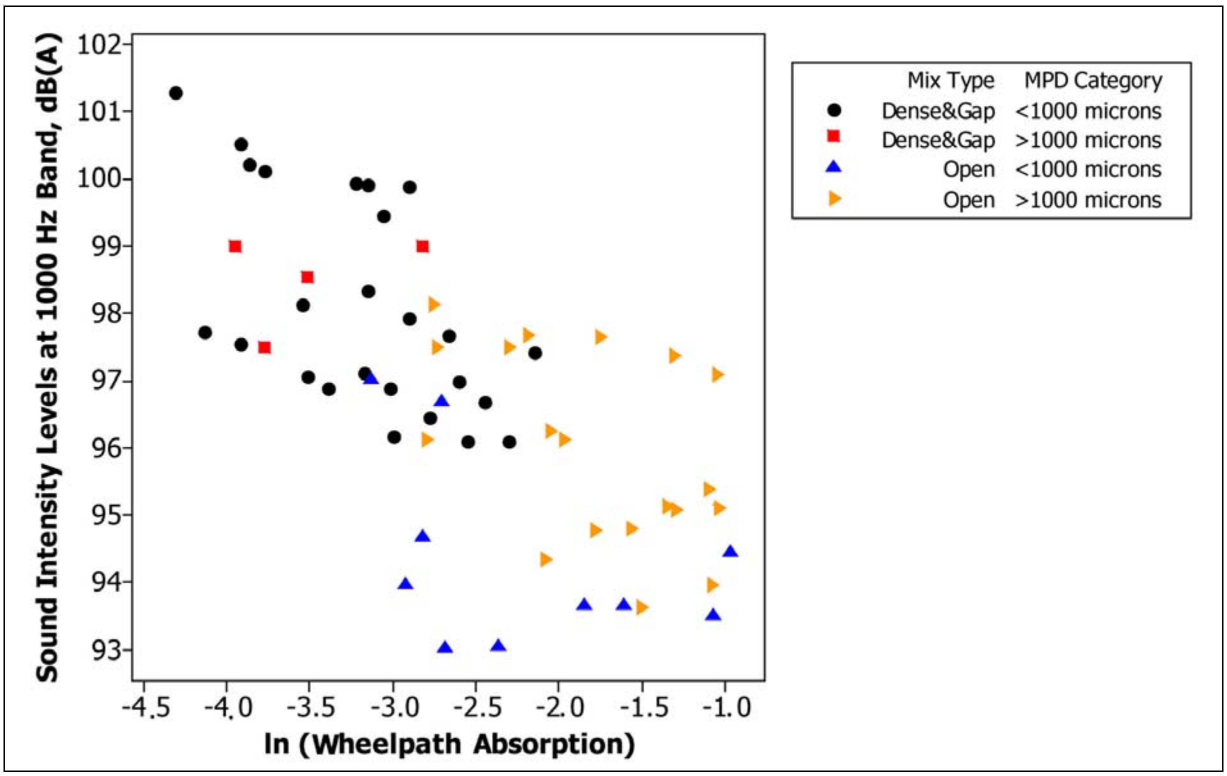


Figure 2.1: Sound intensity levels at the 1,000 Hz band versus the absorption values for different mix types and different macrotexture values.

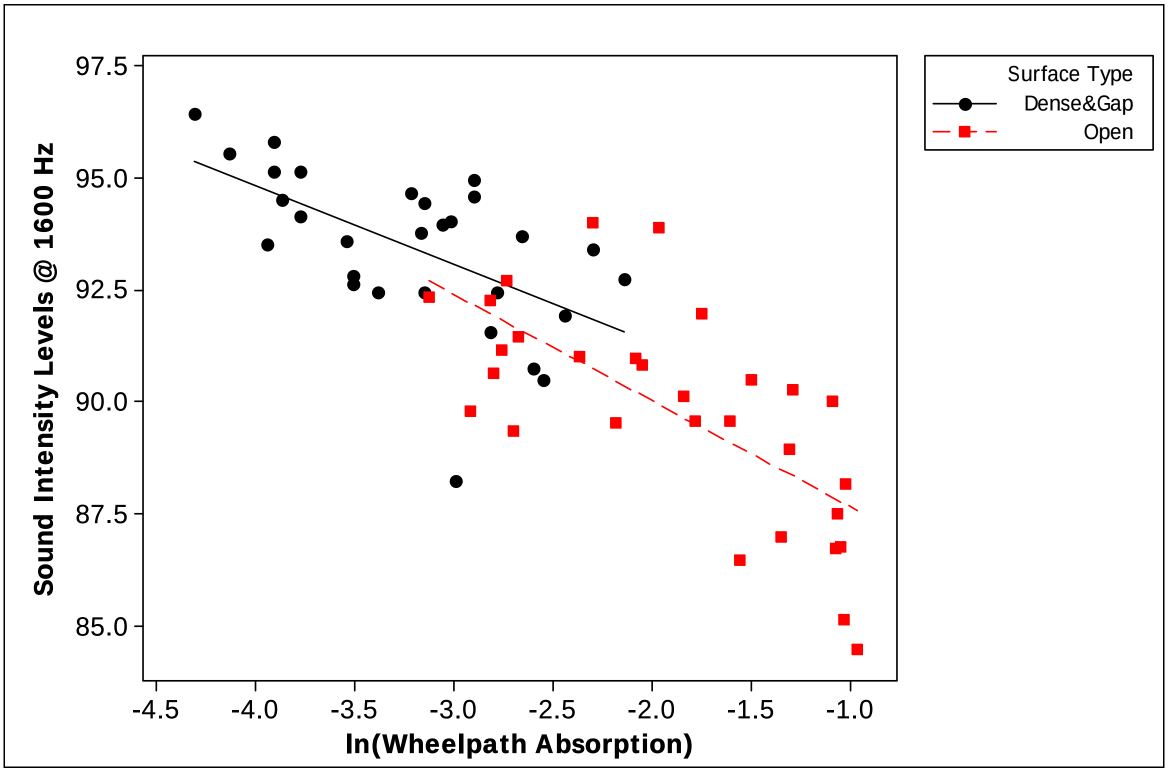


Figure 2.2: Sound intensity levels at the 1,600 Hz band versus the absorption values for different mix types and different macrotexture values.

The strong statistical correlation of absorption with OBSI at frequencies above 1,000 Hz exists because the mechanisms of both absorption and noise are related to the permeability of the pavement surface and the high connectivity of air-voids below the surface.

The correlation of permeability for different categories of MPD and mix type with overall (all frequencies combined) A-weighted OBSI (all frequencies) from field measurements in the wheelpath can be seen in Figure 2.3 *(1)*. A regression model (Equation 18 in *[1])* for predicting overall A-weighted OBSI with log of permeability, MPD, mix type (open-graded versus dense-and gap-graded), and the presence of raveling had an R-squared correlation coefficient of 0.71, with all variables significant at the 0.5% confidence level (p-values less than 0.005).

The correlation of MPD and OBSI at the 500-Hz frequency from field measurements in the wheelpath can be seen in Figure 2.4 *(1)*.

These statistical correlations and understanding of the mechanisms indicate that absorption and permeability can be used as surrogates in the laboratory for estimating field noise levels at high frequencies for different mixes, while macrotexture can be used as a surrogate at low frequencies. Although there is a large variance in the correlations of these three laboratory parameters with OBSI, there are trends that can be seen.

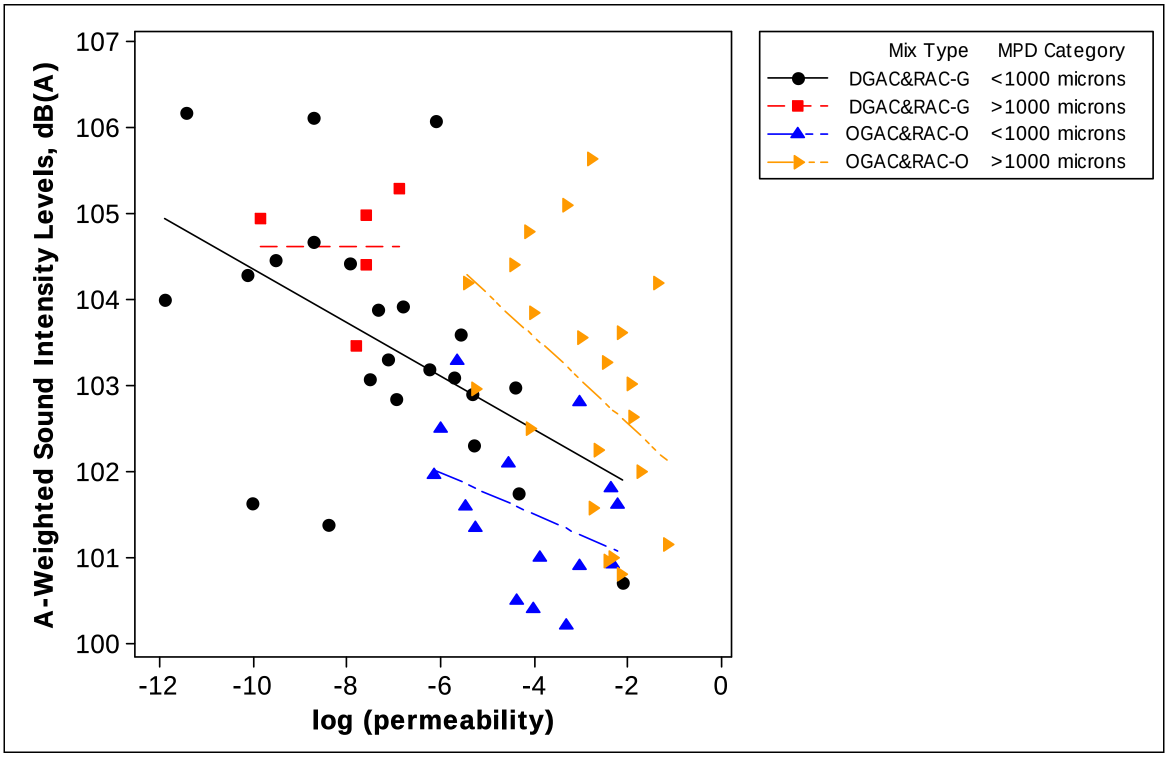


Figure 2.3: Scatter plot of A-weighted sound intensity levels versus log (permeability) for different mix types and for different MPD categories.

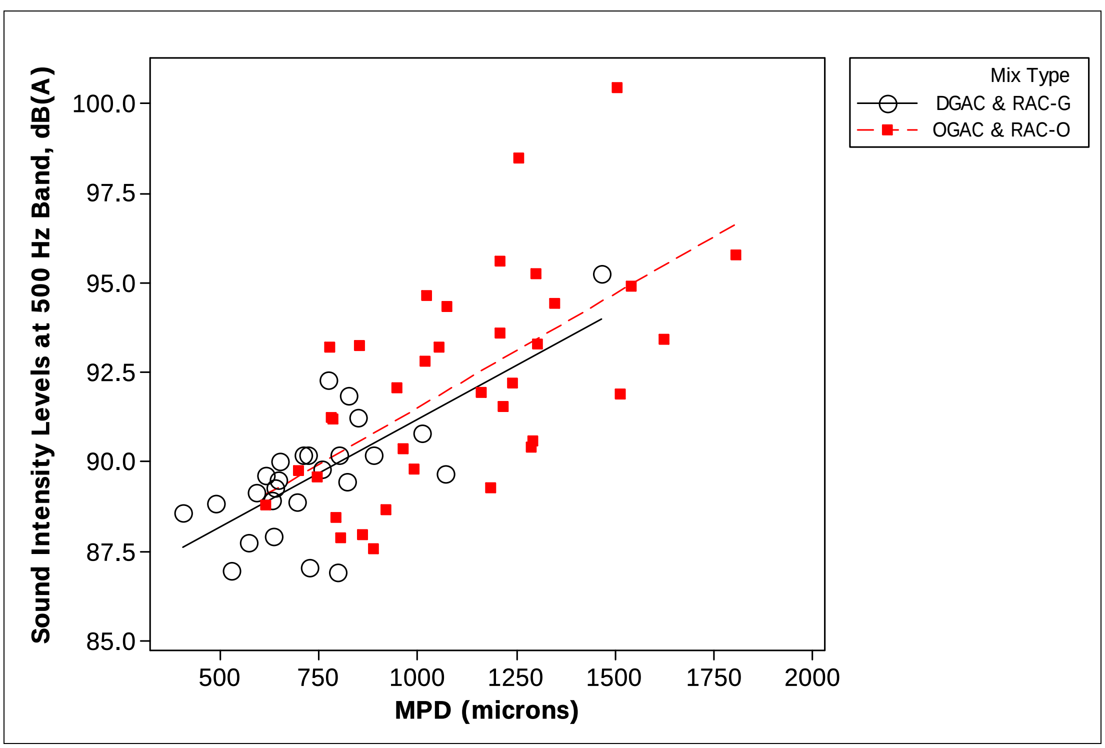


Figure 2.4: 500-Hz band sound intensity levels versus MPD.

2.7 Summary

Significant findings from this literature survey include:

- Almost all studies found that porous asphalt concrete pavement surfaces provide significant noise reduction benefits in addition to reduced splash and improved skid resistance. These benefits tend to diminish in a few years as the voids in the mixes become clogged and as raveling increased, with the time to clogging and increased noise ranging from a little more than a year to many years, depending on the mix and the traffic and environmental conditions.
- Porous mixes with smaller aggregate sizes and greater thickness tend to provide more significant noise reduction.
- The durability of porous asphalt pavement materials is dependent on a number of factors, including mix design (certain modified binders were found to improve raveling resistance), construction quality, traffic, and the ambient environment. A universal solution is not realistic, and different types of mixes might be suitable for different locations.
- The use and research of double-layered, gap-graded asphalt mixes was rare in the U.S. Some European countries have found that this type of mix/structure could potentially solve the clogging problem. Research on this topic is needed.
- Acoustical absorption, permeability, macrotexture (represented by mean profile depth [MPD]), and mix gradation can be used in the laboratory to provide an indication of field tire/pavement noise levels.

3 SELECTION OF TESTS AND MIXES

This study's main purpose was to determine a set of the best asphalt surface mixes in terms of overall performance. After a series of appropriate laboratory tests for evaluating the desired aspects of pavement surface performance were identified, the testing was either carried out by the University of California Pavement Research Center (UCPRC) or contracted out to a private company or other institution. Most of the asphalt mixes tested in this study were developed through a series of experiments that will be detailed in Chapter 4. For verification and comparison with current Caltrans mixes, the study also included laboratory testing on a selection of asphalt mixes used elsewhere in the world that had shown promising performance either in the field or in the laboratory.

3.1 Selection of Tests

The list of tests conducted on each asphalt mix is shown in Table 3.1. Through this study, the UCPRC obtained the capability to perform permeability and durability (raveling, stripping, and rutting) tests on asphalt surface mixes in the laboratory. Except the tests listed in Table 3.1, two routine asphalt mix tests were performed on all mixes for air-void content calculation: the CoreLok method following AASHTO T 331 (to measure bulk specific gravity) and the Rice method following AASHTO T 209 (to measure maximum theoretical specific gravity).

Table 3.1: Tests Included in the Experimental Design

Property		Test	Note
Durability	Raveling	Cantabro test on unaged/aged specimens (ASTM D 7064 Appendix X2)	Aging is achieved through 7-day conditioning in 60ºC oven
	Moisture sensitivity	Indirect tensile strength ratio (TSR) test (ASTM D 7064) and Hamburg wheel tracking device (HWTD) test	A fixed vacuum pressure level and duration instead of a specified saturation level were specified for TSR specimens
	Resistance to reflective cracking	TxDOT Overlay Test (Tex-248-F)	Specimens were sent to Texas Transportation Institute (TTI) for testing
	Rutting	Repeated simple shear test (RSST-CH, AASHTO T 320)	Each mix was tested at two stress levels and two temperatures
Acoustic absorption		Impedance tube method (ASTM E-1050-98)	Test was done at Wilson, Ihrig & Assoc., Inc.
Friction	Microtexture	British Pendulum Tester (BPT) (BS 7976)	Tests were done on slab specimens (640 mm length by 571 mm width) compacted by a rolling wheel compactor
		Dynamic Friction Tester (DFT) (ASTM E-1911)	
	Macrotexture	A laser texture scanner from Ames Engineering	
Permeability		Falling head laboratory permeameter (ASTM PS129) and NCAT field permeameter	100-mm diameter specimens for laboratory permeameter

3.2 Selection of Mixes

The asphalt mixes included in this study were determined through two approaches: those designed in this study in a series of experiments with various research objectives, and those selected from the literature for performance verification and comparison with the mixes designed in the study. The design of some asphalt mixes was based on the findings from the field research project PPRC SPE 4.16 by Ongel et al *(1),* and the subsequent years of field testing on the same sections.

Based on the above findings from the field studies, dense-graded or gap-graded mixes and open-graded "F-mixes" were not included in this study as candidates for further study. For OGFC mixes, the following mix design factors, which were significant in affecting the pavement surface performance in the 4.16 project, were included in this laboratory experiment:

- Nominal maximum aggregate size (NMAS), with smaller NMAS minimizing macrotexture by potentially decreasing the initial macrotexture and by minimizing an increase in macrotexture under traffic by improved resistance to raveling;
- Aggregate gradation, with open-gradations providing high permeability, combined with smaller aggregate size open-gradations to increase the resistance to surface distresses (durability);
- Binder type (with or without modifiers and recycled tire rubber [meeting RAC or MB specifications]), with modified or rubberized binders potentially improving durability;
- Binder content, with higher binder contents potentially improving durability, while having the undesired effect of reducing permeability; and
- Fillers to allow higher binder contents by preventing draindown.

By adjusting the values of these factors, new mix design candidates were developed. Some options considered in the designs include:

- Use of different aggregate gradations, including different NMAS, for open-graded asphalt concrete in combination with different binders,
- Use of different PG binder grades than those specified for OGFC mixes by Caltrans,
- Use of binder contents in the rubberized open-graded asphalt concrete (RAC-O) greater than those found using the current Caltrans binder content selection method for these mixes, with increases dependent on aggregate gradation and source.

Some prospective asphalt mixes that have shown good performance in other states or countries include:

- Georgia OGFC mix,
- Arizona rubberized open-graded asphalt mix with high binder content,
- European double-layer porous asphalt (DLPA) mix, and
- Danish SMA mixes with small NMAS

The reasons these were selected are summarized below.

The Georgia Department of Transportation (GDOT) developed its modified OGFC in the early 1990s and has used it extensively statewide since then. This mix is composed of aggregate, polymer-modified asphalt cement (PMAC), stabilizing fibers, and hydrated lime. GDOT also adopted a porous European mix design (PEM), which is coarser and more permeable than the modified OGFC *(23)*. Currently Georgia places OGFCs or PEMs as the wearing course on all their interstate pavements because their open-graded pavements have shown good performance history in terms of noise reduction, permeability, durability, and smoothness *(24)*.

The Arizona Department of Transportation (ADOT) has been using rubberized open-graded asphalt concrete and rubberized asphalt concrete open-graded high binder extensively as overlays for existing PCC or AC pavements. The Arizona open-graded mixes typically contain higher binder contents than California open-graded mixes. In this experiment, the Arizona mix had a binder content more than 50 percent greater than that of a Caltrans mix with conventional binder and the same maximum aggregate size and source, and 30 percent greater than the same Caltrans mix with rubberized asphalt binder. The high-binder rubberized open-graded asphalt mix has performed well in Arizona *(25)*.

Double-layer porous asphalt (DLPA) has been used in European countries to reduce clogging potential. It consists of a coarser, underlying porous layer and a finer porous surface layer, which can minimize clogging through the "sieve effect" of the finer upper layer and the higher water discharge capacity of the bottom layer. Field trials have shown that the DLPA has greater noise reduction potential for all traffic speeds *(26)*.

Stone mastic asphalt (SMA) concepts have been used in Europe to solve the clogging issue that often occurs in OGFC. The idea is to use thin surface layers with fewer air voids which might have a slightly lower noise-reducing capability than double-layer porous asphalt (DLPA), but better durability, so the long-term acoustical benefit will be positive *(27)*. These types of mixes use small maximum aggregate size (4, 6, and 8 mm), high air-voids, a small proportion of oversized aggregates, and aggregates with as cubical a shape as possible (as opposed to flaky or rounded) to achieve an even, smooth, and open surface. In the last few years, mix design of noise-reducing pavements in Denmark has changed toward SMA with the smallest possible maximum aggregate size without endangering stability and friction of the mix. A series of small maximum aggregate size SMA pavements have been optimized and tested in full scale on urban roads. It was found that the tire/pavement noise level could be reduced by more than 3 dB(A) compared to dense-graded HMA for SMA with 4 mm or 6 mm maximum aggregate size and small portions of oversized aggregates when compared to a standard DGAC pavement *(28)*.

4 EXPERIMENTAL DESIGN AND MIX DESIGNS

4.1 Experimental Design

Experiments were designed to include the effects of aggregate gradation, thickness, binder type, binder content, additives (fiber filler and hydrated lime), and layer structure (single and double layer). Given the large number of variables included in the study, a full factorial experimental design was not feasible. Instead, partial factorial and small-scale experiments were designed to achieve each of the specific research objectives.

4.1.1 Overview of Experiments

Five main experiments were designed to achieve the following research goals:

1. Determine the effect of nominal maximum aggregate size (NMAS) on noise reduction and durability,
2. Determine the effect of binder type and additives on noise reduction and durability,
3. Determine the effect of fineness modulus and air-void content on noise reduction and durability,
4. Determine the effect of aggregate shape on noise reduction and durability,
5. Compare the noise and durability performance of prospective asphalt surface mixes from other states or countries.

A sixth preliminary experiment determined appropriate laboratory compaction procedures.

The first experiment included four open-graded asphalt mixes with different nominal maximum aggregate sizes and corresponding gradation curves. The aggregate gradations with different NMASs, shown in Figure 4.1, selected for the experiment were determined from one European fine (4.75-mm) OGFC gradation *(18)*, California Department of Transportation (Caltrans) 9.5-mm and 12.5-mm OGFC gradation specifications, and Indiana DOT 19-mm OGFC gradation specifications. One Superpave performance-graded (PG) asphalt binder, PG 64-16, was used for all mixes. This binder is specified in *California Highway Design Manual* for use with open-graded hot-mixed asphalt in Coastal, Inland Valley, and Low Mountain regions in California when the placement temperature is over 21°C *(29)*. The selected optimum binder contents were determined following Caltrans Test Method 368, which is based upon draindown of asphalt at production temperatures. The mix designation and other parameters of the four mixes are shown in Table 4.1.

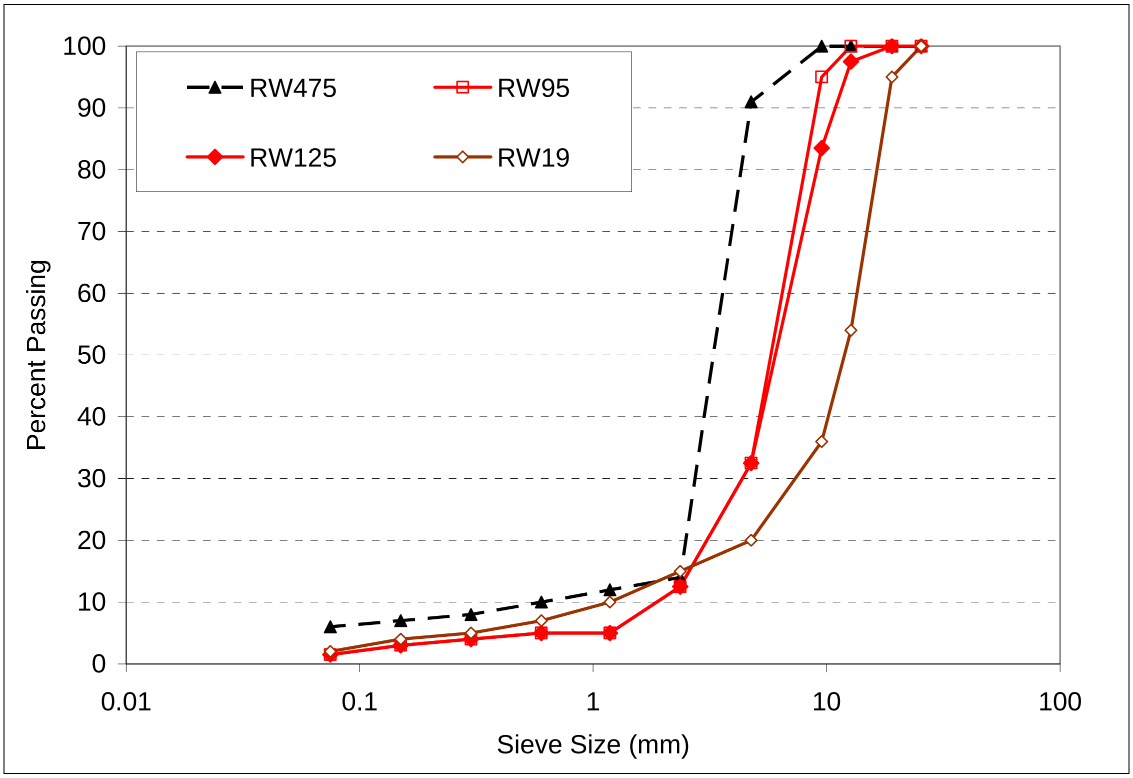


Figure 4.1: Aggregate gradations of mixes included in the first experiment.

Table 4.1: Mixes Included in the First Experiment

Mix ID	NMAS (mm)	Binder	Gradation	Binder Content[1]	Additive
RW475	4.75	PG 64-16	Open	7.9%	None
RW95	9.5	PG 64-16	Open	5.9%	None
RW125	12.5	PG 64-16	Open	5.9%	None
RW19	19	PG 64-16	Open	5.0%	None

[1] By mass of aggregate, same in other tables.

The second experiment included one aggregate gradation (4.75-mm NMAS), five binder types, and two additives. The five binders included PG 64-16, PG 58-34PM, PG 76-22PM, asphalt rubber, and PG 76-22TR. PG 58-34PM and PG 76-22PM are both polymer-modified binders. PG 58-34PM is specified in the *California Highway Design Manual* for use with open-graded hot-mixed asphalt when the placement temperature is below 21°C *(29)*. (PG 76-22PM is specified in the Georgia Department of Transportation Standard Specifications as the only binder to be used with the 12.5 mm OGFC.) Asphalt rubber binder has been used in many OGFC projects in California. The asphalt rubber binder used in this study was produced by adding about 19 percent crumb rubber modifier into a PG 64-16 base binder to meet Caltrans Type 2 specifications. PG 76-22TR was asphalt-modified with rubber through the terminal blend process. The two additives included hydrated lime and cellulose fiber. Hydrated lime was added into two mixes at the rate of 1.5 percent by mass of dry aggregate, in the form of dry lime on damp aggregate. Cellulose fiber stabilizing additive was added into one mix at the rate of 0.3 percent by mass of total mix. The optimum binder content (OBC) was determined following Caltrans Test Method 368. The OBC for mixes using asphalt rubber was 120 percent of the OBC determined for each gradation using PG 64-16 binder. The mix designation and other parameters of mixes in the second experiment are shown in Table 4.2.

Table 4.2: Mixes Included in the Second Experiment
***(Note:* Mixes shown in italics were described in the previous experiment.)**

Mix ID	**NMAS (mm)**	**Binder**	**Gradation**	**Binder Content**	**Additive**
RW475	*4.75*	*PG 64-16*	*Open*	*7.9%*	*None*
AR475	4.75	Asphalt rubber	Open	9.5%	None
P475	4.75	PG 76-22PM	Open	7.9%	None
P475LM	4.75	PG 64-16	Open	7.9%	1.5% hydrated lime by dry mass of aggregate
P58LF	4.75	PG 58-34PM	Open	7.9%	1.5% hydrated lime by dry mass of aggregate and 0.3% cellulose fiber by mass of total mix
TR475	4.75	PG 76-22TR	Open	9.5%	None

The third experiment was to determine the effect of fineness modulus and air-void content on noise reduction and durability. The 4.75-mm NMAS gradation used in the first two experiments was modified to increase the fineness modulus (from 4.58 to 4.86), which brings the portion of aggregates passing the No. 4 (4.75-mm) sieve down from 91 percent to 65 percent, as illustrated in Figure 4.2, with the coarser gradation designated as AR475P (here “P” represents “plus” or “coarser”).

Two nominal air-void contents, 20 percent and 15 percent, were selected for the experiment. The 20 percent air-void content is a typical minimum value required in the design of open-graded friction courses, and a typical value found in newly constructed Caltrans OGFC sections with 9.5 and 12.5 NMAS *(2)*. The 15 percent air-void content was the maximum value recommended in the previous field study *(1, 22)* to both reduce tire/pavement noise and increase mix durability. The lower air-void content was achieved with greater compactive effort. The mix designation and other parameters of mixes in the third experiment are shown in Table 4.3. In the table, AR475D and AR475 designate the same mix, with the letter “D” meaning the “denser” mix achieved by the increased compaction, while the aggregate gradation was kept the same. Specimens labeled as AR475PD had both the coarser gradation (hence the “P”) and the increased compaction to reduce their air-void content to 15 percent (hence the “D”).

Table 4.3: Mixes Included in the Third Experiment
***(Note:* Mixes shown in italics were described in the previous experiment.)**

Mix ID	NMAS (mm)	Binder	Gradation	Binder Content	Air-Void Content (%)
AR475D	4.75	Asphalt rubber	Open	9.5%	15
AR475	*4.75*	*Asphalt rubber*	*Open*	*9.5%*	*20*
AR475PD	4.75+	Asphalt rubber	Open-coarser	8.4%	15
AR475P	4.75+	Asphalt rubber	Open-coarser	8.4%	20

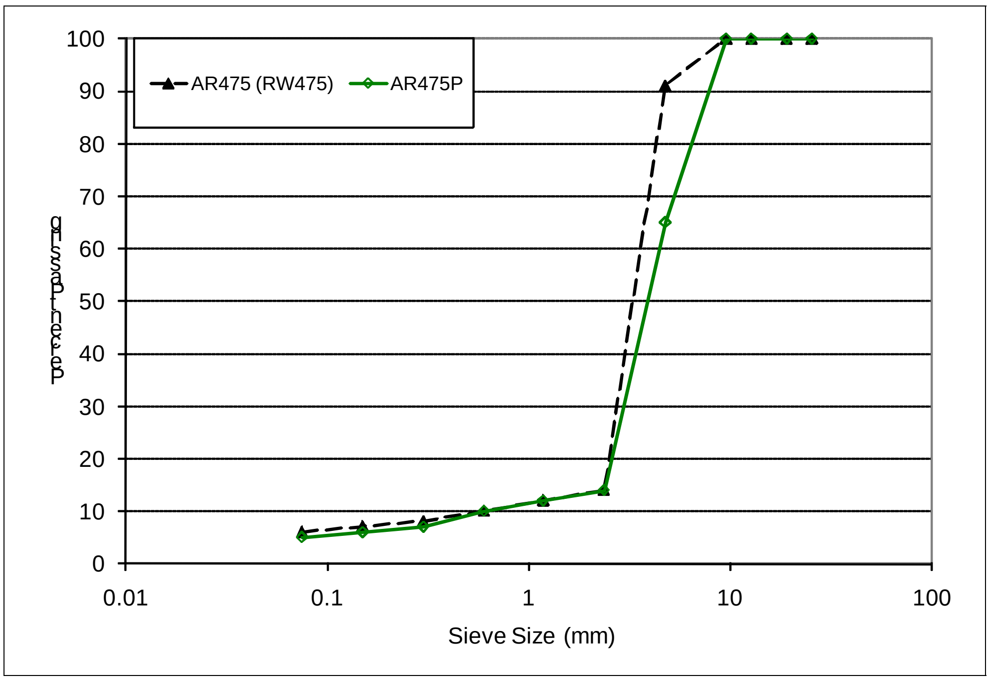


Figure 4.2: Aggregate gradations of mixes included in the third experiment.

The fourth experiment was designed to determine the effect of aggregate shape on noise reduction and durability. Included in the experiment were aggregates from three quarries, Syar Lake Herman (near Benicia in Solano County), Graniterock Aromas (near Watsonville in Santa Cruz County), and Teichert Jackson Road (east of Sacramento in Sacramento County), which have different angularities, dimensions, and textures. Samples of aggregates of the size between 19 mm (3/4 in.) and 1.16 mm (#100) were sent to the Texas Transportation Institute for shape characterization using the recently developed aggregate imaging system (AIMS). The results, as shown in Appendix D, indicate that the coarse aggregates (sized between 4.75 mm [#4] and 12.5 mm [1/2 in.]) from Syar and Teichert had a more angular shape than those from Watsonville, which were bulkier; the Syar aggregate was also slightly more angular than the Teichert aggregate. The Teichert aggregates had the roughest surface of the three types. The 2D form values (an index that reflects the extent of elongation of fine aggregates) *(30)*, showed that the fine aggregates (between 1.18 mm and 2.36 mm) of Teichert were more elongated than the Syar fine aggregates, which were more elongated than the Watsonville fine aggregates. This experiment also included two aggregate gradations (NMAS 4.75 mm [#4] and NMAS 9.5 mm [3/8 in.]) and two binder types (PG 64-16 and asphalt rubber). Table 4.4 shows the mix designation and other parameters of mixes in the third experiment.

Table 4.4: Mixes Included in the Fourth Experiment
***(Note:* Mixes shown in italics were described in the previous experiment.)**

Mix ID	Aggregate/NMAS (mm)	Binder	Gradation	Binder Content	Additive
RW475	*Syar (4.75)*	*PG 64-16*	*Open*	*7.9%*	*None*
PG475W	Watsonville from Graniterock Aromas (4.75)	PG 64-16	Open	7.9%	None
AR475	*Syar (4.75)*	*Asphalt rubber*	*Open*	*9.5%*	*None*
AR475T	Teichert from Jackson Road (4.75)	Asphalt rubber	Open	9.5%	None
RW95	*Syar (9.5)*	*PG 64-16*	*Open*	*5.9%*	*None*
PG95T	Teichert from Jackson Road (9.5)	PG 64-16	Open	5.9%	None
AR95	Syar (9.5)	Asphalt rubber	Open	7.1%	None
AR95W	Watsonville from Graniterock Aromas (9.5)	Asphalt rubber	Open	7.1%	None

The fifth experiment compared the noise and durability performance of some prospective asphalt surface mixes being used or developed in other states and countries. A total of seven mixes were included in this experiment, as shown in Table 4.5.

AZ95 is a high-binder, rubberized open-graded mixture that has been used widely and successfully in Arizona. It has a nominal maximum aggregate size of 9.5 mm (3/8 in.) and contains over 50 percent more asphalt than an OGFC with conventional binder. DL is a double-layer porous asphalt (DLPA) that has been used in European countries. It uses mix E8 (8 mm NMAS) as the upper layer and mix E16 (16 mm NMAS) as the lower layer. Both cellulose fiber and hydrated lime were added in the mixture to improve its durability. SMA4P and SMA6P are two stone mastic asphalt (SMA) mixtures designed in Denmark to solve the clogging issue that often occurs in OGFC. These two mixtures use small maximum aggregate sizes (4 and 6 mm) and a small proportion of oversized aggregates to achieve a smooth but open surface. G125 is an OGFC developed by the Georgia Department of Transportation (GDOT) in the early 1990s and used extensively statewide since then. The mix uses polymer-modified asphalt binder, and contains both fiber and hydrated lime. To provide reference values for comparison, a control mix, D 125, 12.5-mm (1/2 in.) dense-graded asphalt concrete (DGAC), was also included in the experiment. The gradation of the control mix followed the middle values of Caltrans Standard

Specifications for NMAS 12.5-mm DGAC, and an OBC of 6 percent was selected based on past experience. The OBCs of these mixes were either directly taken from the literature or determined in the laboratory following their corresponding mix design procedures. The aggregate gradations of mixes included in this experiment are plotted in Figure 4.3.

Before these five experiments were conducted, a small-scale experiment was carried out to determine the appropriate compaction method for porous asphalt specimens in the laboratory. The four open-graded mixes included in the first experiment were compacted into cylindrical specimens (100 mm [4 in.] in diameter and 63.6 mm [2.5 in.] thick) in the laboratory using Hveem kneading, Marshall impact, and Superpave gyratory compactors, and their surface textures, permeability, and air-void contents were compared to those of specimens cored from slabs compacted with a rolling wheel compactor.

Table 4.5: Mixes Included in the Fifth Experiment

Mix ID	Mix Name	NMAS (mm)	Binder	Gradation	Binder Content	Additive	Structure
AZ95	Arizona mix	9.5	Asphalt rubber	Open	9.2%	1.0% hydrated lime by dry mass of aggregate	One layer
DL	DLPA	8/16	PG 64-16	Open (E8 for upper layer, E16 for lower layer)	6.4%/4.6%	0.25% cellulose fiber by mass of total mix, 1.5% hydrated lime by dry mass of aggregate	Two layers (25/40 mm)
SMA6P	Danish SMA 6+8 (Opt)	6+5/8	PG 58-34PM	Gap	6.5%	0.3% cellulose fiber by mass of total mix	One layer
SMA4P	Danish SMA 4+8	4+ 5/8	PG 58-34PM	Gap	6.7%	0.3% cellulose fiber by mass of total mix	One layer
G125	Georgia mix	12.5	PG 76-22PM	Open	6.3%	0.4% mineral fiber by mass of total mix, 1.4% hydrated lime by dry mass of aggregate	One layer
E8	European OGFC	8	PG 64-16	Open	6.4%	0.25% cellulose fiber by mass of total mix, 1.5% hydrated lime by dry mass of aggregate	One layer
D125	DGAC, control mix	12.5	PG 64-16	Dense	6.0%	none	One layer

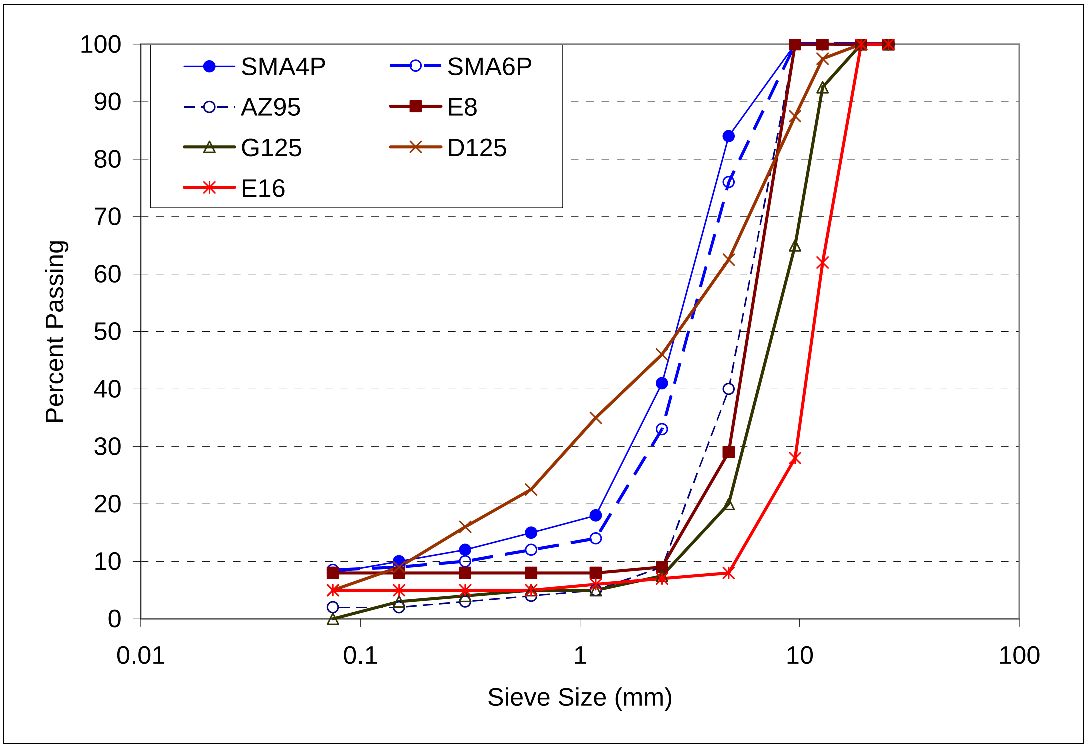


Figure 4.3: Aggregate gradations of mixes included in the fifth experiment.

4.1.2 Materials

Except for some mixes in the fourth experiment that used the Watsonville (Graniterock) or Teichert aggregates, all the other mixes used aggregates from the same Syar Lake Herman quarry, which is a basaltic-volcanic source, and has been used on several Caltrans OGFC overlay projects. The Graniterock Aromas material (W) is a granitic source, and the Teichert Jackson Road source (T) is a crushed gravel source.

Five binders were used in the study:

- PG 64-16 binder from the Shell Martinez Refinery
- Asphalt rubber from one Syar Industries plant, with 19 percent crumb rubber added through wet process into PG 64-16 base binder from the Valero Refining Company in Benicia
- PG 76-22PM, PG 58-34 PM, and PG 76-22TR binders all obtained from the Valero Refining Company in Benicia.

Hydrated lime was obtained from Chemical Lime Company. Both cellulose and mineral fiber stabilizing additives were obtained from one provider approved by the Georgia Department of Transportation.

4.2 Mix Designs

A total of 22 mixes were included in this study, including one dense-graded asphalt mixture, two stone mastic asphalt mixtures, and nineteen open-graded (porous) asphalt mixtures. A summary of the mix designs and characteristics are shown in Appendix A: Mixes Included in the Study.

The mix designs were performed following different procedures for various mixes. For the mixes in the first four experiments, the optimum binder contents were determined following Caltrans Test Method 368, which is based upon draindown of asphalt at production temperatures. For the mixes in the fifth experiment, the optimum binder contents were directly obtained from the literature and/or verified in the laboratory following the corresponding procedures documented in the literature.

4.2.1 Mixes in the First Four Experiments

All the mixes in the first four experiments were open-graded, designed from various combinations of binder type, additive type, and five aggregate gradation curves. In Caltrans Test Method 368 an approximate bitumen ratio (ABR) is first determined following CT 303. Several asphalt contents around this ABR value, in 0.7% increments, were then used for specimens that were subjected to the Caltrans draindown test. The test was conducted by leaving a sample of freshly prepared, loose mix in an extraction thimble, as used in CT 310, at a temperature of 135ºC for 30 minutes under a weight of 4,000 g. The materials retained along the inner side and at the bottom of the thimble after the conditioning were weighed and recorded as the mass of drainage. For open-graded asphalt concrete using unmodified asphalt, the optimum binder content (OBC) was selected as the binder content corresponding to 4.0 g asphalt drainage. For mixes using polymer-modified asphalts AR 4000 binder was used to determine the OBC, which was also determined at 4.0 g of drainage. For open-graded mixes containing asphalt rubber (RHMA-O), however, the OBC was increased to 120 percent of the value determined at 4.0 g of drainage using the AR4000 binder.

Results of the CT 368 tests for the five aggregate gradations, with PG 64-16 binder (similar to AR4000 binder) and Syar aggregate, are shown in Appendix B: Test Results for OBC Following CTM 368. The OBCs determined from the test results were 7.9, 5.9, 5.9, 5.0, and 8.4 percent for RW475, RW95, RW125, RW19, and AR475P respectively. The OBCs of mixes using the Watsonville or Teichert aggregates were the same as those of corresponding mixes using the Syar aggregates. That is, no adjustment of binder content was made for the difference in aggregate type.

4.2.2 Arizona High-Binder Rubberized Open-Graded Mixture (AZ95)

The optimum binder content of the Arizona asphalt rubber open-graded friction course (AR-OGFC) was determined in a manner similar to Caltrans Test 368. In the Arizona procedure the binder content was also selected based on the results of a draindown test. A Schellenberg test *(31)* was used to determine the draindown, in which loose asphalt mix is placed in a beaker, left in an oven for one hour, and then percentage of mass loss is checked. The aggregate gradation and optimum binder of the AZ95 mix included in this study were taken directly from the literature *(25)*. The Schellenberg draindown test was not performed due to a lack of detailed procedure description. Instead, the Caltrans Test 368 draindown test was used to check the draindown potential. The final selected OBC for the AZ95 mix was 9.2 percent.

4.2.3 Double-Layer Porous Asphalt (DL)

The double-layer porous asphalt consisted of two layers of asphalt mixes with different aggregate gradations and sizes. In this study, mixes E8 (8 mm NMAS) and E16 (16 mm NMAS) were used for the upper and lower layers, respectively. Both mixes were selected from the typical mixes used in DL surfacings in Europe *(18).* The optimum binder contents used in Europe are 5.4 percent and 3.9 percent (by mass of aggregate) for E8 and E16 respectively. In this study, Caltrans Test 368 was followed to verify and adjust these binder contents, and the finally selected binder contents were 6.4 percent and 4.6 percent for the E8 and the E16 mixes respectively.

4.2.4 Danish Stone Mastic Asphalt (SMA)

SMA4P is an SMA with a maximum aggregate size of 4 mm (0.16 in.) and an additional amount of oversize aggregate of 8 mm (0.32 in.). In the Danish Road Institute/Danish Road Directorate (DRI) research that was part of EU project SILENCE, the optimum binder content was established with respect to volumetric composition and the ability to retain the high binder content on the aggregate skeleton. An optimum binder content of 6.7 percent (by mass of mix) was used by DRI for this mix (designated as “SMA 4+8” in the DRI study) and the average air-void content of the Marshall specimens was 10.2 percent *(28).*

SMA6P is an SMA with a maximum aggregate size of 6 mm (0.24 in.) and an additional amount of oversize aggregate of 8 mm. It is optimized for high noise reduction. The optimum binder content used by DRI was 6.5 percent (by mass of mix) and the average air-void content of the Marshall specimens was 13.9 percent *(28).* This mix was designated “SMA 6+8 (Opt.)” in the DRI study *(28).*

The optimum binder contents were verified in this study. Marshall specimens with five binder contents varying around the optimum binder content determined by DRI were fabricated in the laboratory following the Marshall mix design procedure and tested for additional performance indices, including permeability, Cantabro loss, and indirect tensile strength. The five trial binder contents were 6.3, 6.7, 7.1, 7.5, and 7.9 percent by mass of aggregate for the SMA4P, and 5.7, 6.1, 6.5, 6.9, and 7.3 percent by mass of aggregate for the SMA6P. Four Marshall specimens were fabricated at each binder content for each mix, with 50 blows on each side of the specimen. Bulk specific gravity was measured on all specimens using the CoreLok method.

Three specimens were then randomly selected from the set of four specimens for permeability testing. After the permeability was determined, Cantabro loss was determined for two of the four specimens and the indirect tensile strength (ITS) test was applied to the remaining two. The ITS test was included because the mixes did not show a maximum stability value in the Marshall test. Instead, the Marshall stability kept increasing until the gaps between the upper and lower cylindrical sections of the breaking head closed; therefore, no Marshall stability and flow value were obtained for the two mixes.

The test results for SMA4P are plotted in Figure 4.4. As can be seen, when the asphalt content is between 6.3 and 7.1 percent, the air-void content, permeability, bulk specific gravity, and VFA are relatively stable. However, when the asphalt content is over 7.1 percent, air-void content and permeability start to decrease significantly. Low permeability reduces the noise-reducing capability of the surface mix, which was undesirable for the study. Therefore, it was determined that the optimum binder content of SMA4P should be between 6.3 and 7.1 percent by mass of aggregate for this aggregate and gradation. Considering the higher Cantabro loss value at 6.3 percent binder content, an OBC of 6.7 percent by mass of aggregate was selected, which is slightly lower than the value determined in the DRI study (7.2 percent by mass of aggregate) (*24*).

The test results for SMA6P are plotted in Figure 4.5. As can be seen, when the asphalt content is over 6.5 percent, the permeability decreases significantly; on the other hand, when the asphalt content is below 6.5 percent, the Cantabro loss value increases significantly. To achieve a balance between permeability and durability, an OBC of 6.5 percent by mass of aggregate was selected, slightly lower than the value determined in the DRI study (7.0 percent by mass of aggregate) *(28).*

4.2.5 Georgia Open-Graded Friction Course (G125)

The Georgia open-graded mix G125 uses polymer-modified asphalt binder PG 76-22 and a nominal maximum aggregate size of 12.5 mm (1/2 in.), and contains 0.4 percent mineral fiber by mass of total mix and 1.4 percent hydrated lime by dry mass of aggregate. The OBC was determined following Georgia Test GDT 114. This test includes three procedures: The first uses a procedure similar to CT 303 (which determines the approximate bitumen ratio) to determine the surface capacity of coarse aggregate, the second uses a modified Marshall design method to determine the asphalt content corresponding to a lowest volume in mineral aggregate (VMA), and the third uses a Pyrex bowl method to determine an asphalt content that ensures ample bonding between the asphalt-film coating and a glass pan without excessive drainage. The OBC is determined by averaging the three asphalt content values obtained with these procedures. Once this is done, stripping potential is evaluated using the Boil Test (GDT 56) at the determined OBC level.

In this study, the percent asphalt determined from surface capacity was 6.3 percent. The Marshall test results are summarized in Figure 4.6. As can be seen, the asphalt content at the lowest point of the VMA curve is 6.3 percent. The Pyrex bowl test results are shown in Figure 4.7. The percentage of the bowl bottom area that is covered with asphalt is an indicator of the amount of draindown. Since no detailed instructions are given in the test procedure on how to interpret the results, subjective engineering judgment was used to determine an optimum binder content. Visual observation indicates that a binder content between 6.0 and 6.5 percent corresponds to ample film coating without excessive drainage. Therefore, 6.3 percent was selected as the OBC of the G125 mix.

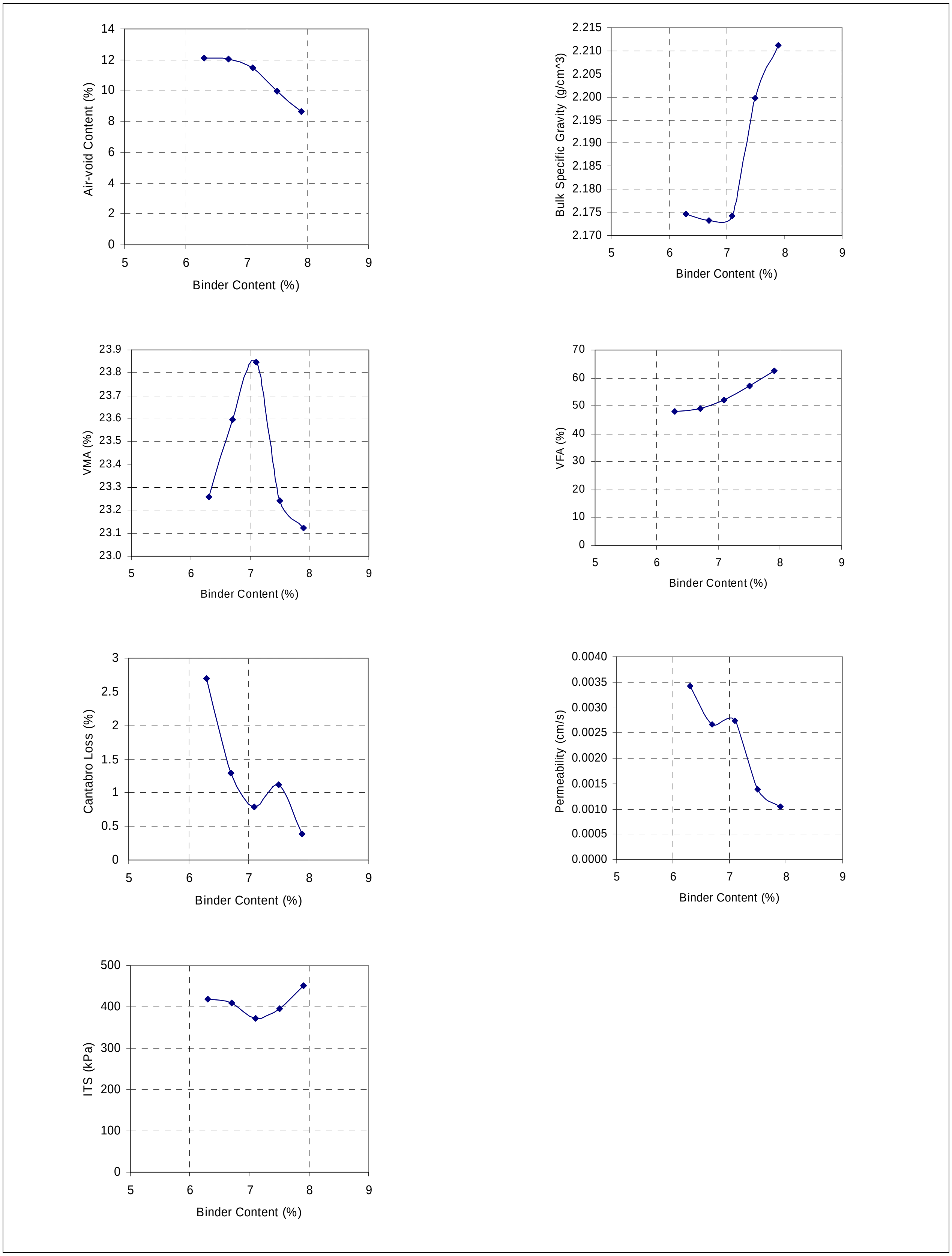


Figure 4.4: Properties of SMA4P at different binder contents.

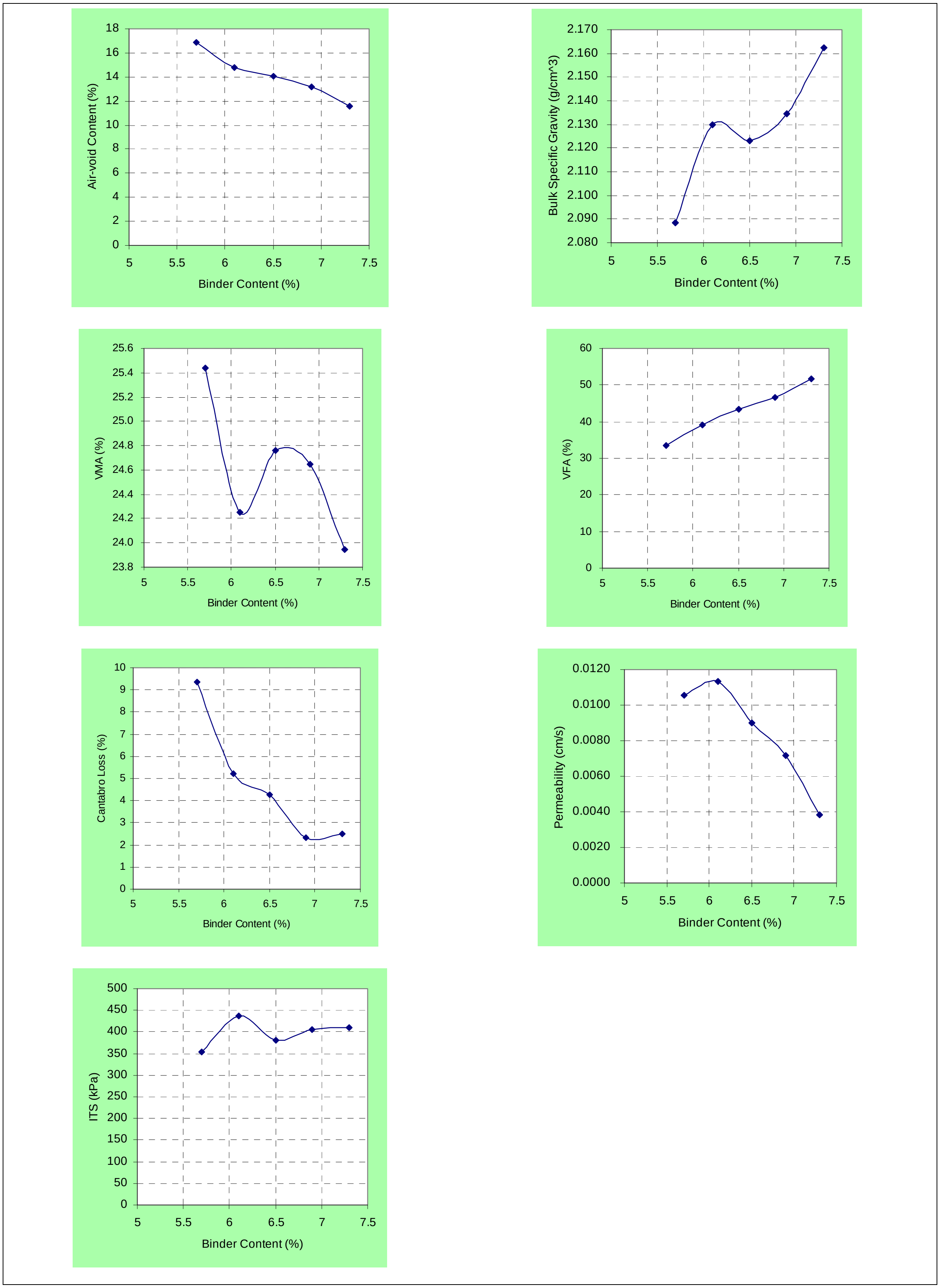


Figure 4.5: Properties of SMA6P at different binder contents.

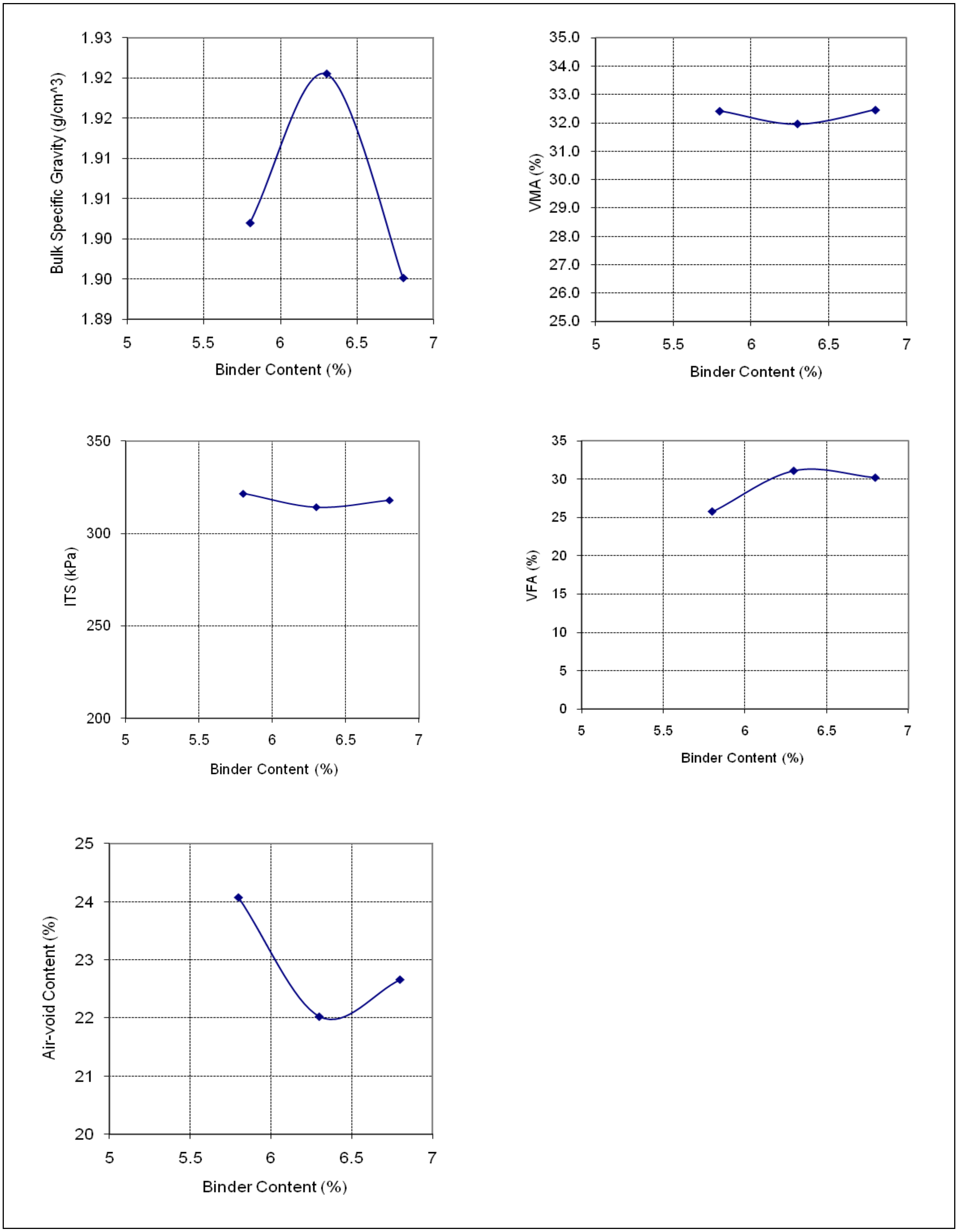


Figure 4.6: Marshall test results for G125 mix.

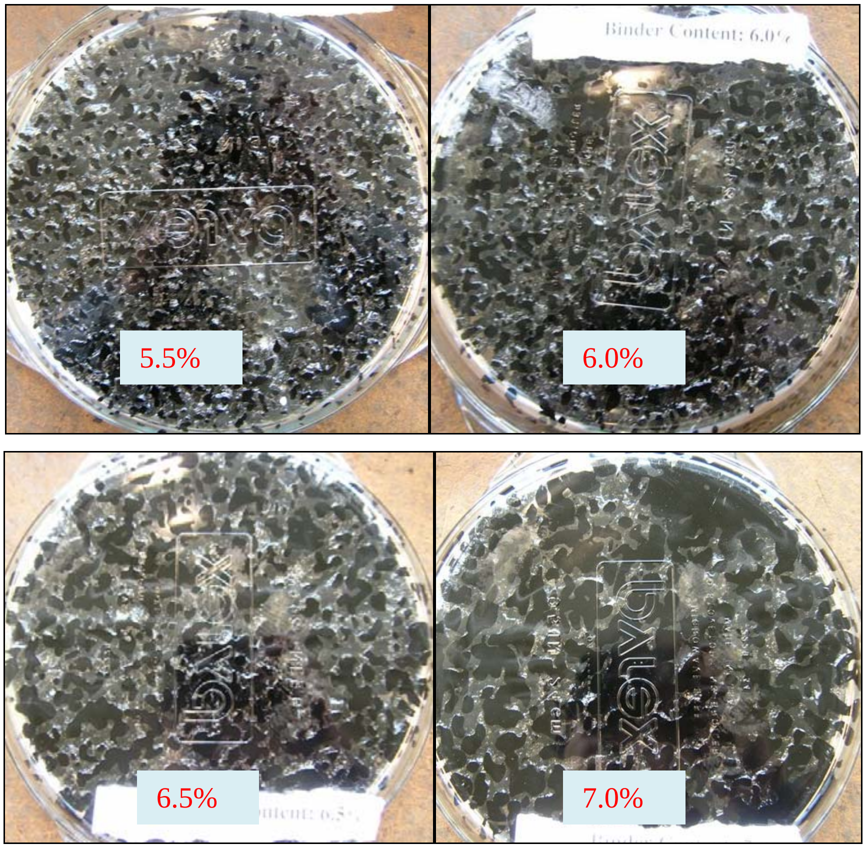


Figure 4.7: Pyrex bowl test results at various binder contents.

4.3 Compaction Methods

Initially four compaction methods were selected and compared in the study: Hveem kneading compaction, Superpave gyratory compaction, Marshall impact compaction, and rolling wheel compaction.

Hveem kneading compaction consolidates a mix by a series of tamps made by a ram with a face shaped as a circle sector. This compaction method was developed Caltrans in the early 1950s to simulate the shearing of a roller wheel, and has been used since then for fabricating laboratory specimens for asphalt mix design. In this study, the compaction procedure generally follows California Test 304, "Method of Preparation of Bituminous Mixtures for Testing," with a few modifications. Specifically, weighted loose mix was distributed into a compaction mold in one lift, and then rodded 10 times in the middle and 10 times around the edge with a bullet-nosed steel rod. Next the mix was compacted at a tamper foot pressure of 1.7 MPa for 25 tamping blows, and then leveled under a compression load at a speed of 6.35 mm/min to a height of 63.5 mm.

Superpave gyratory compaction was conducted following the procedure in AASHTO T 312, with 50 gyrations for each specimen, as specified in ASTM D 7064, "Standard Practice for Open-Graded Friction Course (OGFC) Mix Design."

Marshall impact compaction followed the procedure widely used by other researchers, particularly in European countries, for OGFC specimen fabrication *(27)*. Specifically, 50 blows of a Marshall hammer were applied on each side of the specimens.

Rolling wheel compaction simulates field compaction on a smaller scale. Preweighed loose mix was distributed in a steel mold of 635 mm length and 560 mm width, and then compacted by a BOMAG 90 AD ride-on tandem roller (with an approximate weight of 2,000 kg). The compaction was done in static mode and generally 30 passes were applied to make the slab surface flush with the mold edge.

The actual air-void content of the Marshall specimens may not be equal to the nominal air-void content because the amount of loose mix put into the compaction mold was predetermined based on the nominal air-void content and the required bulk volume of a specimen. In the Marshall compaction, the same compaction energy was applied to all specimens (50 blows on each side of a specimen), but the height of the specimen cannot be controlled. On the other hand, in the rolling wheel compaction, the slab specimen was compacted until its surface was flush with the edge of the mold. Generally, 30 passes of rolling wheel compaction were applied but extra passes were applied in some cases when the slab surface was not flush with the edge of the mold at 30 passes.

Before being compacted by any of these methods, all the loose mixes were short-term aged in accordance with AASHTO PP2, i.e., aged in a forced draft oven at 135°C for four hours.

After a pilot comparison study (Appendix C: Selection of Compaction Methods for Specimen Fabrication), it was decided to fabricate the Cantabro test and moisture sensitivity (Indirect Tensile Strength Ratio) test specimens using the Marshall compactor, and to fabricate specimens for all other tests using the rolling wheel compactor. British Pendulum and dynamic friction tests, permeability testing, and texture scanning were first conducted on the large rolling wheel–compacted slab specimens, after which the slabs were cored or cut into smaller specimens for other tests.

4.4 Test Methods

The mix properties that were identified as being critical to pavement surface performance were evaluated in the study, following the test methods summarized in Section 3.1. The following gives a brief description of each test.

4.4.1 Air-Void Content

The air-void content of each specimen was calculated from the theoretical maximum specific gravity measured in accordance with AASHTO T 209 and the bulk specific gravity measured using the CoreLok method following AASHTO T 331.

Air-void content by itself is not a performance property. However, higher air-void contents often result in greater permeability, particularly if the interconnection of air-voids increases as the air-void content increases. Higher air-void contents are generally associated with lower durability as well. In this study, air-void content was measured on each specimen, so about 20 specimens were measured for air-void content for each mix.

4.4.2 Permeability

Permeability was primarily measured with a field falling head permeameter developed by National Center for Asphalt Technology (NCAT) on slab specimens compacted by the rolling wheel compactor. The test was typically conducted at three positions (left edge, center, right edge) on each slab, with at least three repetitions of measurement at each position. Generally two slab specimens were compacted for each mix in this study. For the mixes included in the first experiment, the mix permeability was also measured with a flexible-wall falling-head permeameter on the 100-mm diameter specimens, following the procedure specified in ASTM PS 129. A comparison of the results from the two devices showed consistent permeability, so only the NCAT field permeameter was used in later work to characterize the mix permeability.

Higher permeability increases the pavement's capacity to carry water through its surface layer to the side of the road, thus improving safety by reducing water film thickness and splash from rain. Higher permeability is also associated with reduction of the air pumping mechanism that causes tire/pavement noise and with greater acoustical absorption, which may reduce noise at the side of the road.

4.4.3 Acoustic Absorption

The acoustic (sound) absorption coefficient of a material represents the proportion of acoustic energy not reflected by the surface of the material for a normal incidence plane wave. Acoustical absorption was measured for this study by Wilson, Ihrig & Assoc., Inc. following ASTM E 1050, using a Bruel & Kjaer Type 4206A impedance tube fitted with custom sample holders ranging in diameter from 101.5 to 104.5 mm to accommodate cores of different diameters *(21)*. Three replicates were tested for each mix.

As noted earlier, acoustic absorption is correlated with lower tire/pavement noise for higher noise frequencies. It may also result in some reduction of noise between the tire/pavement interface and the side of the road.

4.4.4 Moisture Sensitivity

Moisture susceptibility of the mixtures was determined using the AASHTO T 283 test method with some modifications as specified in ASTM D 7064. Moisture-conditioned specimens were first saturated in a vacuum of 87.8 kPa (13 psi) for 10 minutes, and then submerged in water during the 16-hour freeze cycle. In the 24-hour thaw cycle, specimens were wrapped with plastic tube walls to prevent breakdown of the porous mixture in the 60°C (140°F) water bath. Instead of five freeze/thaw cycles as specified in ASTM D 7064, only one cycle was applied. An earlier study by Watson et al. found no significant difference in tensile strength when one, three, and five freeze/thaw cycles are used in the moisture conditioning of open-graded asphalt mixtures, and suggested only one freeze-thaw cycle is needed *(32)*. Three replicates were tested for each conditioning status.

A Hamburg wheel tracking device (HWTD) was also used to measure the premature failure potential (including both moisture sensitivity and rutting resistance). For each mix, a 38-mm (1.5 in.) thick slab compacted by the rolling wheel compactor was cut into four 280-mm width by 315-mm length (11 by 12.4 in.) HWTD specimens, two of which were randomly selected for the HWTD test, which was performed following AASHTO T 324, and the other two slabs were reserved for future testing in dry condition (not included in this study).

Greater resistance to moisture damage increases the life of the pavement, improving its performance with respect to raveling, cracking, and rutting.

4.4.5 Resistance to Raveling

Resistance to raveling was evaluated using the Cantabro test on both unaged and aged specimens, following the procedure described in the report by Kandhal et al. *(33)*. Specifically, compacted specimens (4 in. in diameter and 2.5 in. in height, compacted by Marshall compactor) were put inside a Los Angeles Abrasion machine drum without steel balls, and the drum was turned for 300 revolutions in 10 minutes. The percentage of mass loss during this process was used to evaluate the resistance of asphalt mixtures to raveling. A custom environmental chamber was built to enclose the machine to keep the test temperature at 25±1°C (75±2°F). Aging was accomplished by placing specimens in a forced draft oven set at 60°C for 168 hrs. To prevent breakdown of the highly porous mixtures, the specimen side was retained by a plastic tube wall during the entire process. Three replicates were tested for each mix.

Raveling increases road roughness and it also increases tire/pavement noise, particularly at lower frequencies of noise because of tire vibration.

4.4.6 Friction

Friction was measured with both a British Pendulum Tester (BPT), following ASTM E 303, and a Dynamic Friction Tester (DFT), following ASTM E 1911, on two large slab specimens compacted by the rolling wheel compactor for each mix. On each slab, three separate test locations were randomly selected for both tests.

Friction is primarily associated with lower-speed skid resistance, with increasing friction resulting in improved skid resistance.

4.4.7 Macrotexture

The surface macrotexture of each slab specimen was measured with a laser texture scanner developed by AMES Engineering, as shown in Figure 4.8.

Figure 4.8: The AMES Engineering laser texture scanner.

The Ames Engineering laser texture scanner is a standalone unit that can be placed on a surface on three point contact feet. It is designed to measure the two decades (50 mm to 0.5 mm) in the macrotexture waveband and one decade (0.5 mm to 0.05 mm) of the microtexture waveband. The laser has a dot size of approximately 0.050 mm at 42 mm standoff distance, a vertical sample resolution of 0.015 mm, and a horizontal sample spacing of 0.015 mm. The scanner scans a surface directly underneath it in multiple line scans with a scan line length of 100 mm and a maximum scan width of 75 mm. The number of lines to be scanned can be set by the user up to 1,200, so the average spacing between scan lines at maximum can be as small as 0.064 mm. It takes about 9 seconds to complete one scan line. Scanning more lines takes more time. In this study, the texture was scanned at multiple randomly selected locations on each slab, with 152 lines scanned at each location. Based on the quality of the data, results from 8 to 12 locations (replicates) were included in the analysis.

The scanned data was downloaded to a computer using a standard Ethernet interface, and reanalyzed by software to calculate surface indices and display a 3D graph of the scanned surface. Figure 4.9 shows an example of the 3D plot of a scanned surface. Six index calculations were available for calculation in the software, including Mean Profile Depth (MPD), Estimated Texture Depth (ETD), Texture Profile Index (TPI), Root Mean Squared (RMS) and band passed filtered elevation and slope variance calculations.

Greater macrotexture is primarily associated with improved high-speed skid resistance, and is also associated with greater tire/pavement noise because of the tire vibration phenomenon.

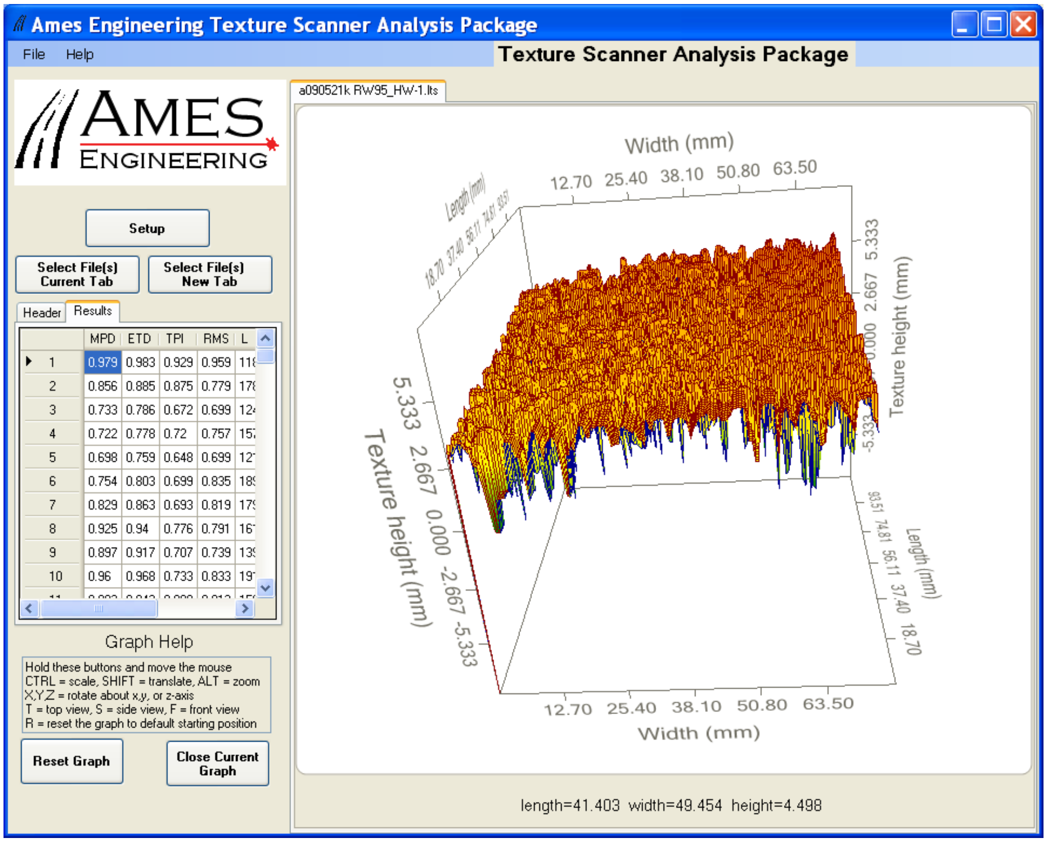


Figure 4.9: Example 3D plot of a scanned surface from the AMES Engineering laser texture scanner.

4.4.8 Resistance to Permanent Deformation

The rutting resistance of each mix was evaluated by the repeated simple shear test at constant height (RSST-CH), following the AASHTO T 320 procedure. Four standard specimens (50 mm [2 in.] thick and 150 mm [6 in.] in diameter) were cored from the large slab specimens, with two specimens tested at 45°C (115°F)and 70 kPa (10 psi) shear stress, and the other two specimens tested at 45°C and 130 kPa (19 psi) shear stress. Failure was defined by five percent permanent shear deformation.

Rutting is a potential distress in surface mixes that affects ride quality and safety.

4.4.9 Resistance to Reflective Cracking

The resistance to reflective cracking of each mix was evaluated with an Overlay Tester, following Texas DOT test procedure Tex-248-F. The overlay tester is an electrohydraulic system that applies repeated direct tension loads to specimens. The machine has one fixed block and one sliding block. The sliding block applies tension in a cyclic triangular waveform to a constant maximum displacement of 0.6 mm (0.024 in.). This block reaches maximum displacement and then returns to its initial position in 10 sec. This process repeats until a 93 percent reduction or more of the maximum load measured from the first opening cycle occurs, or until it reaches 1,200 cycles, whichever comes first. The test is conducted at a constant temperature 25±0.5°C. In this study, the overlay test was conducted at Texas Transportation Institute (TTI), with two specimen replicates for each mix. The specimens were cut from 150-mm diameter cylindrical cores, with a thickness of 38 mm and a width of 76 mm.

Cracking at the surface of an asphalt pavement increases tire/pavement noise as the cracks widen and begin to spall and deform the pavement surface.

4.5 Test Matrix

For each mix included in the experimental design, twelve 101-mm (4 in.) diameter cylindrical specimens were fabricated with the Marshall compaction method. Six of them were used in the Cantabro test (three unaged and three aged); and the remaining six were used in the moisture sensitivity (indirect tensile strength ratio) test (three unconditioned and three conditioned). For each mix, two large slabs (635 mm [2.1 ft] long by 560 mm [1.8 ft] wide) were also compacted using the rolling wheel compactor, one at a thickness of 38 mm [1.5 in.] and the other at a thickness of 50 mm [2.0 in.]. One exception was that for the double layer porous asphalt (DL), both slabs were 65 mm (2.6 in.) (25 mm [1 in.] top layer and 40 mm [1.6 in.] bottom layer). After the texture, permeability, and friction tests on the slabs, the thinner one was cut into four equally-sized slabs for the Hamburg wheel tracking device test, and the thicker one was cored into nine 150-mm diameter cores for the shear test and the overlay test, and five 100-mm diameter cores for the impedance tube test. A total of about 726 specimens were fabricated and about 506 specimens were tested.

5 TEST RESULTS AND ANALYSIS

The test results presented and analyzed in this chapter follow the experiments described in Chapter 4. Descriptions of the mixes included in the study, their mix designs and preparation, and the acronyms used in the presentation of results are summarized in Table 5.1. Expanded descriptions of each mix type were presented in Sections 4.1 and 4.2 of this report.

5.1 Effect of Nominal Maximum Aggregate Size (NMAS)

The first experiment was designed to investigate the effect of aggregate size on noise reduction, durability, and other performance criteria for asphalt surface mixes. Four open-graded asphalt mixes with different nominal maximum aggregate sizes and gradations were included in the experiment: RW475, RW95, RW125, and RW19.

5.1.1 Air-Void Content and Permeability

A target air-void content of 20 percent was selected for fabricating all specimens in this experiment. As discussed in Section 4.3, the actual air-void contents differed from the target depending on the compaction method.

Figure 5.1 shows the average air-void content, as well as the range of one standard deviation, of the four mixes, measured from 100-mm diameter core specimens compacted by the two methods. As can be seen, under Marshall compaction, the air-void content of mix RW475 is close to the nominal value, while the air-void contents of mixes RW95 and RW125 are higher and that of mix RW19 is lower. Under the rolling wheel compaction, the air-void contents of mixes RW95 and RW125 are close to the nominal value, and that of the mix RW475 is slightly lower, while that of mix RW19 is significantly lower. The smaller air-void content of mix RW19 in both compactions does not mean that mix RW19 is easier to compact. Instead, this was caused by the penetration of the CoreLok sample bag into the large surface pores of RW19 specimens. For mix RW19 with a NMAS of 19 mm, use of a larger specimen size may be more appropriate so that the effect of specimen size can be reduced.

The average permeability of each mix, along with the corresponding one standard deviation range, is shown in Figure 5.2. The purpose of the figure is to show how the permeability changes with gradation, evaluated two ways: on Marshall-compacted specimens using one permeability test suited to cylindrical specimens, and on rolling wheel slab specimens using another permeability test suited to slab or field specimens.

The permeability of Marshall specimens was measured with a flexible-wall falling-head permeameter following ASTM PS 129, while the permeability of rolling wheel compacted slab specimens was measured using the

NCAT field permeameter. Based on the results measured on the slab specimens, which are more representative of field compaction, it can be seen that permeability generally increases with NMAS, indicating more interconnected pores inside the mix. The permeability of mix RW475 was about half of the value of RW95 and RW125, and about one fourth of the value of RW19. The Marshall specimens, which were used for testing of raveling potential using the Cantabro test, did not show the same trend.

5.1.2 Acoustic Absorption

The acoustic absorption test was conducted on 100-mm (4-in.) diameter cylindrical specimens cored from rolling wheel–compacted slabs. The result is a vector containing the absorption coefficient in the one-third octave frequency bands from 100 to 2,000 Hz. Each absorption coefficient value ranges from 0 to 1 depending on the fraction of the sound energy that is reflected back at any given frequency, with $\alpha = 0$ indicating complete reflection and $\alpha = 1$ indicating complete absorption.

Figure 5.3 presents the average spectra of sound absorption coefficients in the one third octave frequency bands for each of the four mixes, along with the curve of the reference DGAC mix (D125). As can be seen, the resonant frequencies (The frequency at which the maximum absorption occurs, see Section “Acoustic Absorption” in Appendix C) are not very different for the four mixes, generally between 400 and 650 Hz, with the resonant frequency of RW475 slightly lower than that of the other three mixes. The peak sound absorption coefficient of RW475 and RW19 is about half the value of RW95 and RW125. Note that the impedance tube test was conducted on small size (100-mm [4-in.] diameter) cores for all mixes. For mix RW19, which has an NMAS of 19 mm, the specimen size effect may have influenced the results and the test results may not be representative of the field performance. Compared to the sound absorption coefficient curve of the reference DGAC mix, all four open-graded mixes showed significantly higher sound absorption capability.

Figure 5.4 shows the overall absorption coefficient averaged from values between 200 Hz and 1,600 Hz, along with the average thickness of specimens used in the test. Generally a thicker specimen will have a higher absorption coefficient. As can be seen, the overall sound absorption capability of mix RW475 was lower than that of the other three mixes with larger aggregates, but the difference was not very large. It appears that mix RW125 had better sound absorption than mix RW95, but this was mainly caused by the fact that thicker specimens of RW125 were used in the test. If corrected for specimen thickness, RW125 should have a sound absorption property similar to RW95, which is consistent with the fact that mixes RW125 and RW95 have similar air-void content and permeability (as shown in Figure 5.1 and Figure 5.2). Mix RW19 has lower sound absorption, although it has the highest permeability for the rolling wheel compacted cores, with the difference probably attributable to the large aggregate size in the small absorption tube.

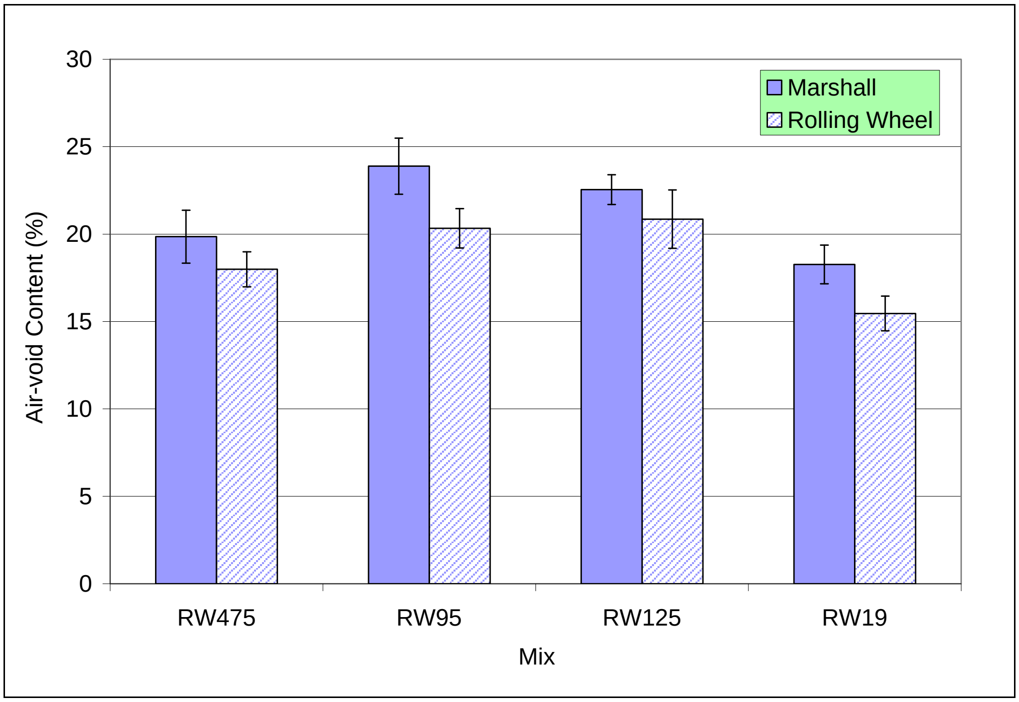


Figure 5.1: Air-void contents of specimens of various NMAS.

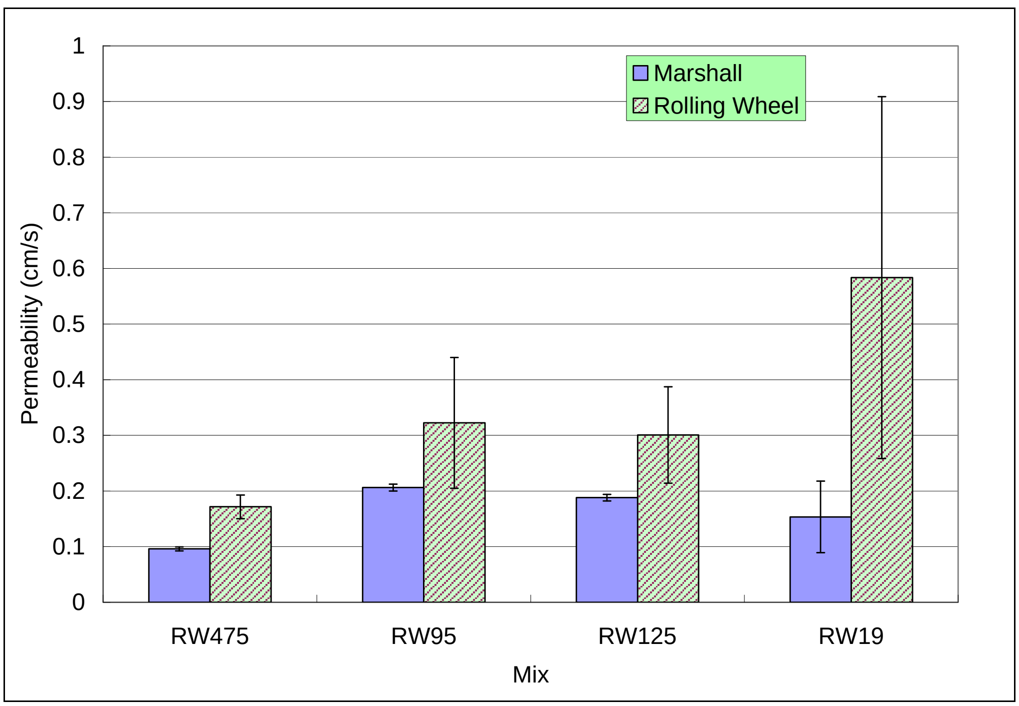


Figure 5.2: Permeability of specimens of various NMAS.

Table 5.1: Summary of Mixes Included in the Study: Acronyms, Descriptions, Mix Designs and Specimen Preparation

Mix ID	Description	Binder Content (%)[1]	Binder Type	Fiber[2]	Hydrated Lime	NMAS (mm)	Mixing Temperature (ºC)	Compaction Temperature (ºC)	Fineness Modulus
RW19	¾ in. (19 mm) open-graded mix with conventional binder	5.0	PG 64-16	none	0	19	135	125	6.08
RW125	Caltrans ½ in. (12.5 mm) open-graded mix with conventional binder	5.9	PG 64-16	none	0	12.5	135	125	5.55
RW95	Caltrans 3/8 in. (9.5 mm) open-graded mix with conventional binder	5.9	PG 64-16	none	0	9.5	135	125	5.43
RW475	No. 4 (4.75 mm) open-graded mix with conventional binder	7.9	PG 64-16	none	0	4.75	135	125	4.58
AR475, AR475D	No. 4 (4.75 mm) open-graded mix with rubberized binder	9.5	Asphalt rubber	none	0	4.75	163	149	4.58
TR475	No. 4 (4.75 mm) open-graded mix with modified (polymers and rubber) binder	9.5	PG 76-22TR	none	0	4.75	163	149	4.58
P58LF	No. 4 (4.75 mm) open-graded mix with polymer-modified binder, lime treatment and fibers	7.9	PG 58-34PM	0.3% CF	1.5%	4.75	155	138	4.58
P475	No. 4 (4.75 mm) open-graded mix with polymer-modified binder	7.9	PG 76-22PM	none	0	4.75	163	149	4.58
AR475T	Same as AR475, except Teichert aggregate source[3]	9.5	Asphalt rubber	none	0	4.75	163	149	4.58
PG475W	Same as RW475 except Graniterock aggregate source[3]	7.9	PG 64-16	none	0	4.75	135	125	4.58
AR95W	Same as RW95 except Graniterock aggregate source[3]	7.1	Asphalt rubber	none	0	9.5	163	149	5.43
PG95T	Same as RW95 except Teichert aggregate source[3]	5.9	PG 64-16	none	0	9.5	135	125	5.43
P475LM	Same as RW475 except lime treated	7.9	PG 64-16	none	1.5%	4.75	135	125	4.58
AR95	3/8 in. (9.5 mm) open-graded mix with rubberized binder	7.1	Asphalt rubber	none	0	9.5	163	149	5.43
AR475P, AR475PD	Same as AR95 except gradation changed (P) and more compaction (PD)	8.4	Asphalt rubber	none	0	4.75+	163	149	4.86
AZ95	Arizona high-binder content open-graded rubberized mix	9.2	Asphalt rubber	none	1.0%	9.5	163	149	5.37
E8	European 8 mm open-graded mix,	6.4	PG 64-16	0.25% CF	1.5%	8	135	125	5.30

Mix ID	Description	Binder Content (%)[1]	Binder Type	Fiber[2]	Hydrated Lime	NMAS (mm)	Mixing Temperature (ºC)	Compaction Temperature (ºC)	Fineness Modulus
	top layer of double layer porous asphalt								
E16	European 16 mm open-graded mix, bottom layer of double layer porous asphalt	4.6	PG 64-16	0.25% CF	1.5%	16	135	125	6.36
SMA6P	Stone mastic asphalt 6 mm maximum aggregate size and polymer-modified binder	6.5	PG 58-34PM	0.25% CF	0	6+	155	138	4.46
G125	Georgia DOT ½ in. (12.5 mm) open-graded mix with polymer-modified binder, lime treatment, and fibers	6.3	PG 76-22PM	0.4% MF	1.4%	12.5	165	160	5.91
SMA4P	Stone mastic asphalt 4 mm maximum aggregate size and polymer-modified binder	6.7	PG 58-34PM	0.25% CF	0	4+	155	138	4.20
D125	Caltrans ½ in. (12.5 mm) dense-graded hot-mix asphalt with conventional binder	6.0	PG 64-16	none	0	12.5	144	125	4.22

[1] By mass of aggregate
[2] CF is cellulose fibers, MF is mineral fibers
[3] All aggregate sources are Syar Lake Herman unless otherwise noted.

5.1.3 Moisture Sensitivity

Moisture sensitivity was evaluated with the indirect tensile strength ratio (TSR) test and the Hamburg wheel tracking device (HWTD) test.

Figure 5.5 and Figure 5.6 show the indirect tensile strength and tensile strength ratio (TSR) of each of the four mixes. Here the TSR is calculated as the ratio of average indirect tensile strength from moisture-conditioned specimens and average indirect tensile strength from unconditioned (dry) specimens. The figures show that mixes RW475 and RW19 have similar tensile strength in both dry and wet (moisture-conditioned) conditions, and these values are significantly higher than those of mixes RW95 and RW125.

With regard to TSR, RW475 performed better than the other three mixes. However, even the TSR value of RW475 (68%) was not high compared to the TSR criteria established for conventional dense-graded mixes (DGAC), which were around 75 to 80 percent. If these criteria are used, the low TSR values suggest that all the four open-graded mixes are moisture sensitive and that treatment is needed to improve their TSR values. However, the criteria for DGAC may not be well calibrated for moisture damage in open-graded mixes. Observation of the split faces of test specimens revealed no stripping inside the mixes, indicating that there was not adhesive failure, that is, failure of the bond between the mastic and the aggregate. Considering the high binder contents in these open-graded mixes, it is also unlikely that there was cohesive failure, meaning that the binder-fines mastic was probably not significantly weakened by moisture. The current TSR test itself, instead, may not be appropriate for evaluating the moisture sensitivity of open-graded mixes. One reason is that part of the conditioning procedure of this test, a 24-hour 60°C water bath, exposes the open-graded specimens to a high temperature for a long time. This procedure allows the specimens to creep under self weight and to loosen since they lack the rigid circumferential confinement they would have in the field. Susceptibility to this procedure is much less of a problem for dense-graded mixes.

Figure 5.7 presents the rut depth curves of the four mixes from the HWTD. Each curve in the plot is the average of results from two replicates. It can be seen from the figure that RW19 performed much better than the other three mixes. This is likely due to the better aggregate interlock in RW19 because the mix contains mostly large aggregates. Mix RW475 performed no worse than mixes RW95 and RW125. These results indicate that in terms of resistance to premature failure due to a combination of moisture damage and rutting, reducing the aggregate size from NMAS 12.5 mm to NMAS 4.75 mm does not harm the mix performance.

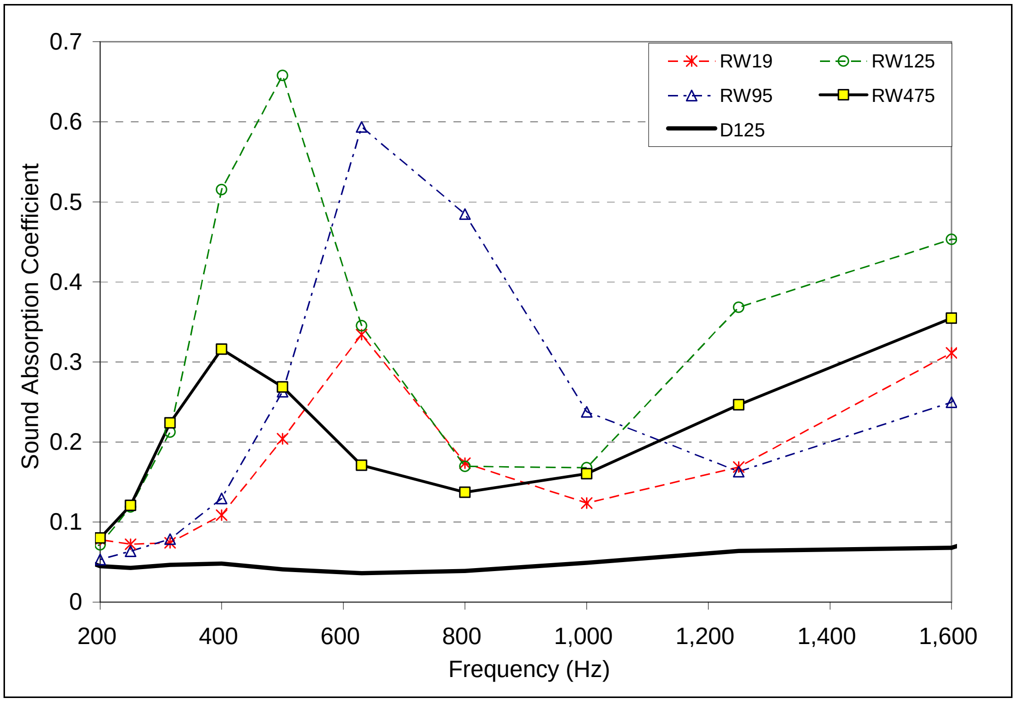


Figure 5.3: Spectra of sound absorption coefficients of mixes of various NMAS.

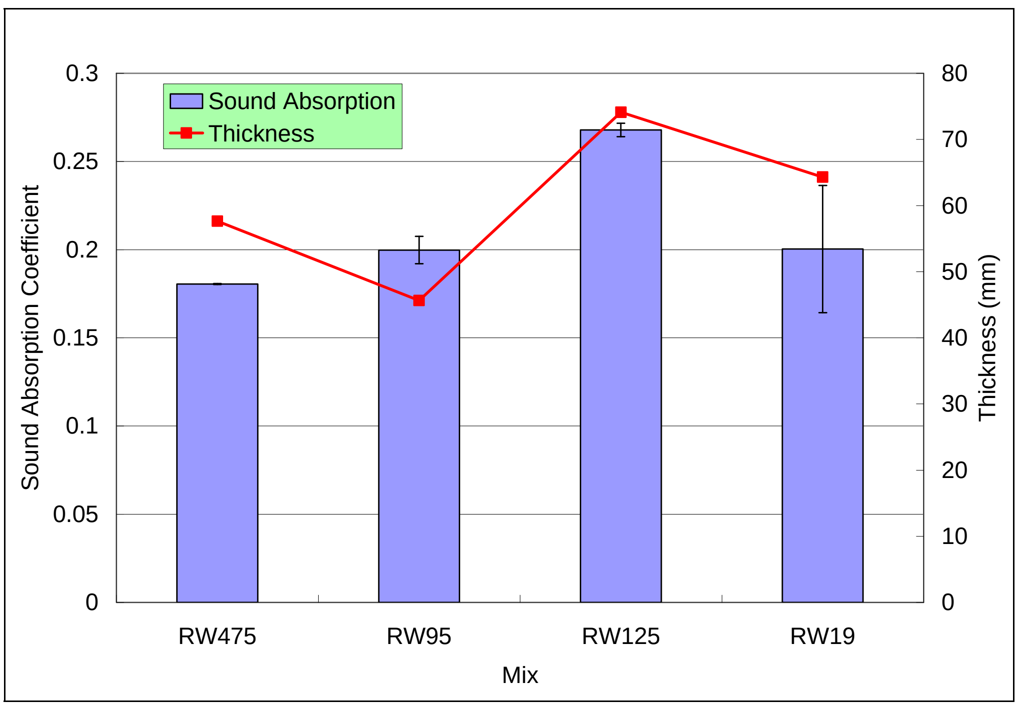


Figure 5.4: Average sound absorption coefficients of mixes with different NMAS.

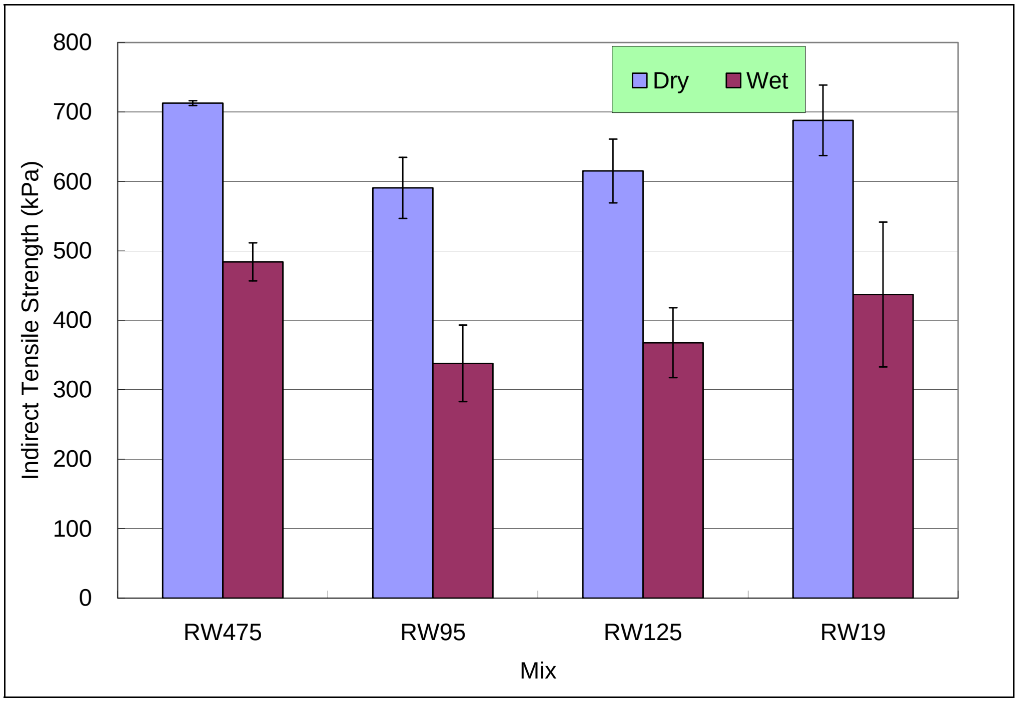


Figure 5.5: Indirect tensile strength of dry and moisture-conditioned specimens of various NMAS.

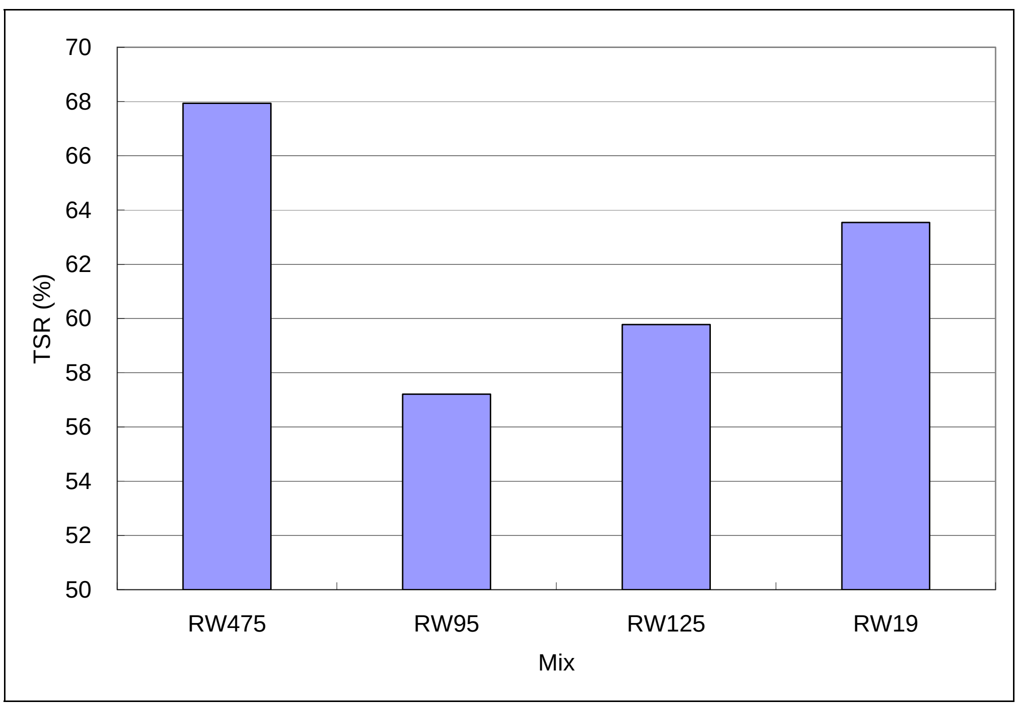


Figure 5.6: Indirect tensile strength ratio of mixes of various NMAS.

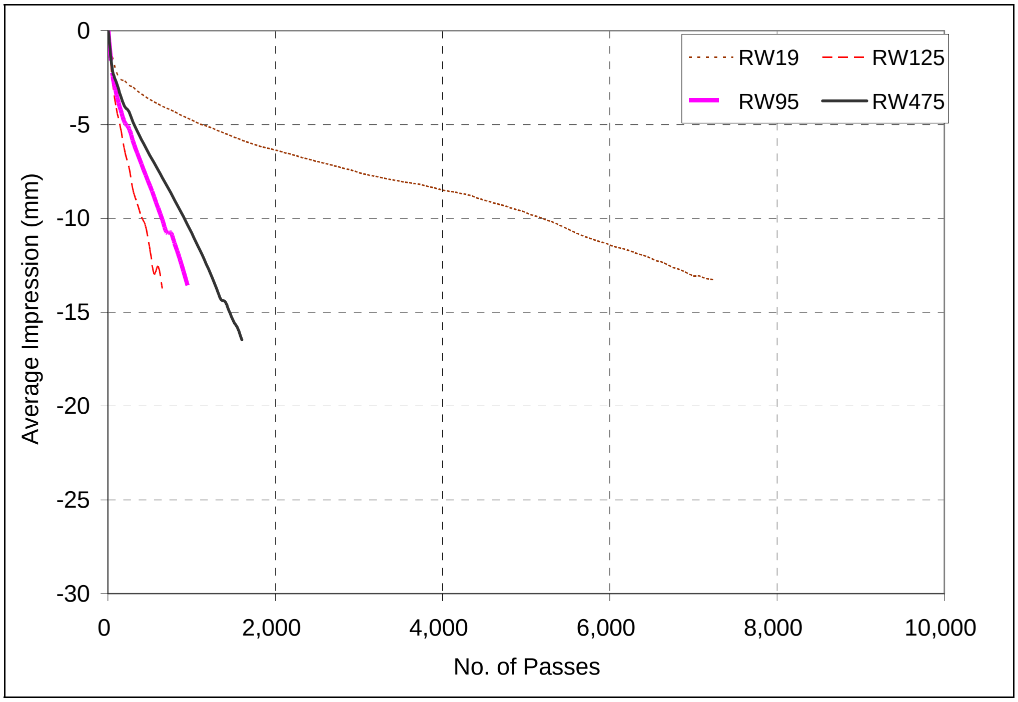


Figure 5.7: Rut progression curve of mixes of various NMAS.

5.1.4 Resistance to Raveling

Resistance to raveling was evaluated using the Cantabro test. Figure 5.8 shows the average and range of one standard deviation of the Cantabro loss values for aged and unaged specimens. The figure shows that the Cantabro loss for aged specimens is always higher than that of unaged specimens.. This is because the one-week aging at 60°C makes the asphalt binder more brittle and more prone to abrasion loss in the test, which is intended as an indicator of raveling performance. The relative ranking of mixes, however, is the same based on aged or unaged specimens. Among the four mixes investigated, RW95, RW125, and RW19 all showed severe material loss during the test, indicating poor resistance to raveling. Mix RW475, on the other hand, showed better resistance to raveling, likely due to its high binder content.

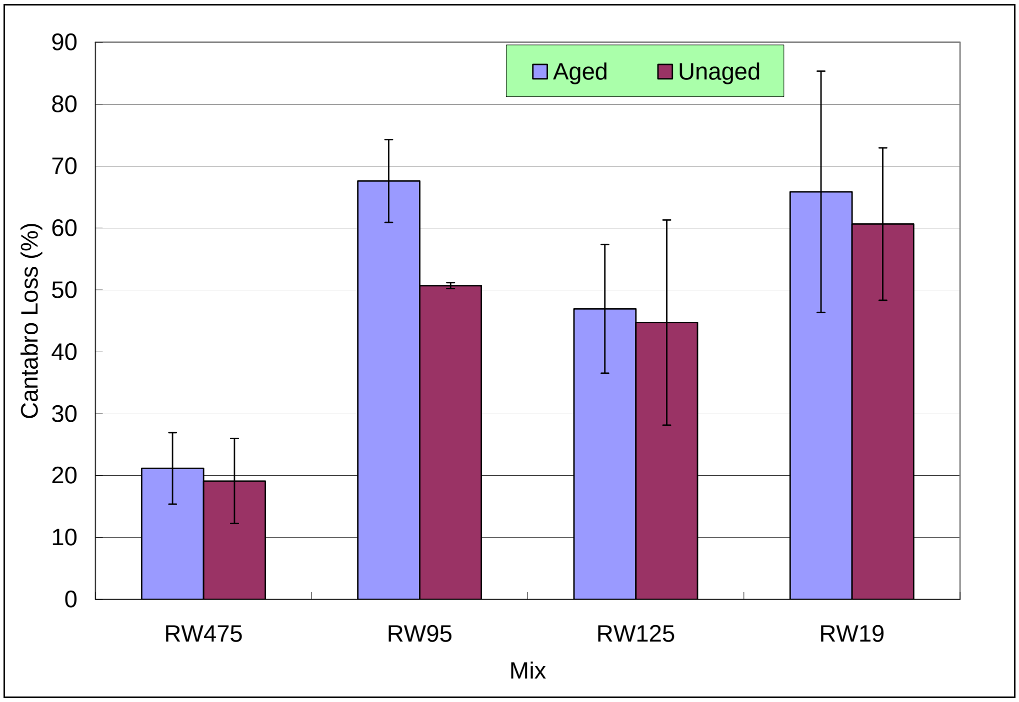


Figure 5.8: Cantabro loss results of aged and unaged mixes of various NMAS.

5.1.5 Friction

Friction was measured on slab specimens with both a British Pendulum Tester (BPT) and a Dynamic Friction Tester (DFT). Figure 5.9 shows the average and range of one standard deviation of the British Pendulum Number (BPN) results for each of the four mixes, and reveals that the BPN is generally in the 60 to 70 range for all of them. Although RW475, RW95, and RW19 exhibited statistically similar BPN values, the BPN of RW125 was statistically significantly lower than that of the other three mixes. It is unclear why this one gradation had lower BPT results. Generally, the BPT did not distinguish among the various mixes that had the same aggregate source, as was the case in this experiment, regardless of differences in the mixes besides the aggregate source. In addition, during this study it was found that the BPN testing was sensitive to operators and test spots, and often showed poor repeatability.

On the other hand, in the DFT results shown in Figure 5.10, RW475, which had the smallest aggregates, had a lower friction coefficient than the other three mixes at any test speed from 0 to 90 km/h. RW19, with the largest aggregates, showed the highest friction coefficient when the slip speed was over 25 km/h. RW95 and RW125 showed similar friction properties at all test speeds, which is to be expected since these two mixes have nearly the same gradation except for the largest size aggregates.

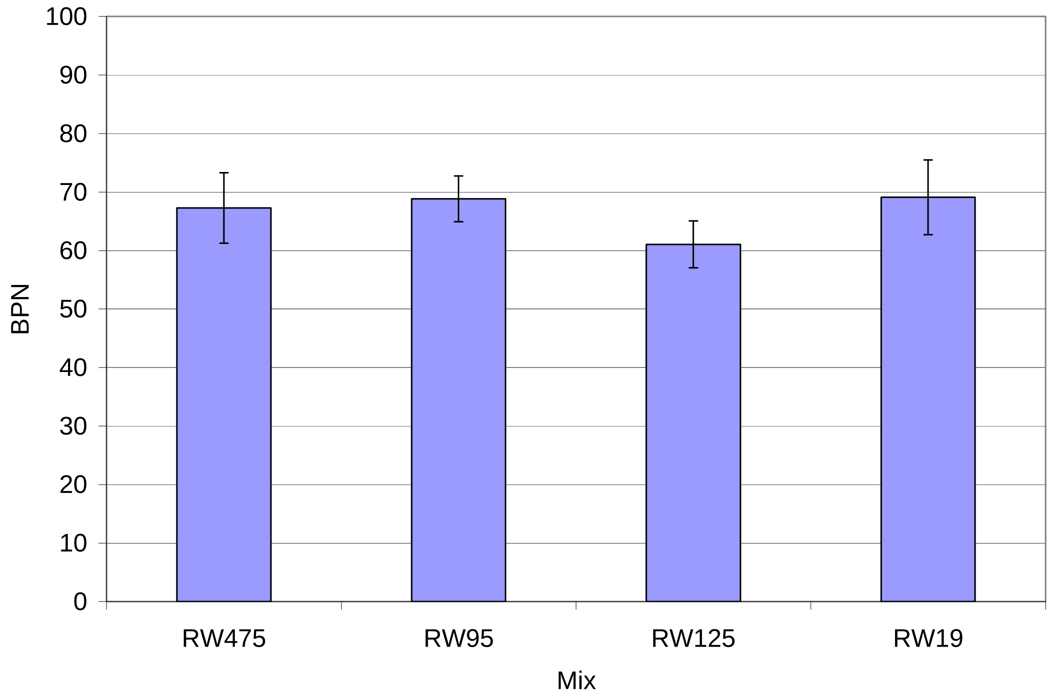


Figure 5.9: BPT results of mixes of various NMAS.

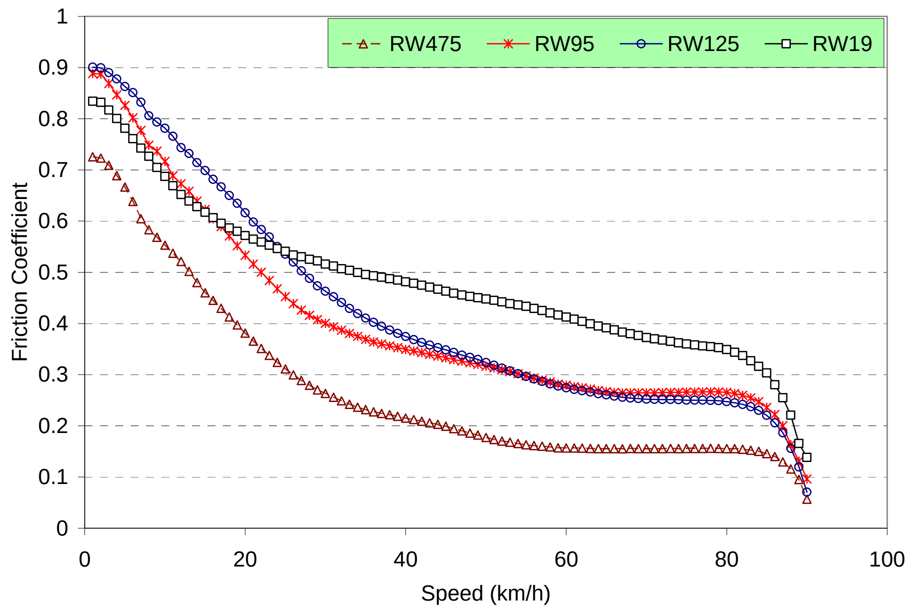
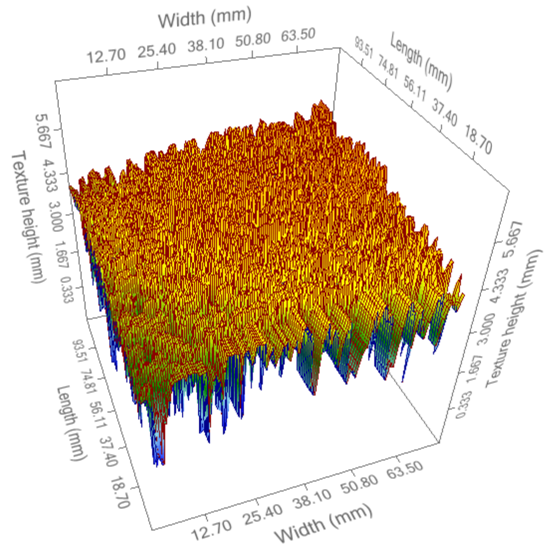


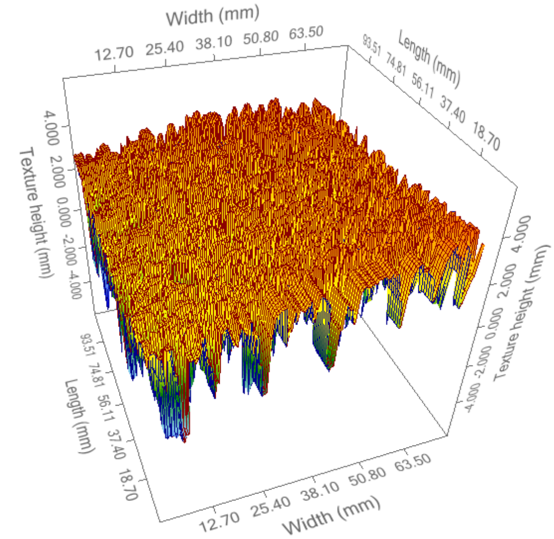
Figure 5.10: DFT results of mixes of various NMAS.

5.1.6 Texture

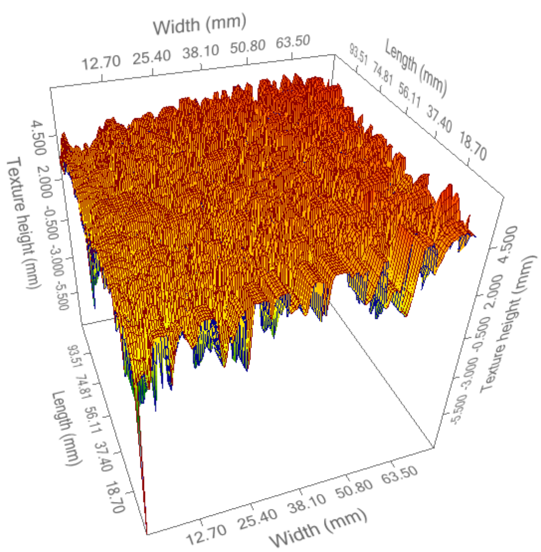
The surface profiles of the four mixes, as measured using the AMES Engineering laser texture scanner, are illustrated in Figure 5.11. (A picture of the compacted specimen surface of each mix is included in Appendix E: Surface Photos of Mixes Included in the Study.) The mean profile depths (MPD) calculated from these profiles are summarized in Figure 5.12, which shows that MPD increases with NMAS, with the RW475 mix having the lowest MPD. Lower texture depth often corresponds to less low frequency tire/pavement noise, and also to lower friction on wet pavement, which is consistent with the DFT results.



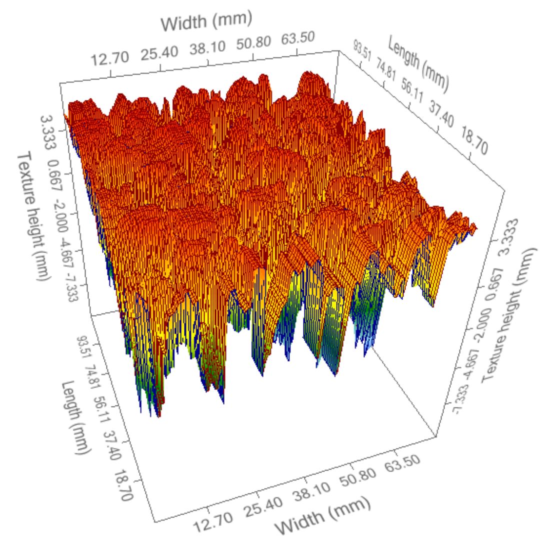
(a) RW475



(b) RW95



(c) RW125



(d) RW19

Figure 5.11: Surface profiles of mixes of various NMAS.

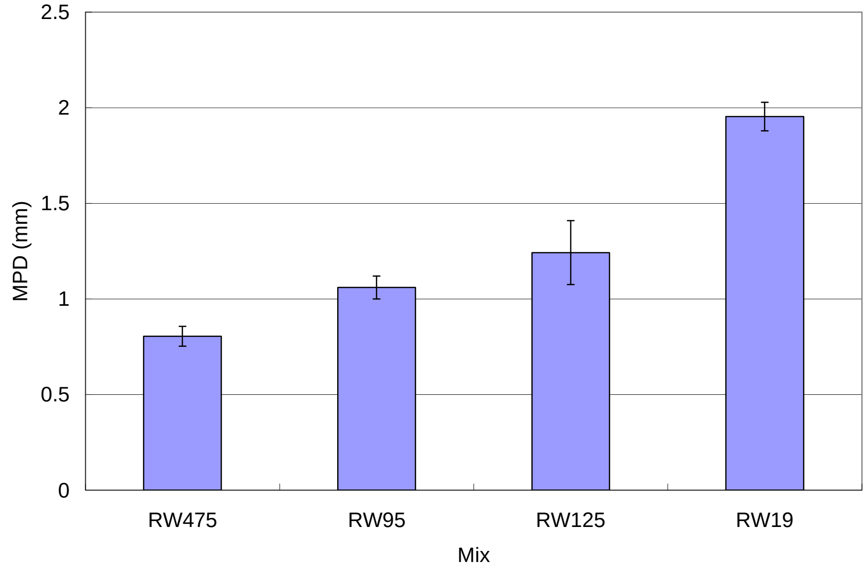


Figure 5.12: MPD of mixes of various NMAS.

5.1.7 Resistance to Permanent Deformation

The initial shear modulus and cycles to failure (5 percent permanent shear strain) are shown in Figure 5.13 and Figure 5.14, respectively. As can be seen, mix RW19 had higher initial shear modulus and much larger number of cycles to failure than other mixes, while the other three mixes showed no significant difference in terms of rutting resistance. RW475, RW95, and RW125 all failed rapidly in the RSST-CH test. This result is consistent with the observations in the HWTD test. Again, the rutting resistance of RW475 is no worse than that of RW95 and RW125.

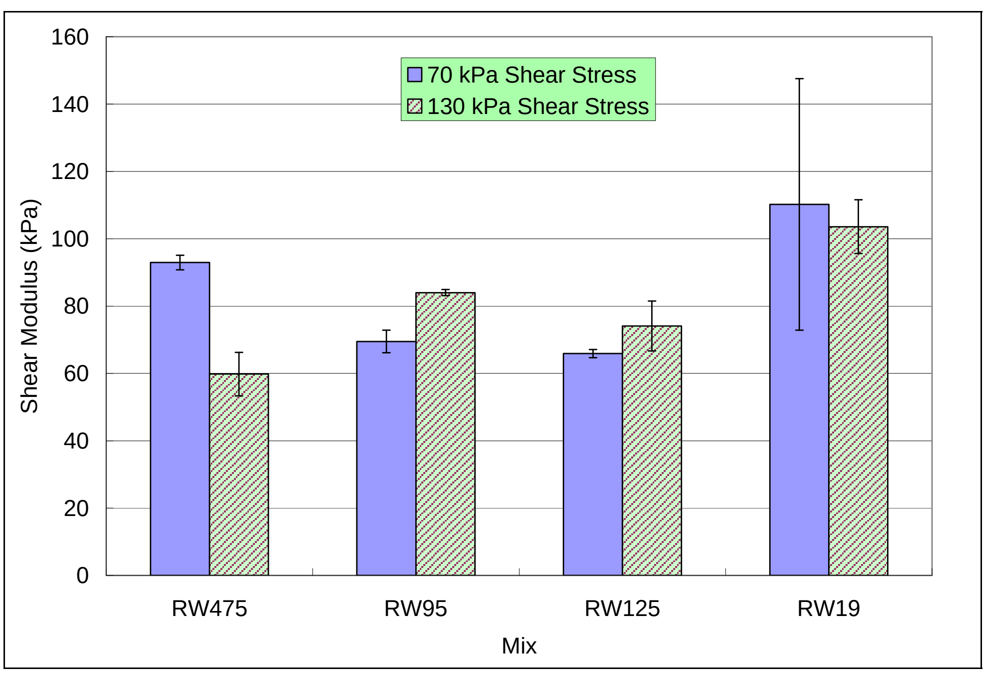


Figure 5.13: Initial shear modulus of mixes of various NMAS.

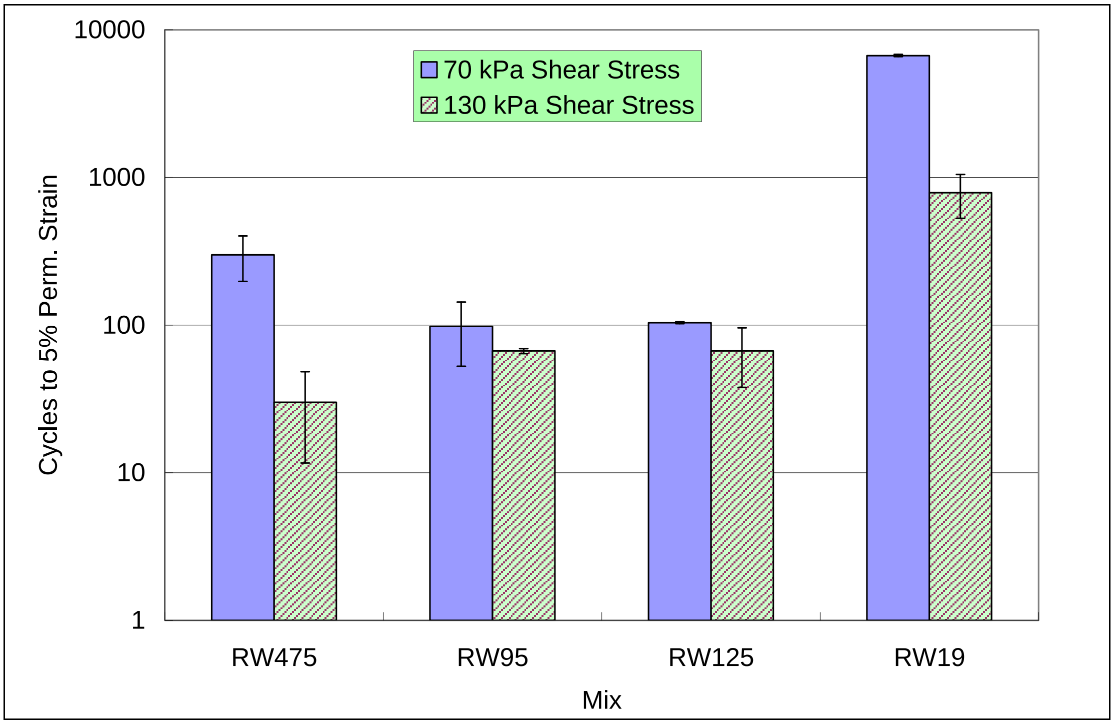


Figure 5.14: Cycles to 5 percent permanent shear strain of mixes of various NMAS.

5.1.8 Resistance to Reflective Cracking

Resistance to reflective cracking of the mixes was evaluated using the Texas Overlay Tester. Two parameters were recorded in this test, the maximum load, which reflects the initial stiffness of a mix, and the number of cycles to failure, which reflects the resistance of a mix to cracking. Figure 5.15 and Figure 5.16 summarize the test results for these two parameters for the four mixes.

As can be seen from Figure 5.15, the average maximum load of RW475 was close to that of RW19, and higher than those of RW95 and RW125, indicating a higher initial stiffness. RW19 showed a larger variation of maximum load, indicating that the specimens used were not uniform, which is due to the small specimen size relative to the 19 mm NMAS.

Figure 5.16 shows that the average number of cycles to failure is inversely correlated to the size of aggregate NMAS. RW475 had the highest resistance to reflective cracking while RW19 had the lowest.

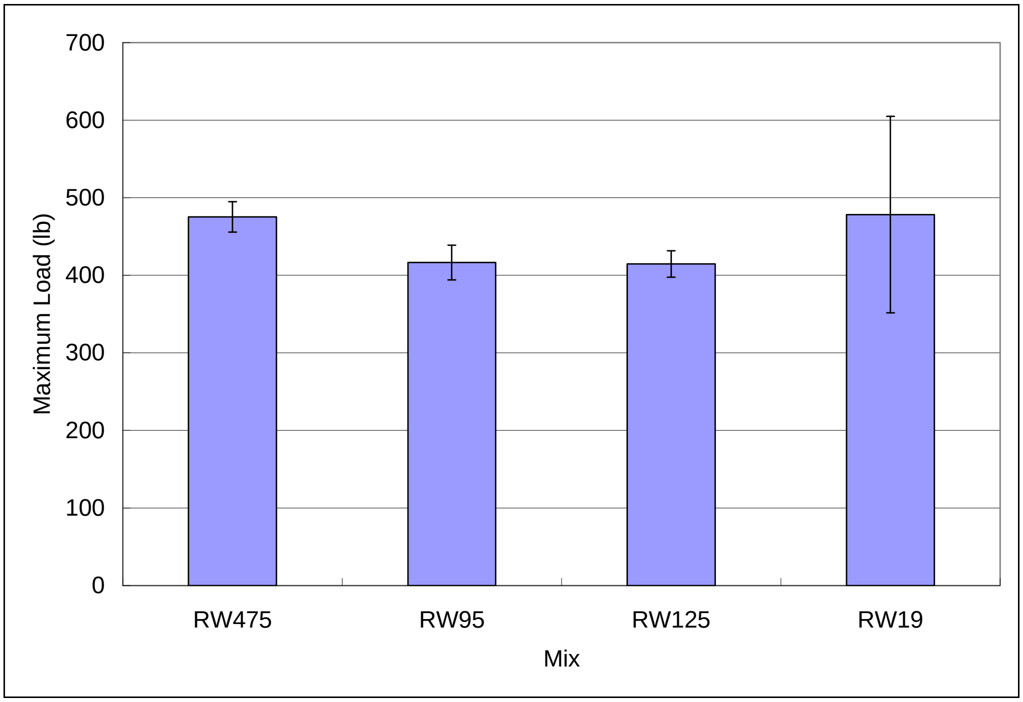


Figure 5.15: Maximum load of mixes of various NMAS.

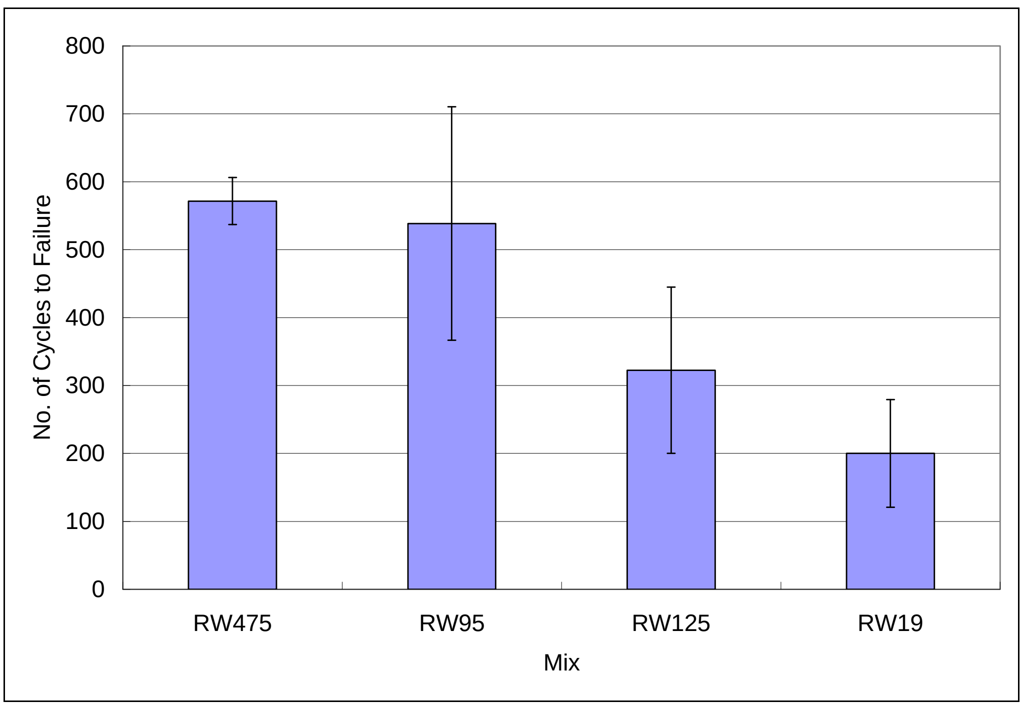


Figure 5.16: Number of cycles to failure of mixes of various NMAS.

5.1.9 Summary of Results from the First Experiment

The primary observations from the results of the first experiment regarding the effects of aggregate gradation are summarized as follows:

Property	Primary Observations
Air-void content	• Mixes had approximately the same air-void contents. • Laboratory compaction methods have an effect on specimen air-void contents.
Permeability	• Larger nominal maximum aggregate size (NMAS) results in higher permeability. • Reducing NMAS from ½ inch (12.5 mm) or 3/8 inch (9.5 mm) to No. 4 (4.75 mm) reduced permeability by half.
Raveling	• 4.75 mm gradation improved resistance.
Moisture sensitivity	• 4.75 mm moisture sensitivity expected to be same as for 9.5 and 12.5 mm mixes.
Reflective cracking	• 4.75 mm gradation improved resistance.
Rutting	• No significant effect of aggregate size.
Surface friction	• Surface friction at speeds over 12 mph (20 km/hr) of 4.75 mm NMAS mix approximately 50 to 60 percent less than that of 9.5 and 12.5 mm NMAS mixes.
Noise-related properties	• 4.75 mm NMAS mix had slightly reduced sound absorption and reduced permeability compared with 12.5 mm NMAS mix, indicating 4.75 mm mix will have slightly greater high frequency noise. • Improved resistance to raveling and cracking indicates that 4.75 mm mix will have lower low frequency noise.

Based on the above observations, it can be concluded that using the 4.75 mm NMAS mix may be a way to retain the noise-reducing properties of conventional 9.5 and 12.5 mm open-graded mixes while increasing the durability of the surface. However, the surface friction of the 4.75 mm mix, as measured by the DFT, is reduced compared with the 9.5 and 12.5 mm mixes. Therefore, the friction indicated in the laboratory by the DFT needs to be checked in the field, and if it is found to be unacceptably low, additional measures are needed to counteract the reduction in friction when a 4.75-mm NMAS is used in the asphalt surface mix.

5.2 Effect of Binder Type and Additives

The second experiment was designed to investigate the effect of binder type and additives on noise reduction and durability. The experiment included one aggregate gradation (4.75-mm NMAS), five binder types (PG 64-16, PG 58-34PM, PG 76-22PM, asphalt rubber, and PG 76-22TR), and two additives (hydrated lime and cellulose fiber). A total of five new mixes were included in the experiment: AR475, P475, P475LM, P58LF, and TR475, as summarized in Table 4.2, along with the reference mix RW475 tested in the first experiment.

5.2.1 Air-Void Content and Permeability

A nominal air-void content of 20 percent was selected for fabricating all specimens in this experiment. Figure 5.17 shows the average air-void content, as well as the range of one standard deviation, of each mix from specimens compacted by two methods. As can be seen, rolling wheel compaction produced specimens with slightly lower air-void contents than Marshall compaction. Comparison with the air-void contents of the mix containing PG 64-16 binder (RW475) revealed slightly higher values in the mixes containing PG 76-22PM (P475) and PG 64-16 with hydrated lime (P475LM), and slightly lower values in the mix containing PG 76-22TR (TR475). It should be remembered that different permeability tests were used for the Marshall-compacted cylindrical specimens and the slabs produced by the rolling wheel compactor, as was discussed previously with regard to the first experiment.

Figure 5.18 shows the average permeability of each mix compacted by the rolling wheel compactor, along with the corresponding one standard deviation range, as measured using the NCAT field permeameter. It can be seen that permeability was generally reduced when the conventional binder (PG 64-16) was replaced with polymer-modified binder (PG 76-22PM, PG 58-34PM) or rubberized asphalt (asphalt rubber and PG 76-22TR), or treated with hydrated lime. It should be remembered that the rubberized asphalt mixes have 20 percent more binder than the conventional and polymer-modified mixes.

Note that the difference in air-void content of various mixes was not as significant as the difference in permeability. This indicates that in mixes containing the polymer-modified binder or asphalt rubber, or treated with hydrated lime, air voids are less interconnected than the air voids in the untreated conventional mix. There seems to be no significant difference in permeability among mixes containing asphalt rubber or polymer-modified binders, while the mix containing the PG 76-22TR binder (TR475) showed the lowest permeability among all 4.75 mm NMAS mixes. However, it must also be noted that the permeability of mix TR475 is still one or two orders of magnitude higher than that of conventional DGAC mixes.

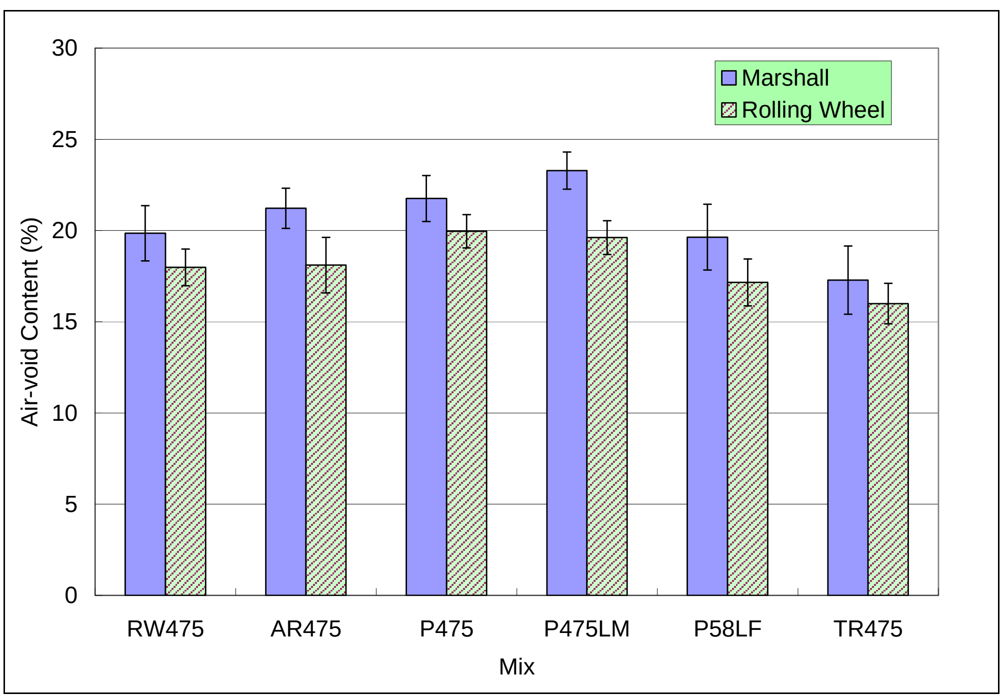


Figure 5.17: Air-void contents of mixes with 4.75 mm NMAS and various binders and additives.

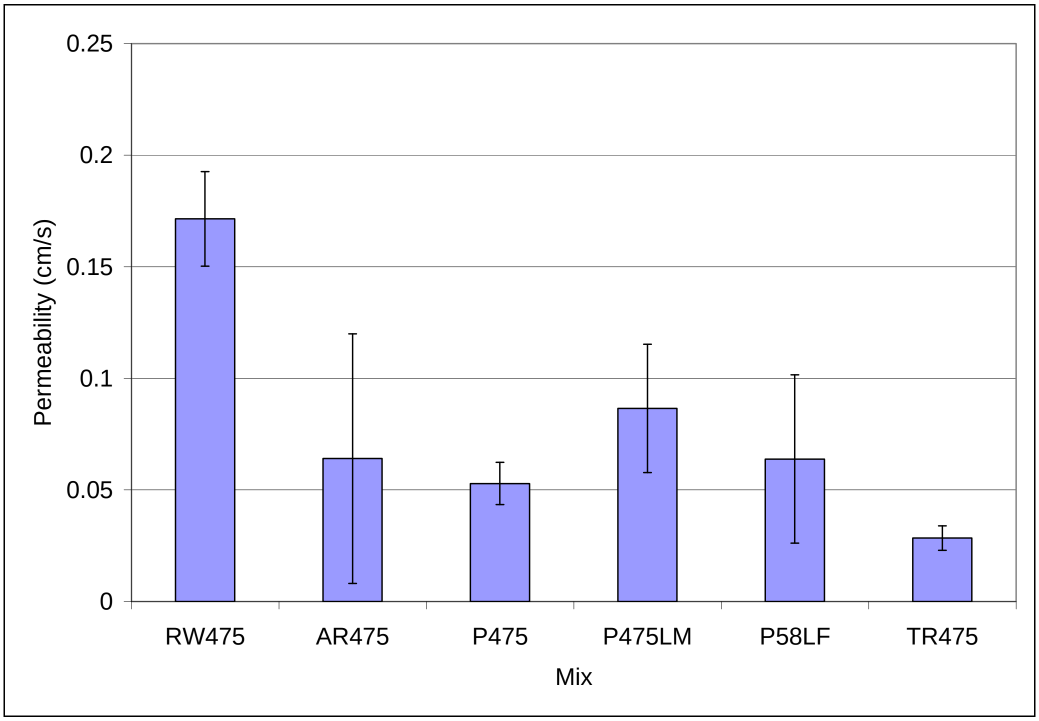


Figure 5.18: Permeability of mixes with 4.75 mm NMAS and various binders and additives compacted by rolling wheel.

5.2.2 Acoustic Absorption

Figure 5.19 presents the average spectra of sound absorption coefficients in the one-third octave frequency bands for each mix except P475LM (which was not measured in this study), along with the curve of the reference DGAC mix. As can be seen, the peak acoustic absorption and resonant frequency of mixes containing polymer-modified binders or rubberized binders were generally higher than those of the mix with conventional binder (RW475). The mix with asphalt rubber (AR475) showed the highest peak acoustic absorption and resonant frequency.

Figure 5.20 shows the overall absorption coefficient averaged from values between 200 Hz and 1,600 Hz, along with the average thickness of specimens used in the test. A higher overall absorption coefficient was observed in mixes AR475, P475, and TR475, with AR475 showing the highest value.

From Figure 5.18 and Figure 5.20, we see that although using polymer-modified or rubberized binders reduces permeability, it does not reduce acoustic absorption—and even increases it to some extent.

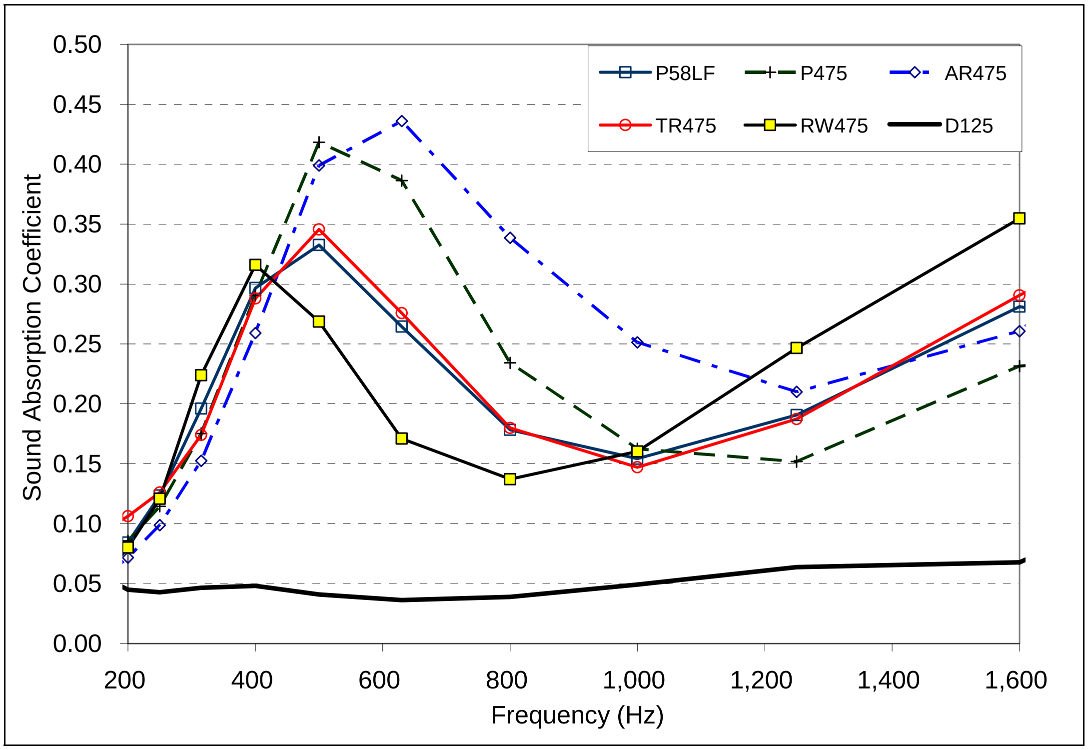


Figure 5.19: Spectra of sound absorption coefficients of mixes with 4.75 mm NMAS and various binders and additives.

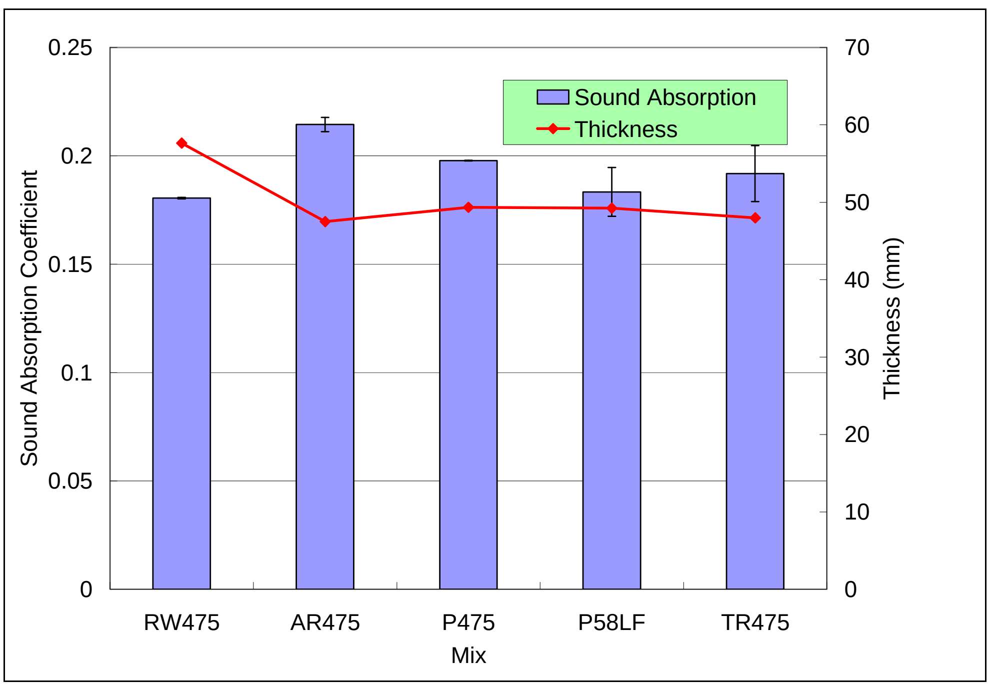


Figure 5.20: Average sound absorption coefficients of mixes with 4.75 mm NMAS and various binders and additives.

5.2.3 Moisture Sensitivity

Figure 5.21 and Figure 5.22 show the indirect tensile strength and tensile strength ratio (TSR) for each mix. As can be seen, mixes with rubberized asphalt (AR475 and TR475) and PG 58-34 PM binder (P58LF) had lower tensile strength in both dry and wet (moisture-conditioned) conditions than the mix with conventional binder (RW475), while the mix with PG 76-22 PM (P475) binder had tensile strength similar to mix RW475. Adding hydrate lime or cellulose fiber did not improve the indirect tensile strength. In terms of TSR, mix AR475 (asphalt rubber binder) showed the lowest moisture resistance. In addition, neither using polymer-modified binder nor adding hydrated lime or fibers showed any improvement in moisture resistance.

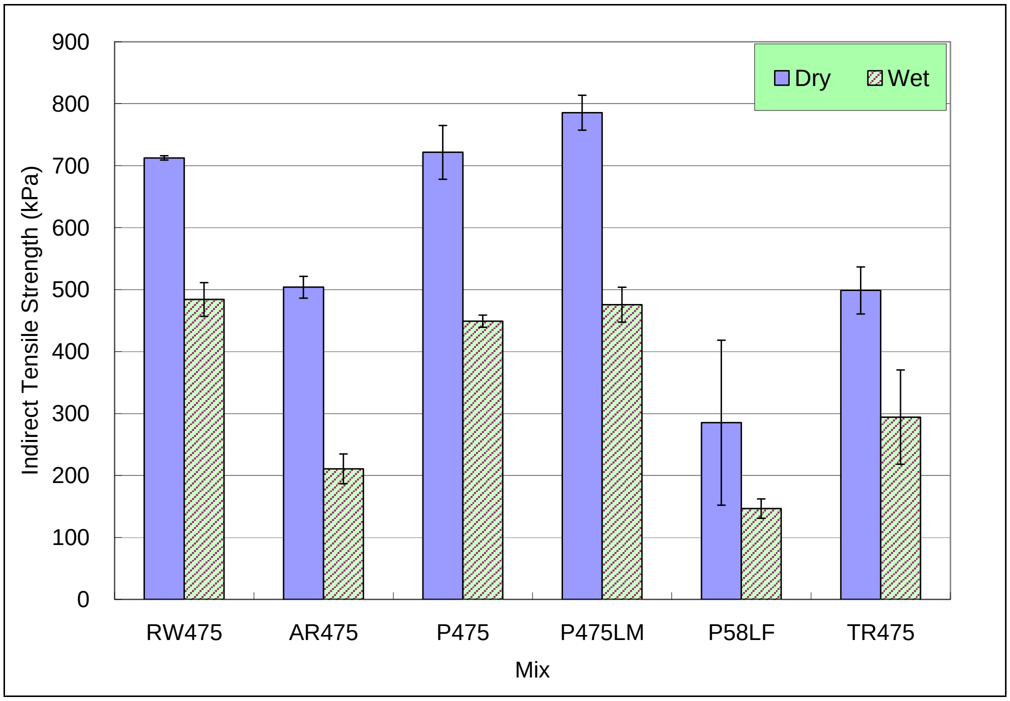


Figure 5.21: Indirect tensile strength of dry and moisture-conditioned specimens with 4.75 mm NMAS and various binders and additives.

Figure 5.23 presents the rut depth curve of each mix from the HWTD. Each curve in the plot is the average of results from two replicates. It can be seen from the figure that P475LM had a rut depth curve similar to that of RW475, indicating that adding hydrated lime (dry lime on damp aggregate) did not improve the resistance of 4.75-mm NMAS open-graded asphalt mix. On the other hand, using polymer-modified asphalt or rubberized asphalt improved the performance of mixes in the HWTD test. Among the four mixes with modified binders, mix P475 (with PG 76-22 PM binder) showed the best performance in the HWTD test, while mix TR475 (with PG 76-22 PM binder) showed the least improvement of performance, compared to mix RW475.

The relative performance of various mixes based on the HWTD test is different from that based on the TSR test. For example, in the HWTD test, mix AR475 performed better than mix RW475, while in the TSR test, mix AR475 showed a lower TSR value than mix RW475. As discussed in Section 5.1.3, the current TSR test may not be appropriate for evaluating the moisture sensitivity of open-graded mixes. It is believed that the HWTD test better simulates the field performance of open-graded mixes. Therefore, using polymer- or rubber-modified binders can improve the resistance of open-graded mixes to moisture/premature damage.

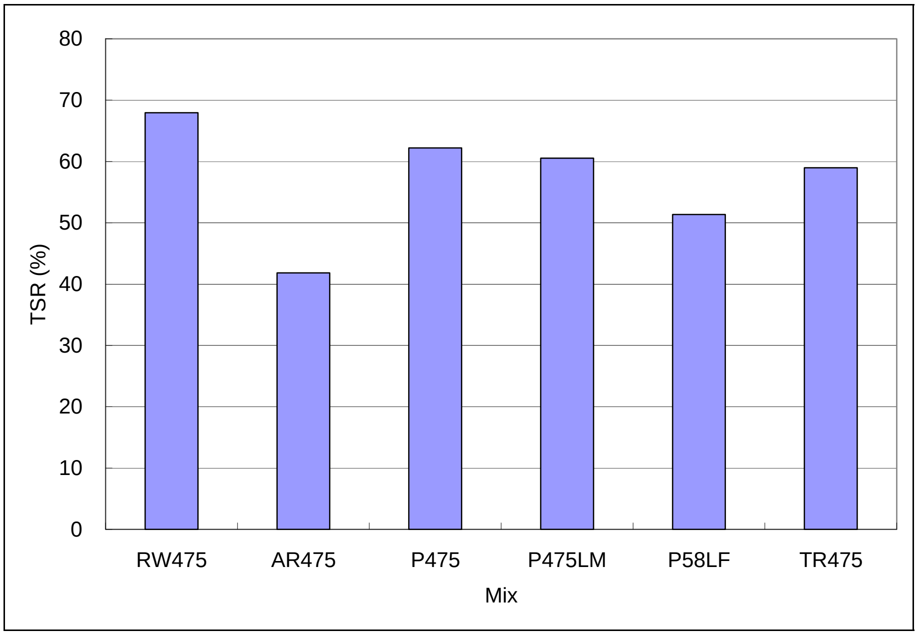


Figure 5.22: Indirect tensile strength ratio of mixes with 4.75 mm NMAS and various binders and additives.

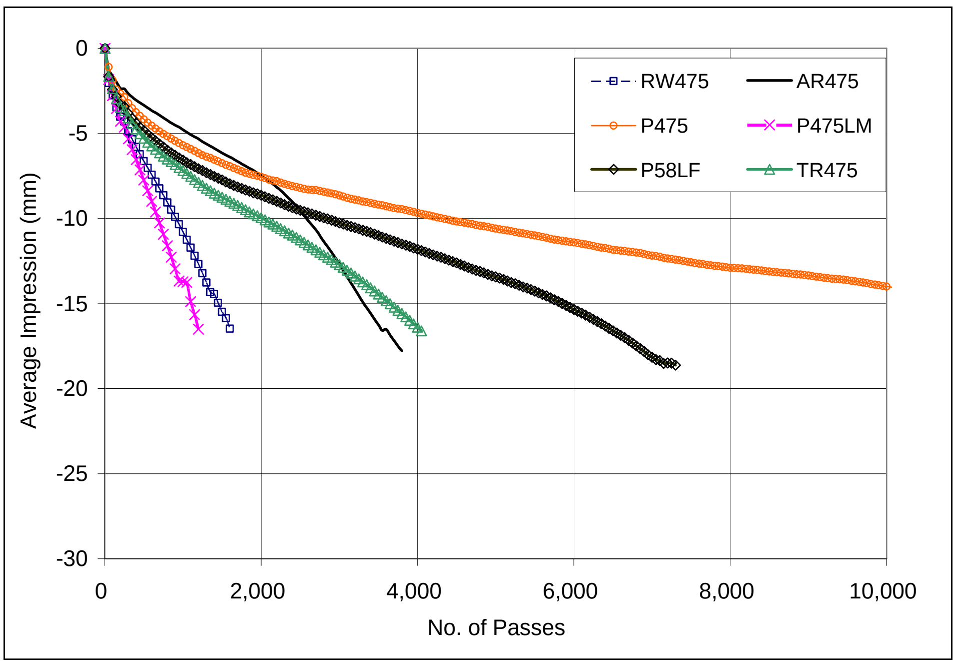


Figure 5.23: Rut progression curve of mixes with 4.75 mm NMAS and various binders and additives from HWTD test.

5.2.4 Resistance to Raveling

Figure 5.24 shows the average and range of one standard deviation of the Cantabro loss values from aged and unaged specimens. Again, the Cantabro loss results of aged specimens are generally higher than those of unaged specimens. The Cantabro loss values of mix P475LM were slightly lower than those of mix RW475, indicating that use of hydrated lime can slightly improve the resistance to raveling of an open-graded mix. These test results suggest that use of asphalt rubber or polymer-modified binders can significantly improve the resistance to raveling of an open-graded mix, with polymer-modified binders performing better.

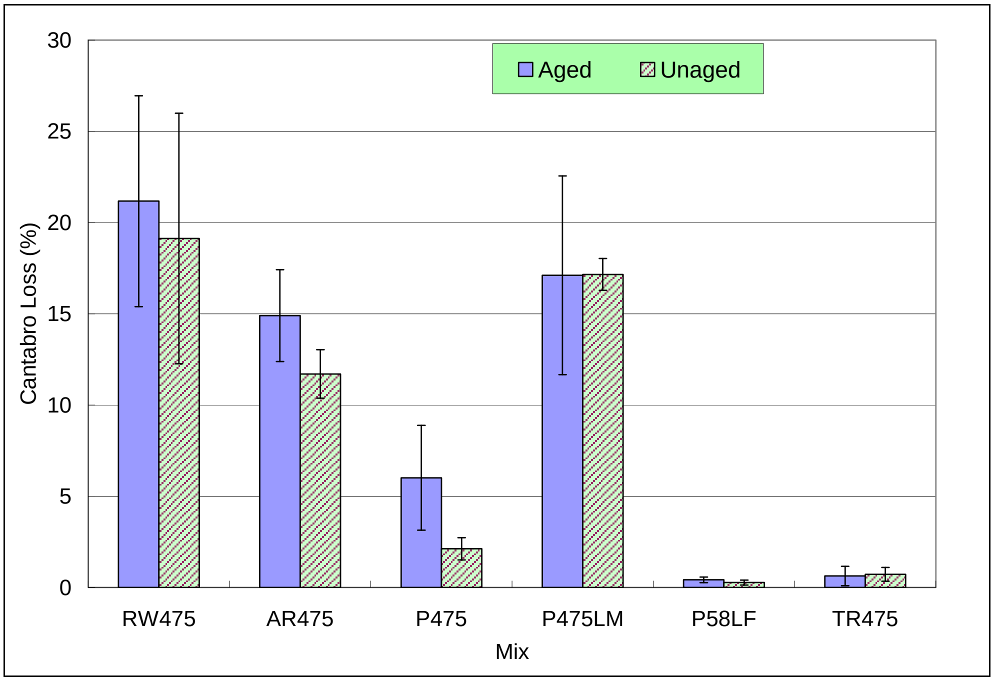


Figure 5.24: Cantabro loss results of aged and unaged mixes with 4.75 mm NMAS and various binders and additives.

5.2.5 Friction

Friction was measured with both a British Pendulum Tester (BPT) and a Dynamic Friction Tester (DFT) on slab specimens. Figure 5.25 shows the average and range of one standard deviation of the British Pendulum Number (BPN) results for each mix. As can be seen, the BPN of mixes containing polymer- or rubber-modified binders or treated with hydrated lime is slightly higher than that of RW475. The results from the DFT, shown in Figure 5.26, show the same relative performance. Using asphalt rubber or adding hydrated lime increases the surface friction of a 4.75-mm NMAS open-graded mix to a level similar to that of mixes with 9.5 mm or 12.5 mm NMAS. This result is encouraging since the only deficiency determined in Section 5.1.9 of this study of the 4.75-mm NMAS OGFC mix for use as surface mix was low friction.

5.2.6 Texture

The surface profiles of the six mixes, as measured using the AMES Engineering laser texture scanner, are shown in Figure 5.27. The mean profile depths (MPD) calculated from these profiles are summarized in Figure 5.28. As can be seen in Figure 5.27, MPD is slightly higher for mixes containing polymer-modified or rubberized binders than for the mix with conventional binder, possibly due to the fact that mixes containing the modifiers are more difficult to compact. Although these mixes are compacted at higher temperatures, heat loss is more significant during compaction due to a larger difference between mix and ambient temperatures. The MPDs of mixes AR475, P475, and TR475 were close to that of mix RW95 (as in Figure 5.12). Because all the mixes included in this second experiment have the same aggregate gradations, the difference in surface macrotexture should arise from the use of various binders or additives. When the conventional PG 64-16 binder is replaced with asphalt rubber, MPD was increased by about 25 percent, to a value around 1 mm. This level of MPD still can ensure pavement smoothness for ride comfort, and it helps the pavement surface to maintain friction at high vehicle speeds under wet pavement conditions. This is consistent with findings from the DFT test in Section 5.2.5.

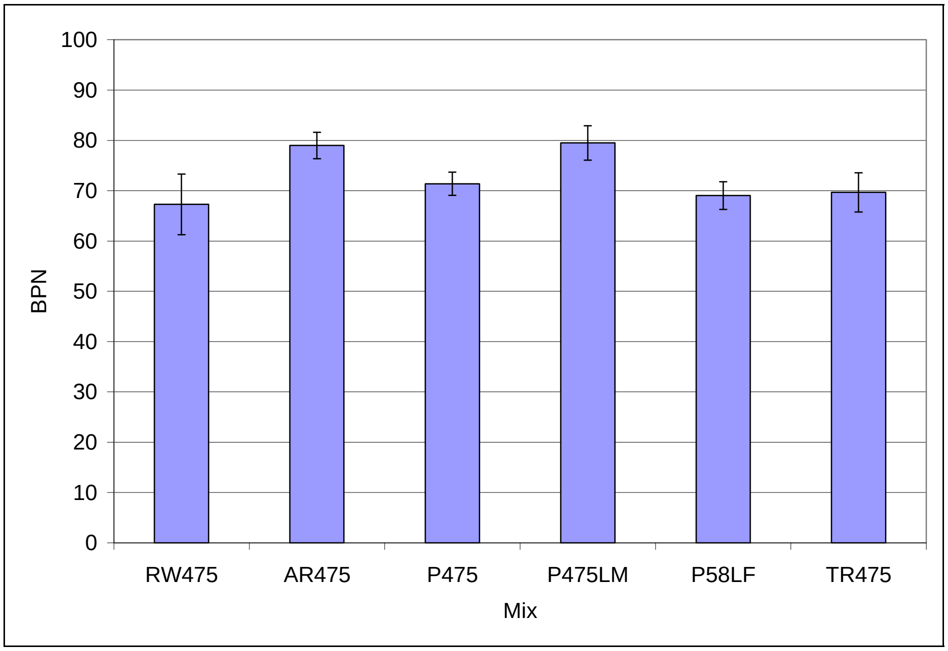


Figure 5.25: BPT results of mixes with 4.75 mm NMAS and various binders and additives.

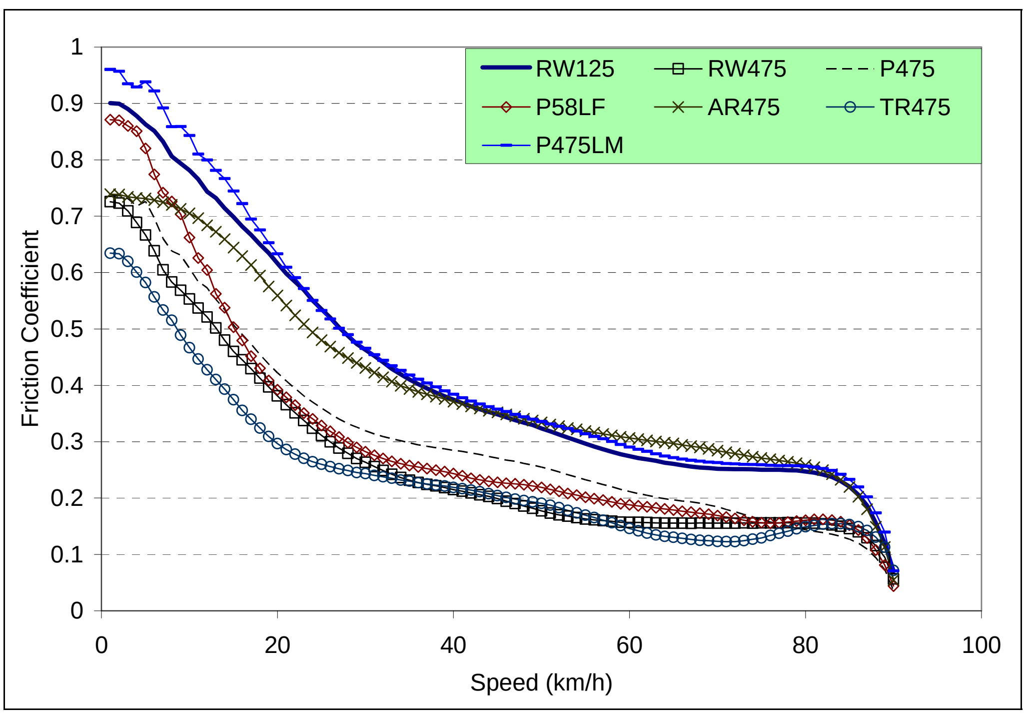


Figure 5.26: DFT results of mixes with 4.75 mm NMAS and various binders and additives.

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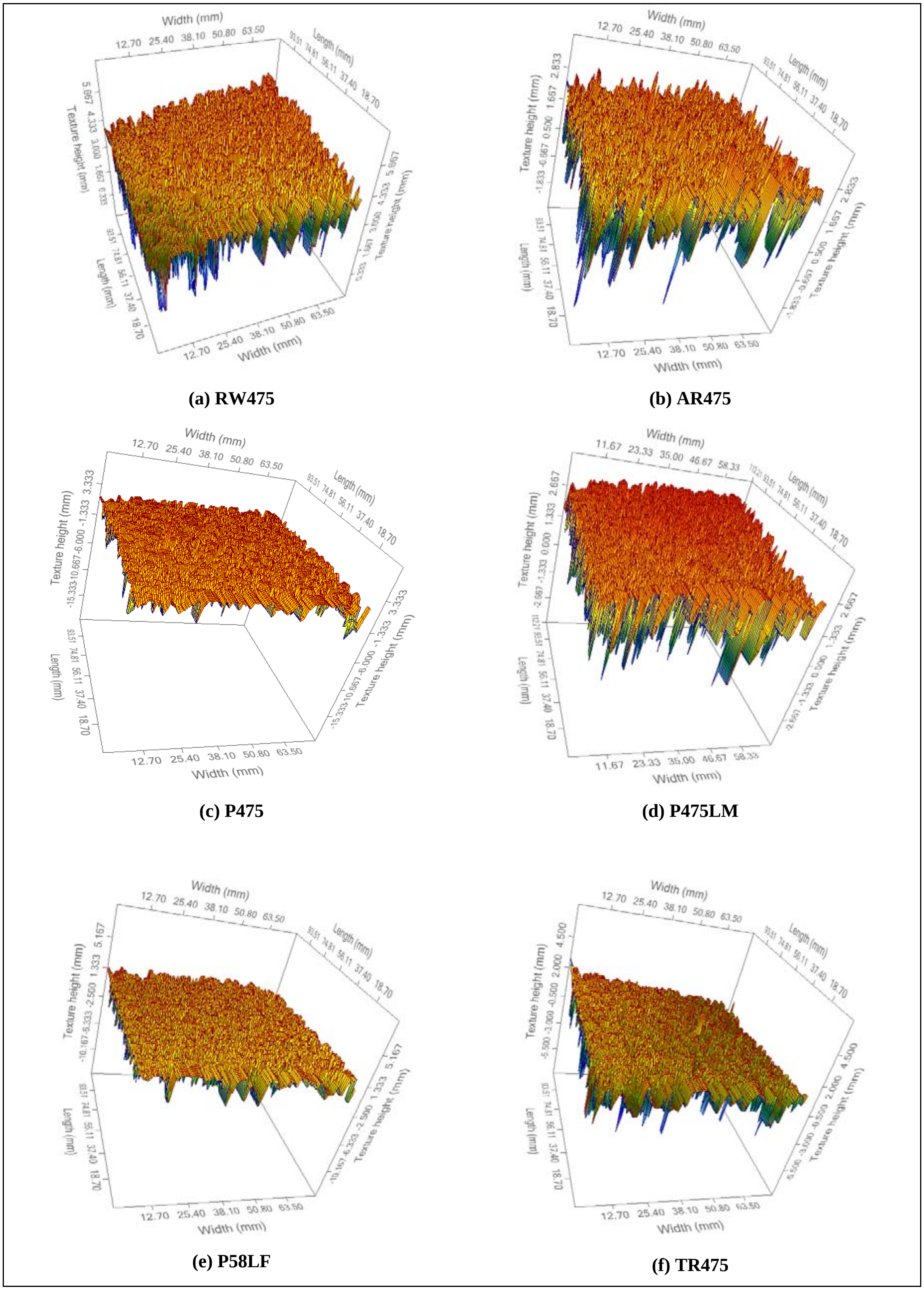


Figure 5.27: Surface profiles of mixes with 4.75 mm NMAS and various binders and additives.

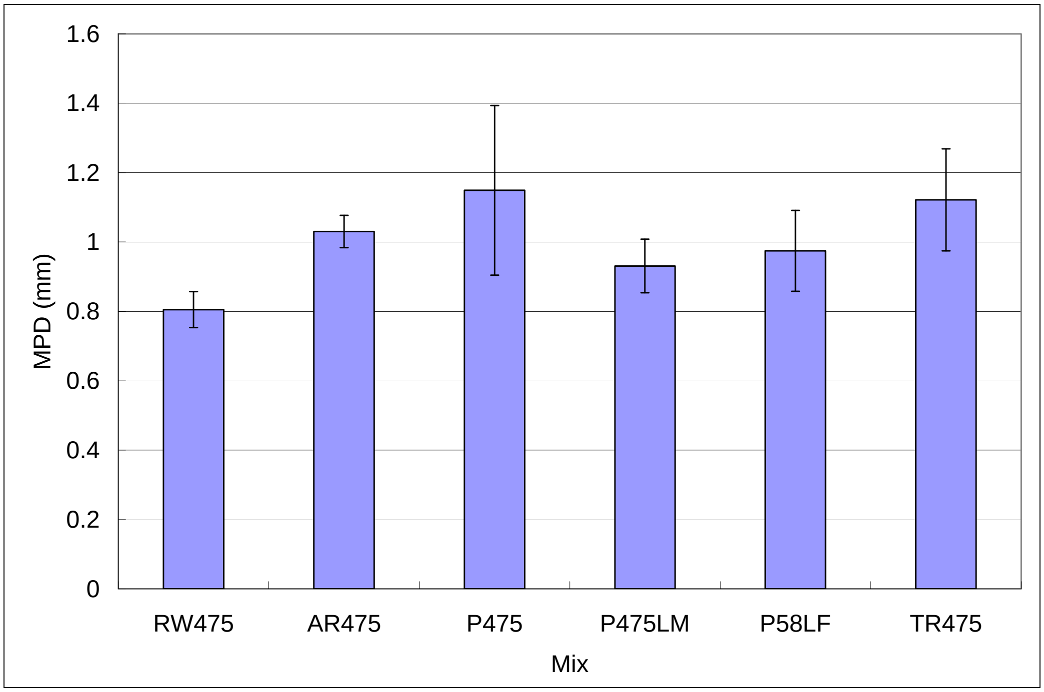


Figure 5.28: MPD of mixes with 4.75 mm NMAS and various binders and additives.

5.2.7 Resistance to Permanent Deformation

The initial shear modulus and cycles to failure (5 percent permanent shear strain) are shown in Figure 5.29 and Figure 5.30, respectively. In general, a higher shear stress should result in more rapid accumulation of permanent shear strain. It can be seen in Figure 5.30 that this was observed for all mixes except P475, which did not have replicate tests, and TR475, which had extremely high variability for the 130 kPA results. If time and funding had permitted, more replicate tests should have been performed for those mixes to reduce the uncertainty in the results.

As can be seen, adding hydrated lime increases the initial shear modulus of mix RW475. Using rubberized asphalt or PG 76-22 PM binder did not significantly change the initial shear modulus of mix RW475, but significantly increased the mix resistance to permanent shear deformation. Use of PG 58-34PM binder, even with hydrated lime and cellulose fiber, did not significantly increase the resistance to permanent shear deformation of 4.75-mm NMAS open-graded asphalt mixes.

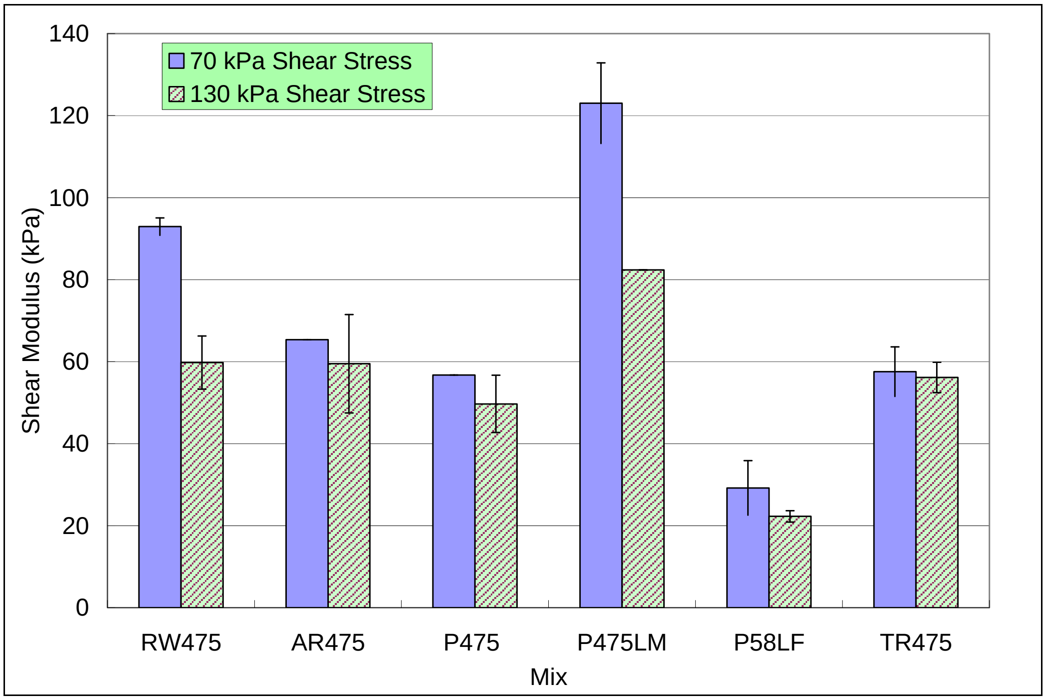


Figure 5.29: Initial shear modulus of mixes with 4.75 mm NMAS and various binders and additives.

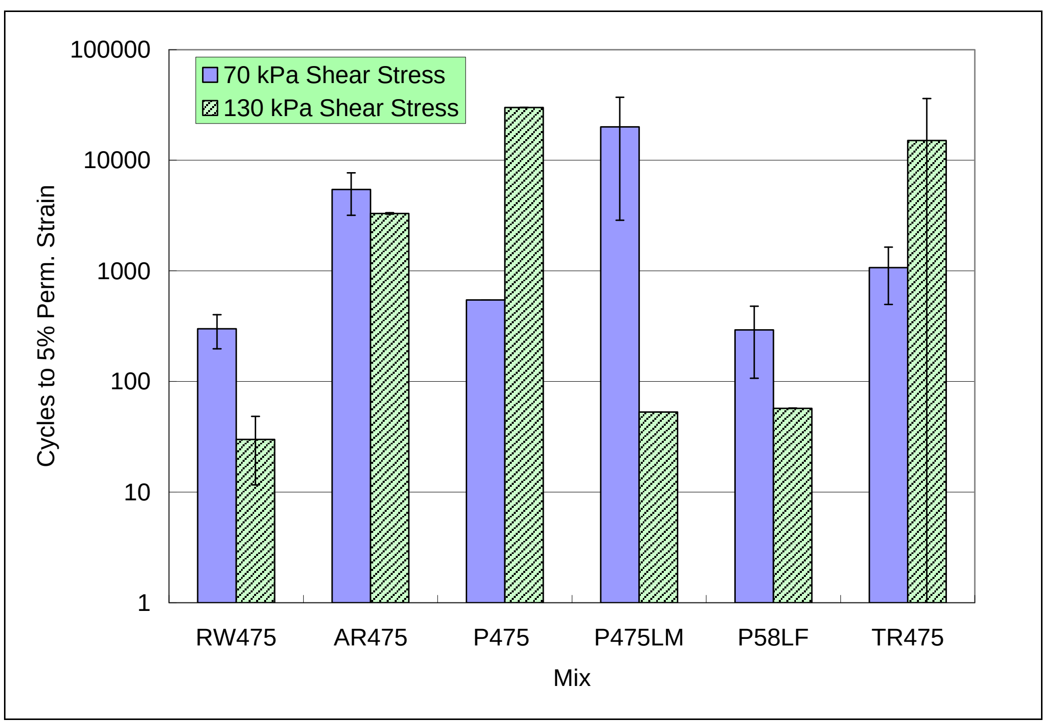


Figure 5.30: Cycles to 5 percent permanent shear strain of mixes with 4.75 mm NMAS and various binders and additives.

5.2.8 Resistance to Reflective Cracking

Figure 5.31 and Figure 5.32 summarize the Texas Overlay Tester results for each mix. The number of cycles to failure in Figure 5.32 was cut off at 1,000 because the test stops at 1,000 cycles. As can be seen from Figure 5.31, adding hydrated lime increased the maximum load of mix RW475, while using polymer-modified or rubberized asphalt reduced the maximum load. Since a higher maximum load indicates a higher initial stiffness, adding hydrated lime increases the stiffness of a conventional OGFC mix, while using polymer-modified or rubberized asphalt reduces the stiffness. This observation is consistent with the findings based on initial shear modulus as described in Section 5.2.7.

Figure 5.32 shows that adding hydrated lime (P475LM) reduced the reflective cracking resistance of a conventional OGFC mix (RW475). The OGFC mix containing asphalt rubber (AR475) also showed lower cracking resistance than a conventional OGFC mix (RW475). It is uncertain why the asphalt rubber binder had lower cracking resistance, since gap-graded asphalt rubber mixes tend to have greater cracking resistance than dense-graded mixes with conventional binder in the field and laboratory, and for these open-graded mixes the asphalt rubber mix had a higher binder content than those with the conventional and polymer-modified binders. On the other hand, polymer-modified binders (PG 76-22 PM or PG 58-34 PM) or terminal blend binder (PG 76-22 TR) significantly increased the cracking resistance of the OGFC mix for this test.

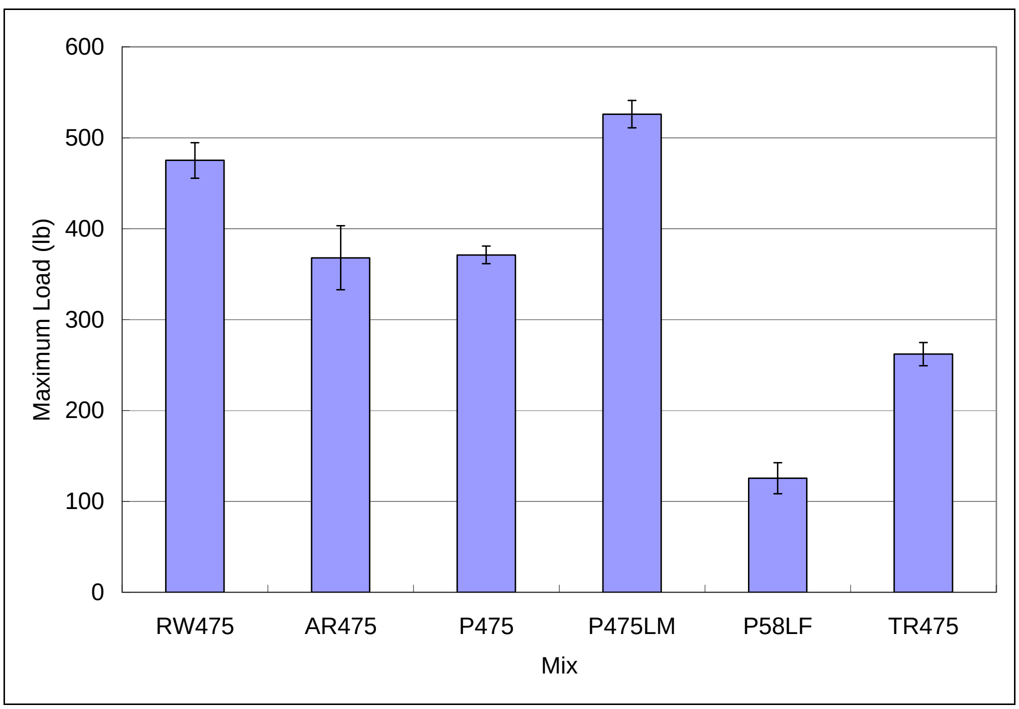


Figure 5.31: Maximum load of mixes with 4.75 mm NMAS and various binders and additives.

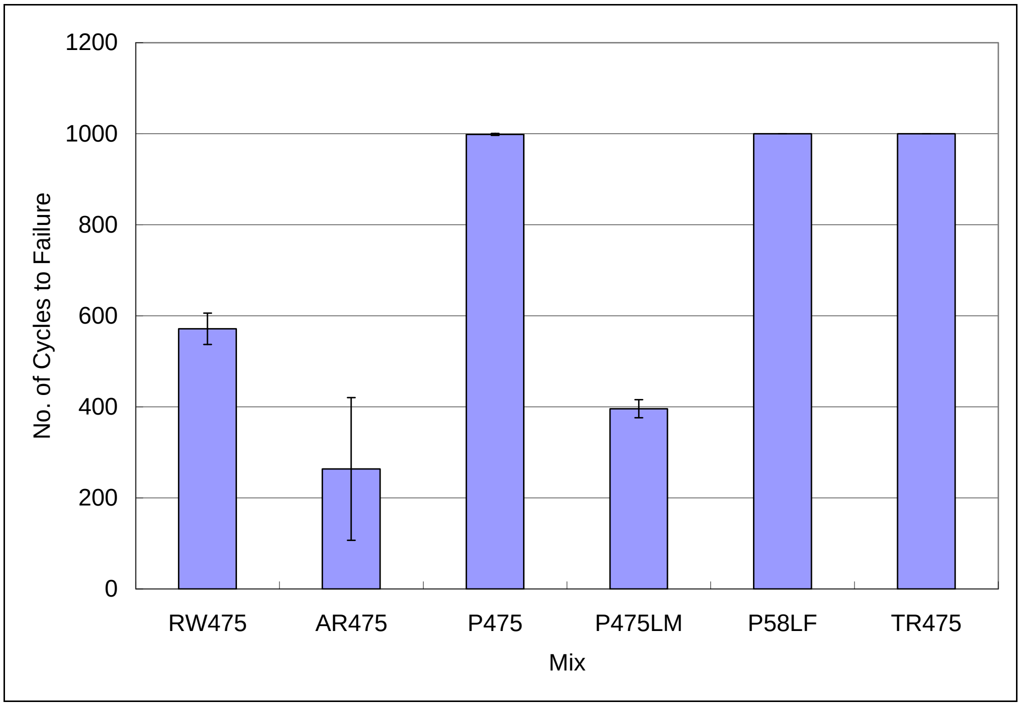


Figure 5.32: Number of cycles to failure of mixes with 4.75 mm NMAS and various binders and additives. (Note that the test is topped at 1,000 cycles.)

5.2.9 Summary of Results from the Second Experiment

The primary observations from the results of the second experiment regarding the effects of binder type and additives on No.4 (4.75 mm) NMAS mixes are summarized as follows:

Property	**Primary Observations**
Air-void content	• Mixes had approximately the same air-void contents, except that lime treatment plus fibers and terminal blend rubber were somewhat lower. • Laboratory compaction methods have an effect on specimen air-void contents.
Permeability	• Polymer-modified and asphalt rubber binders reduced permeability for 4.75 mm NMAS mixes. • Asphalt rubber 4.75 mm mix had one-third the permeability of conventional binder mix (asphalt rubber also has 20 percent more binder). • Permeability of asphalt rubber 4.75 mm mix was more than two orders of magnitude greater than dense-graded mixes.
Raveling	• Lime treatment improved raveling resistance. • Asphalt rubber and polymer-modified binders significantly improved raveling resistance.

Property	Primary Observations
Moisture sensitivity	• Hydrated lime treatment did not improve Hamburg Wheel Tracking Device performance. • Polymer-modified and asphalt rubber binders improved HWTD performance compared with conventional binder.
Reflective cracking	• All alternative binders and treatments improved the reflective cracking resistance measured by the Texas Overlay Tester, except asphalt rubber binder and hydrated lime treatment. • The poor results for the asphalt rubber binder do not match results for asphalt rubber binder in gap-graded mixes *(2)*, and should be investigated further.
Rutting	• Asphalt rubber binder improved rutting test performance.
Surface friction	• Surface friction and macrotexture were greater for asphalt rubber, polymer-modified, and hydrated lime–treated mixes.
Noise related properties	• Polymer-modified and especially asphalt rubber binders reduced permeability but slightly increased acoustic absorption, indicating that overall these binders may reduce higher frequency noise. • Some increase in macrotexture for polymer-modified and asphalt rubber binders may increase initial lower frequency noise. However, much greater resistance to raveling indicated that longer term these binders may have reduced lower frequency noise compared with conventional binders.

Overall, it appears that using asphalt rubber in the 4.75-mm NMAS OGFC mix can increase the acoustic absorption, resistance to moisture damage/premature failure, resistance to raveling, and rutting resistance. Resistance to reflective cracking seems to be reduced by introducing asphalt rubber into the surface asphalt mixes in the laboratory, but field observations did not show more reflective cracking on rubberized asphalt surface mix pavements. Further investigation, by use of field testing or Heavy Vehicle Simulator (HVS) test sections, may shed more light on this issue.

5.3 Effect of Fineness Modulus and Air-Void Content

The third experiment was designed to investigate the effect of variations in fineness modulus (i.e. aggregate gradation) and air-void content on noise reduction and durability. The experimental design was based on the findings from the first two experiments. The promising mix, AR475 (4.75-mm NMAS OGFC mix with asphalt rubber binder), was adjusted to investigate whether its overall performance could be further improved. Specifically, the 4.75-mm NMAS gradation was modified to increase the fineness modulus from 4.58 to 4.86, and the nominal air-void content was reduced from 20 percent to 15 percent. A total of four mix designations were included in this experiment: AR475, AR475D, AR475P, and AR475PD, in which “D” represents “denser,” and “P” represents “plus coarser aggregates.” As explained in Section 4.1.1, AR475 and AR475D are the same mix, however AR475D underwent a greater compactive effort. AR475P and AR475PD are also the same mix, so a total of two different mix designs were included in this experiment.

5.3.1 Air-Void Content and Permeability

Since Marshall compaction applies a fixed compaction energy, specimen air-void content cannot be controlled. Therefore, no Marshall specimens of mixes AR475D or AR475PD were fabricated. In the rolling wheel compaction, more loose mix was placed in the compaction for these mixes in order to reach the target nominal air-void content of 15 percent.

Figure 5.33 shows the average air-void content, as well as the range of one standard deviation, of each mix from specimens compacted by the two methods. As can be seen, the average air-void contents of the Marshall specimens of mixes AR475 and AR475P were close to each other, around 22 percent. The average air-void content of rolling wheel specimens of mix AR475PD was around 17 percent, which is larger than the required nominal air-void content of 15 percent. The average air-void content of the rolling wheel specimens of mix AR475D was around 20 percent, which is much larger than the required nominal air-void content of 15 percent. Difficulty was met during compaction of the slabs with 15 percent nominal air-void content. Although extra wheel passes were applied, it was still very difficult to make the slab surface flush with the compaction mold top face. Under the aggregate interlocking constraint, it seemed impractical to compact a 4.75-mm NMAS open-graded asphalt mix with the gradation used in this study to under 15 percent air-void content since it essentially is reaching a *refusal density* at air-void contents above that value. Refusal density means that no further compaction can be achieved because of stone-on-stone contact. Therefore, no further effort was made in this study to try compacting slabs to 15 percent air-void content.

Figure 5.34 presents the permeability test results on slab specimens. Comparing the results from mixes AR475 and AR475P, it can be seen that inclusion of a few larger aggregates in the mix (or increase of fineness modulus) only slightly increased permeability. For mix AR475P, reducing the air-void content from 20 percent to 17 percent to create mix AR475PD did not significantly affect permeability. For mix AR475, reducing the air-void content from 20 percent to 18 percent to create mix AR475D slightly reduced permeability. (Note that the air-void content of AR475D is higher than that of AR475 in Figure 5.33, due to an unknown abnormality in laboratory compaction.)

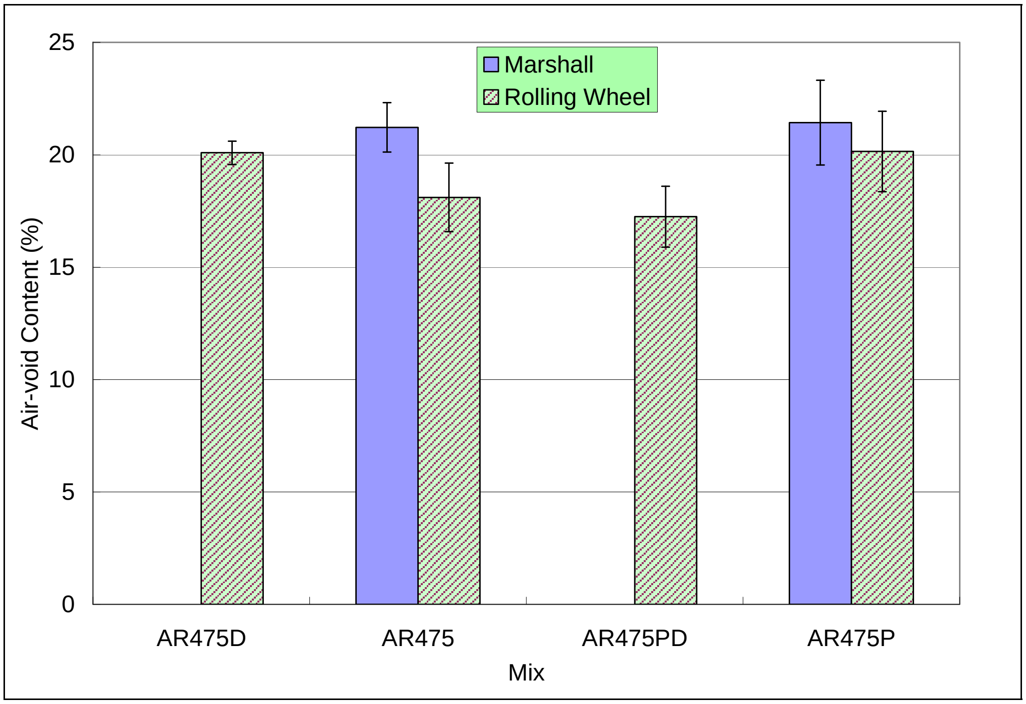


Figure 5.33: Air-void contents of mixes with 4.75 mm NMAS and various gradations and air-void contents.

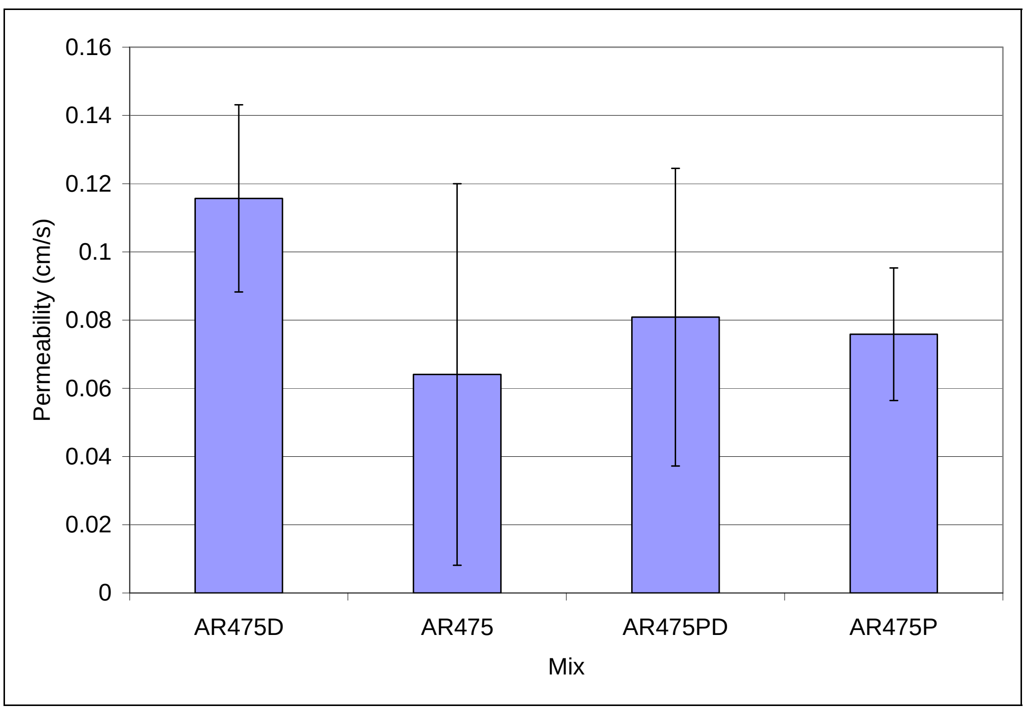


Figure 5.34: Permeability of mixes with 4.75 mm NMAS and various gradations and air-void contents.

5.3.2 Acoustic Absorption

Figure 5.35 presents the average spectra of sound absorption coefficients in the one-third octave frequency bands for each mix, along with the curve of the reference DGAC mix. Comparing mixes AR475D and AR475P (with similar air-void contents), it can be seen that mix AR475P had slightly lower peak acoustic absorption but a slightly higher resonant frequency than mix AR475D. For both the AR475 and AR475P mixes, when the air-void content was reduced, both the peak acoustic absorption coefficient and the resonant frequency were reduced.

Figure 5.36 shows the overall absorption coefficient averaged from values between 200 Hz and 1,600 Hz, along with the average thickness of specimens used in the test. Mix AR475P showed slightly lower overall sound absorption coefficient than mix AR475D. It seems that adding a small percentage of oversized aggregates in the 4.75-mm NMAS OGFC mix does not provide any acoustic benefit in terms of noise absorption.

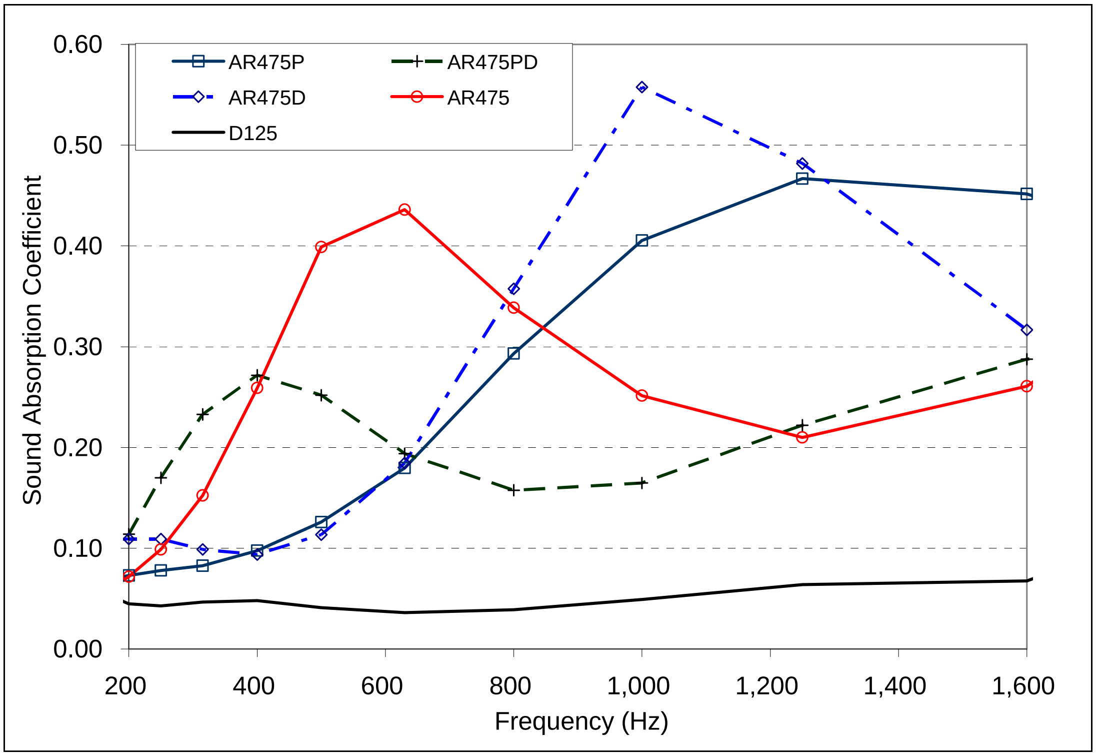


Figure 5.35: Spectra of sound absorption coefficients of mixes with 4.75 mm NMAS and various gradations and air-void contents.

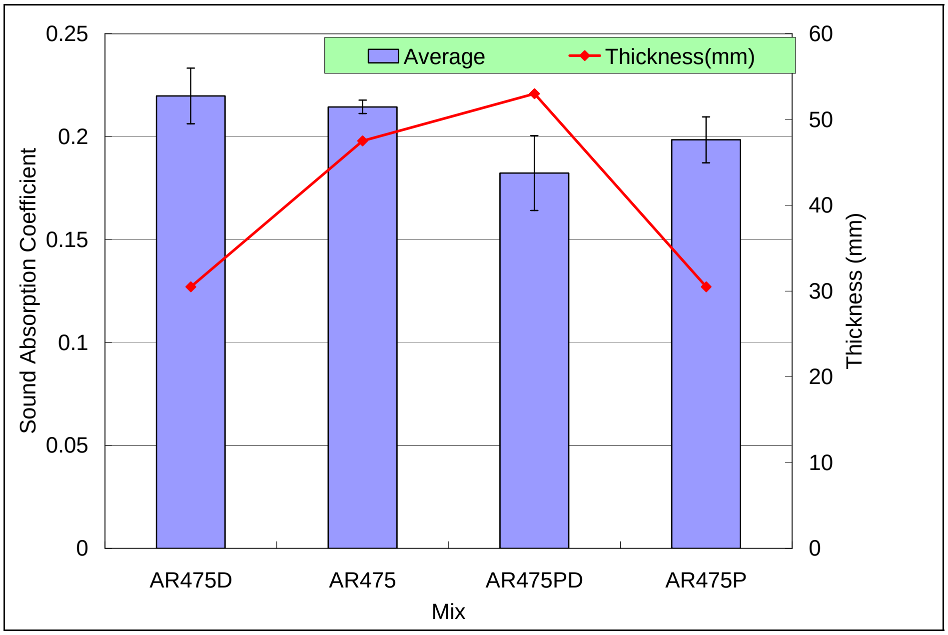


Figure 5.36: Average sound absorption coefficients of mixes with 4.75 mm NMAS and various gradations and air-void contents.

5.3.3 Moisture Sensitivity

Figure 5.37 and Figure 5.38 show the indirect tensile strength and tensile strength ratio (TSR) of mixes AR475 and AR475P. As can be seen, mix AR475P had higher indirect tensile strength and TSR than mix AR475, indicating that adding a small percentage of oversized aggregates in the 4.75-mm NMAS OGFC mix improved the mix resistance to moisture damage. The reason for this observation is unknown. Considering that the TSR test may not be appropriate for evaluating the moisture sensitivity of open-graded mixes, this observation may have no practical meaning.

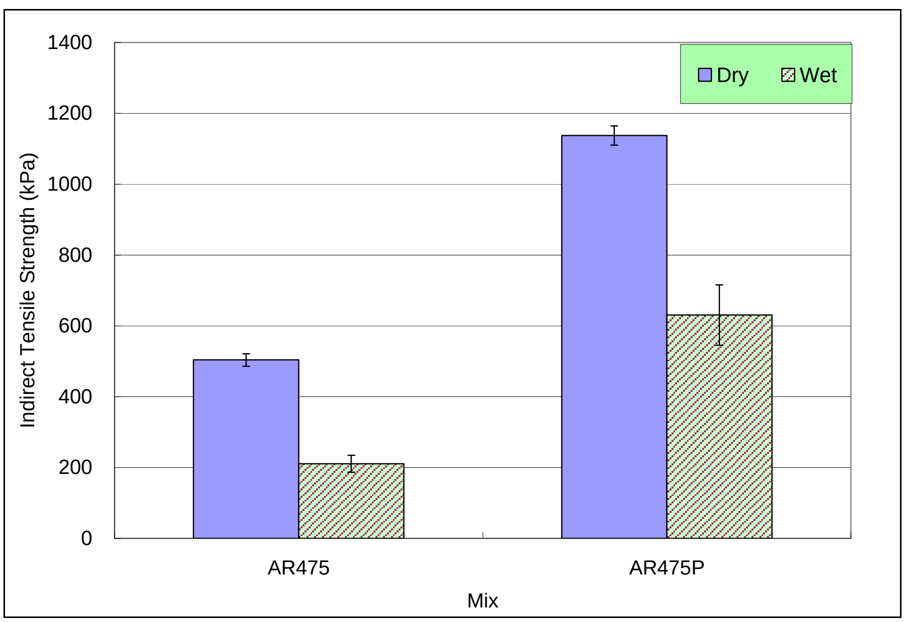


Figure 5.37: Indirect tensile strength of dry and moisture-conditioned specimens with 4.75-mm NMAS and various gradations and air-void contents.

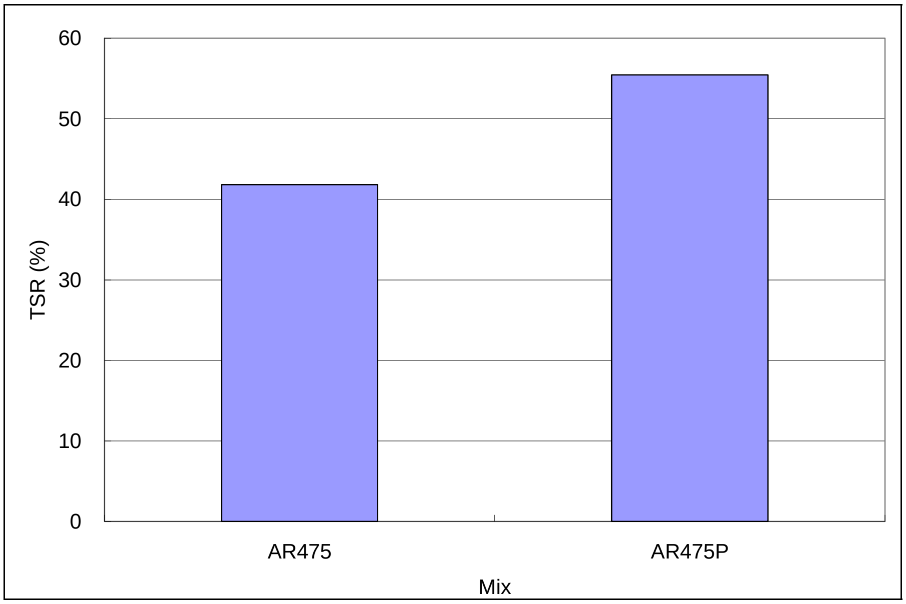


Figure 5.38: Indirect tensile strength ratio of mixes with 4.75-mm NMAS and various gradations and air-void contents.

Figure 5.39 presents the rut depth curve from the HWTD of each mix. Each curve in the plot is an average of results from two replicates. It can be seen from the figure that AR475P performed slightly better than AR475 in the HWTD test, indicating that adding a small percentage of oversized aggregates in the 4.75-mm NMAS OGFC mix slightly improved the mix resistance to moisture damage/premature failure. Specimens (AR475D and AR475PD) with smaller nominal air-void contents (15 percent) exhibited better moisture/rutting resistance than their corresponding specimens with higher nominal air-void contents (20 percent), but the performance improvement resulting from air-void content reduction was slight.

5.3.4 Resistance to Raveling

Figure 5.40 shows the average and range of one standard deviation of the Cantabro loss values from aged and unaged specimens. The Cantabro loss values of mix AR475P were slightly lower than those of mix AR475, indicating that adding a small percentage of oversized aggregates in the 4.75-mm NMAS OGFC mix slightly improved the resistance to raveling of an open-graded mix.

5.3.5 Friction

Figure 5.41 shows the average and range of one standard deviation of the British Pendulum Number (BPN) results for each mix. As can be seen, there was no significant difference in BPN between AR475 and AR475P. The results from the DFT, as shown in Figure 5.42, indicate a higher friction coefficient for mix AR475P than for AR475. Reducing air-void content also reduced friction measured by the DFT.

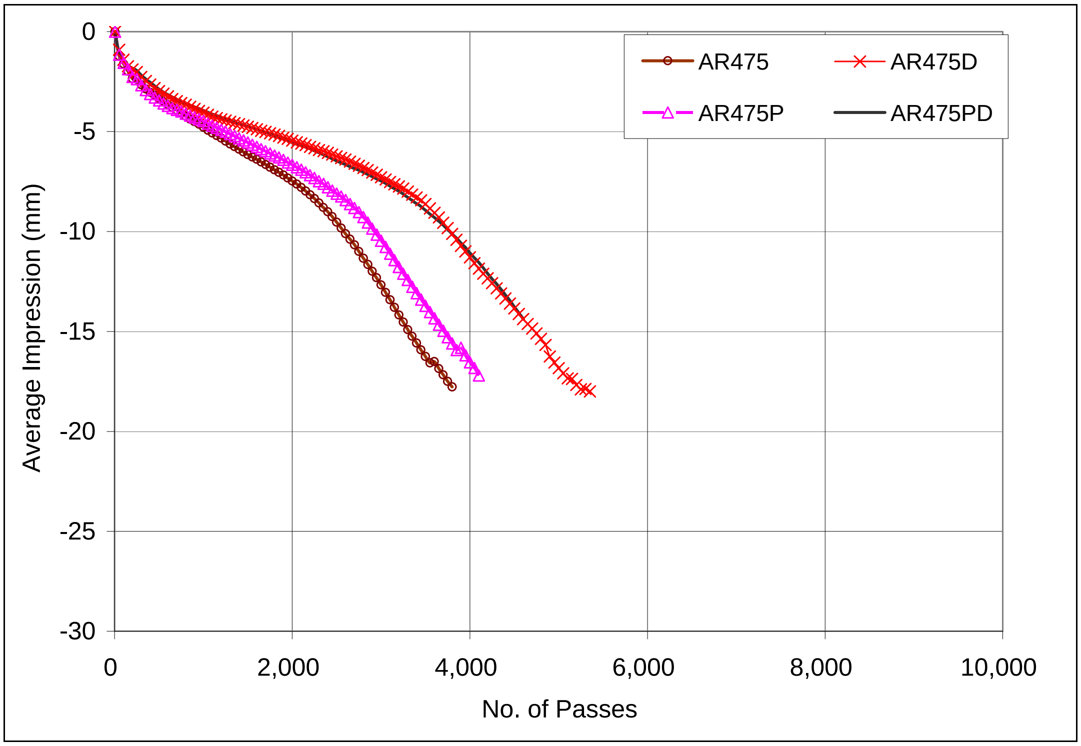


Figure 5.39: Rut progression curve of mixes with 4.75-mm NMAS and various gradations and air-void contents from the HWTD test.

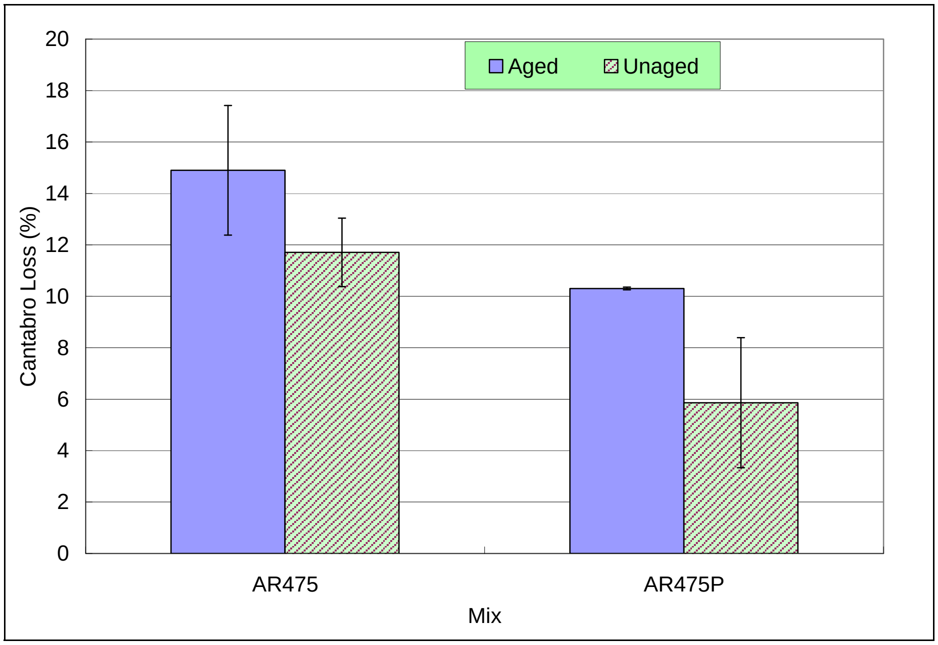


Figure 5.40: Cantabro loss results of aged and unaged mixes with 4.75-mm NMAS and various gradations and air-void contents.

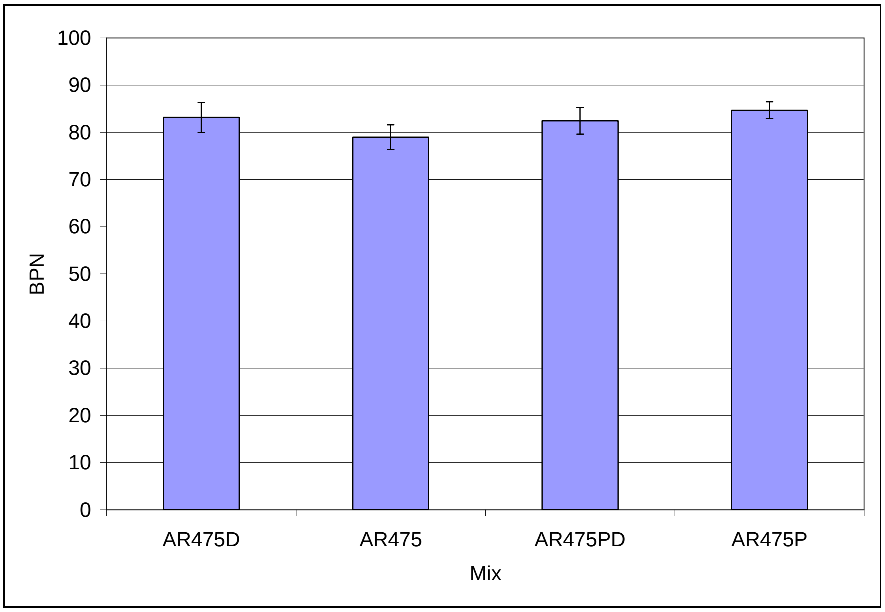


Figure 5.41: BPT results of mixes with 4.75-mm NMAS and various gradations and air-void contents.

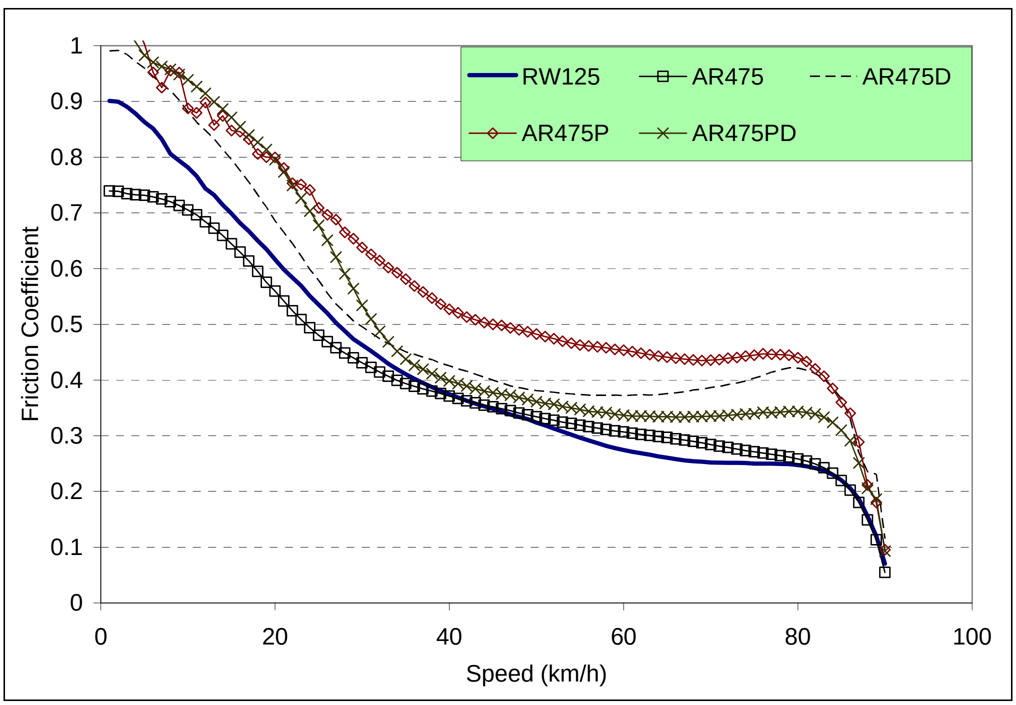


Figure 5.42: DFT results of mixes with 4.75-mm NMAS and various gradations and air-void contents.

5.3.6 Texture

The surface profiles of the four mix designations are shown in Figure 5.43. The mean profile depths (MPD) calculated from these profiles are summarized in Figure 5.44. As can be seen, no significant difference in MPD was detected between mix AR475 and mix AR475P. Adding a small percentage of oversized aggregates in the 4.75-mm NMAS OGFC mix did not seem to affect the macrotexture. Reducing air-void content by 2 or 3 percent did not affect MPD either.

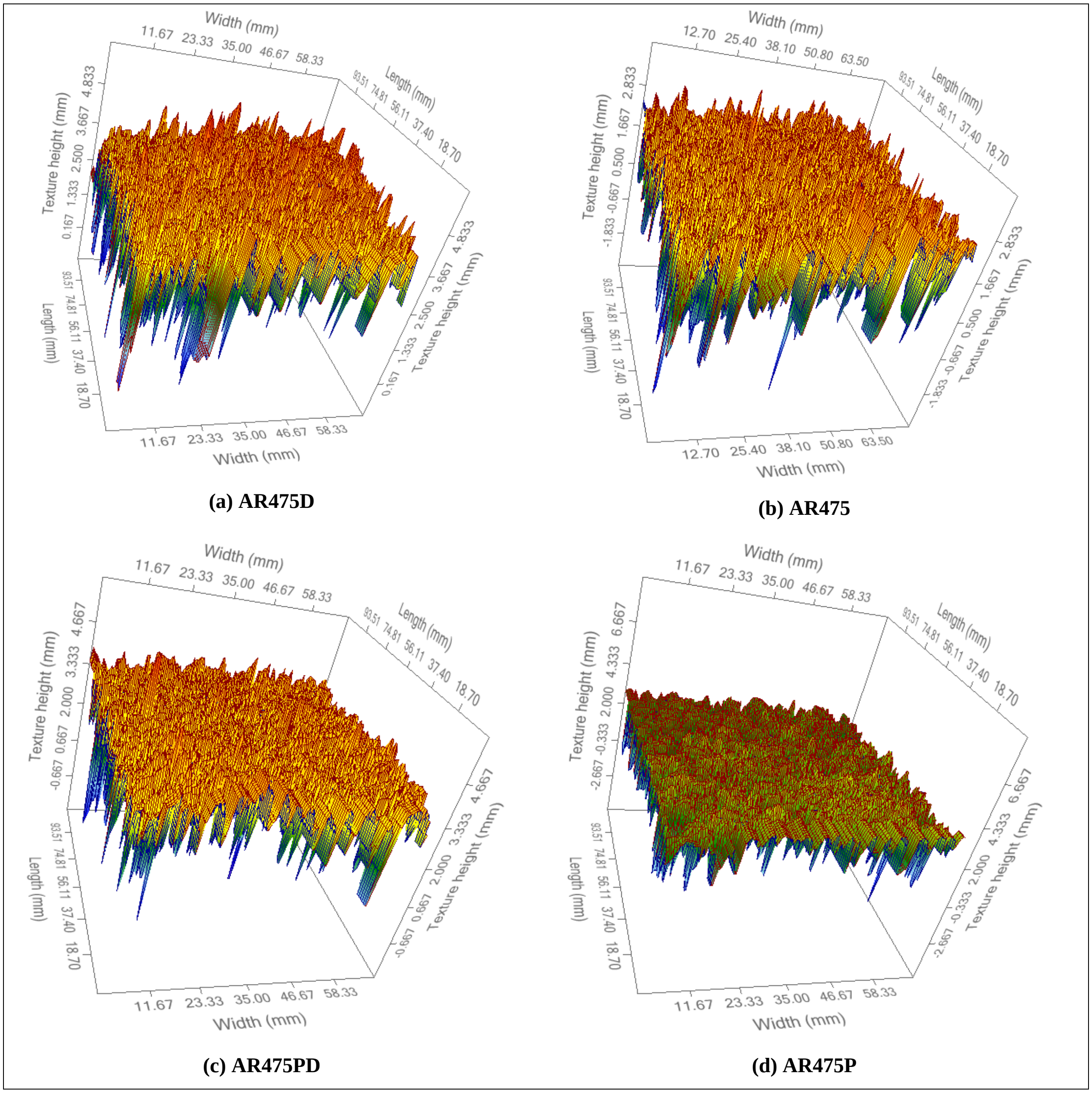


Figure 5.43: Surface profiles of mixes with 4.75 mm NMAS and various gradations and air-void contents.

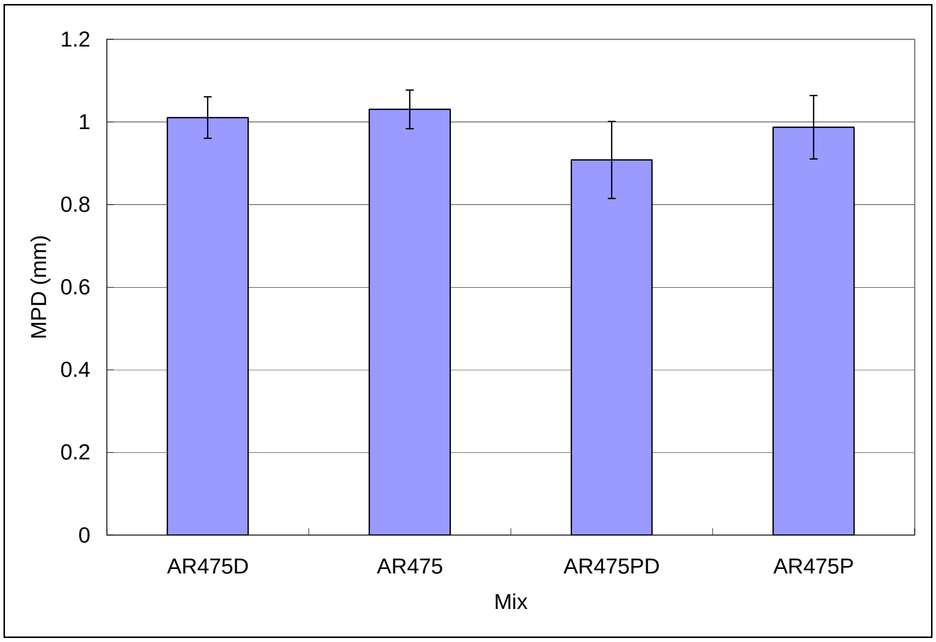


Figure 5.44: MPD of mixes with 4.75-mm NMAS and various gradations and air-void contents.

5.3.7 Resistance to Permanent Deformation

The initial shear modulus and cycles to failure (5 percent permanent shear strain) are shown in Figure 5.45 and Figure 5.46, respectively. As can be seen, adding a small percentage of oversized aggregates in the 4.75-mm NMAS OGFC mix did not significantly affect its shear modulus, and slightly reduced the mix's resistance to permanent deformation.

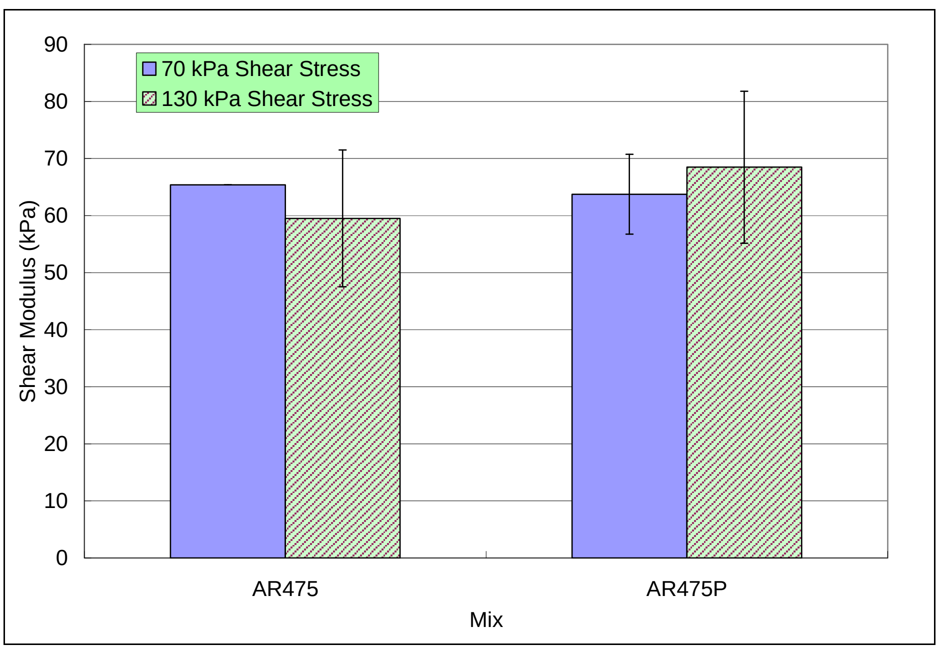


Figure 5.45: Initial shear modulus of mixes with 4.75-mm NMAS and various gradations and air-void contents.

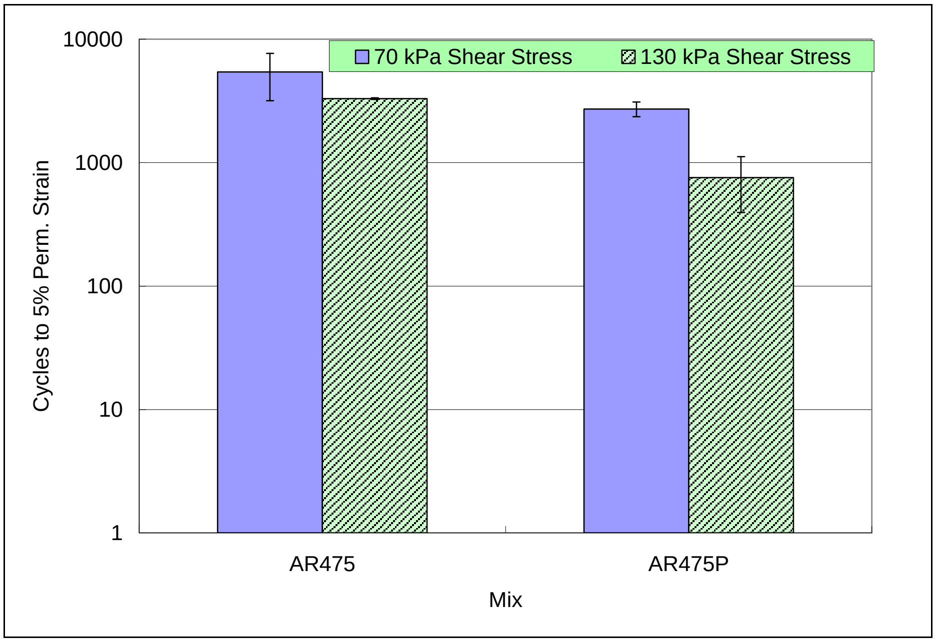


Figure 5.46: Cycles to 5 percent permanent shear strain of mixes with 4.75-mm NMAS and various gradations and air-void contents.

5.3.8 Resistance to Reflective Cracking

Figure 5.47 and Figure 5.48 summarize the overlay test results, including maximum load and number of cycles to failure, of each mix. AR475D was not tested since its air-void content was not significantly different from that of AR475. As can be seen from Figure 5.47, adding a small percentage of oversized aggregates in the 4.75-mm NMAS OGFC mix did not change the initial maximum load, or in other words, the stiffness of the mix. Reducing air-void content, however, increased the initial maximum load, or mix stiffness, which is expected.

Figure 5.48 shows that adding a small percentage of oversized aggregates in the 4.75-mm NMAS OGFC mix reduced the mix's resistance to cracking. Introducing a lower air-void content in the mix, however, can compensate for this reduction.

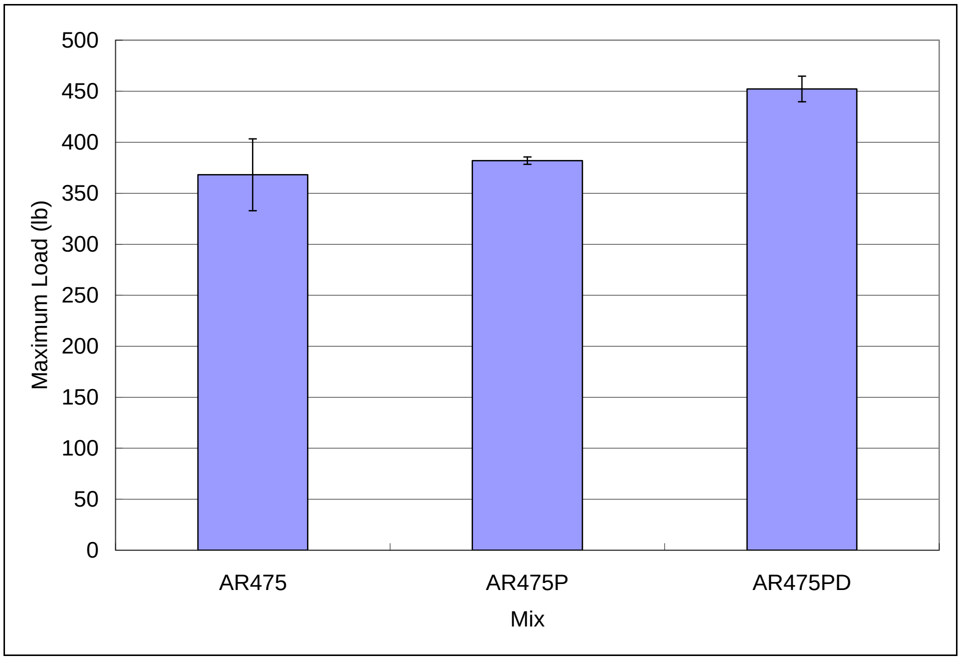


Figure 5.47: Maximum load of mixes with 4.75-mm NMAS and various gradations and air-void contents.

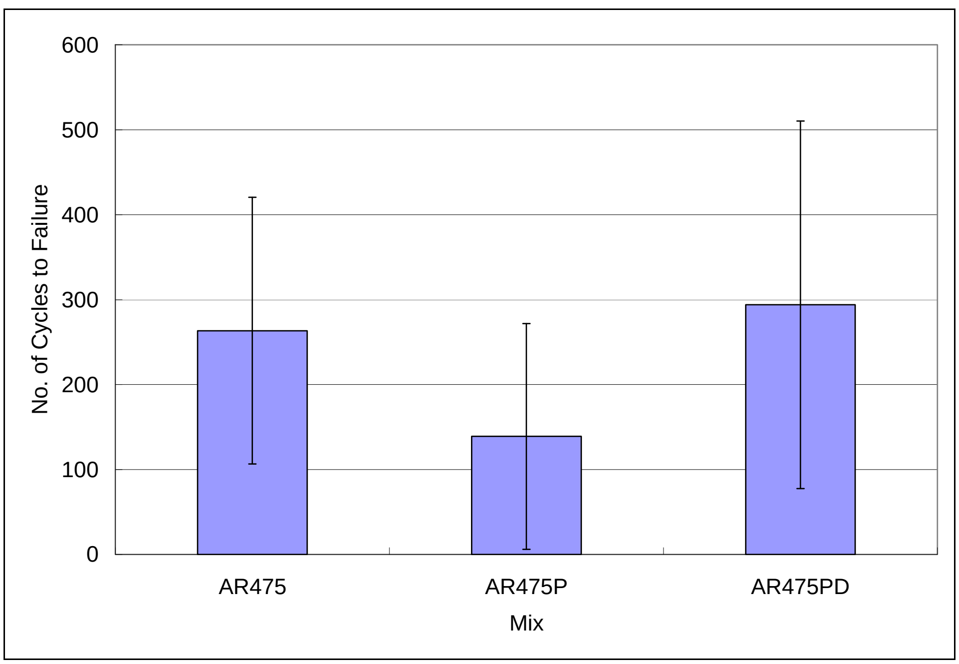


Figure 5.48: Number of cycles to failure of mixes with 4.75-mm NMAS and various gradations and air-void contents.

5.3.9 *Summary of Results from the Third Experiment*

The primary observations from the results of the second experiment regarding the effects of adding some larger size aggregates to the No.4 (4.75 mm) NMAS asphalt rubber mix and applying greater compactive effort are summarized as follows:

Property	**Primary Observations**
Air-void content	• Greater compactive effort resulted in a maximum reduction of air-void content of 2 to 3 percent below 20 percent before reaching *refusal density*. • Addition of a few larger stones slightly increased air-void content.
Permeability	• Additional compaction had little effect on permeability. • Addition of a few larger stones slightly increased permeability.
Raveling	• Addition of a few larger stones slightly improved resistance to raveling.
Moisture sensitivity	• Additional compaction improved resistance to moisture sensitivity measured by the Hamburg Wheel Tracking Device (HWTD). • Addition of a few larger stones slightly improved resistance to moisture sensitivity measured by the HWTD.
Reflective cracking	• Addition of a few larger stones slightly reduced resistance to reflective cracking. • Additional compaction combined with addition of a few larger stones slightly improved resistance to reflective cracking.
Rutting	• Addition of a few larger stones did not have much effect on resistance to rutting.
Surface friction	• Additional compaction slightly improved friction. • Addition of a few larger stones improved friction.
Noise-related properties	• Additional compaction reduced acoustic absorption. • Addition of a few larger stones did not change acoustic absorption.

Based on these results it appears that addition of some larger stones can improve some performance properties, however, this does not change the overall performance of the mix much. Extraordinary compaction does not appear to be necessary, although there are some slight improvements in performance.

5.4 Effect of Aggregate Shape

The fourth experiment was designed to investigate the effect of aggregate shape on noise reduction and durability. Included in the experiment were aggregates from three sources: Syar Lake Herman (near Benicia in Solano County), Graniterock Aromas (near Watsonville in Santa Cruz County), and Teichert Jackson Road (east of Sacramento in Sacramento County), as listed in Table 4.4.

Each of these aggregates has different shape and surface texture characteristics. The results of shape and texture analysis performed by the Texas Transportation Institute on fractions of each aggregate source are summarized in Appendix D. Those results show that the ranking of surface texture and angularity between the different sources is different for different size fractions. In general, the coarser fraction of the Syar aggregate (1/2 to 3/8 in. [12.5 to 9.5 mm]) is more angular yet smoother than the other two. For the next size fraction (3/8 in. to No. 4, 9.5 to 4.75 mm), the Teichert aggregate is more angular and rougher than the other two aggregates. For the smallest fraction (No. 8 to No. 16 [2.36 to 1.18 mm]), the Syar aggregate is somewhat less angular than the other two sources, which are similar to each other. All of these differences are interacting in the different mix gradations which use different proportions of each of these size fractions.

Two aggregate gradations (4.75 mm NMAS and 9.5 mm NMAS) and two binder types (PG 64-16 and asphalt rubber) were also included in this experiment. A total of eight mixes were compared and analyzed in this experiment: RW475, PG475W, AR475, AR475T, RW95, PG95T, AR95, and AR95W, among which three mixes (RW475, AR475, and RW95) were already analyzed in the previous experiments.

5.4.1 Air-Void Content and Permeability

A nominal air-void content of 20 percent was the target in fabricating all specimens in this experiment.

Figure 5.49 shows the average air-void content, as well as the range of one standard deviation, of each mix from specimens compacted by the Marshall hammer and rolling wheel methods. It can be seen that the average air-void contents of mixes containing the Watsonville aggregates were generally lower than those of mixes containing the Syar aggregates (PG475W versus RW475 Marshall hammer, and AR95W versus AR95 both compaction methods), while the average air-void content of mixes containing the Teichert aggregates was similar to that of mixes containing the Syar aggregates (AR475T versus AR475, and PG95T versus RW95). From the aggregate imaging analysis performed at the Texas Transportation Institute it is known that the Watsonville aggregates were less angular and elongated than the Syar or Teichert aggregates, while Syar aggregates were slightly more angular and elongated than the Teichert aggregate. The lesser angularity and elongation of the Watsonville aggregates is the likely reason that mixes containing the Watsonville aggregates had lower air-void contents for same gradations and compactive effort compared to the mixes containing the other two aggregates.

Figure 5.50 presents the permeability test results on slab specimens. Probably in part due to lower air-void contents, mixes containing the Watsonville aggregates showed lower permeability than mixes containing the other two aggregates. Use of asphalt rubber binder instead of conventional asphalt in the 9.5-mm NMAS OGFC mixes reduced their permeability, which was also true for the 4.75-mm NMAS OGFC mixes, as found in previous experiments. It can also be seen that the permeability of a 9.5-mm NMAS OGFC mix could be reduced to a value lower than that of a 4.75-mm NMAS OGFC mix if both asphalt rubber and Watsonville aggregates were used.

Overall, the generally more angular Syar aggregate produced a somewhat greater permeability than the same mix made with either of the other two aggregate sources, except for the AR475 mixes. The permeability of the asphalt rubber 4.75-mm NMAS OGFC mix was somewhat less with the Syar aggregate than with the Teichert aggregate (AR475 compared with AR475T), while for the 9.5 mm NMAS OGFC mix the same change in aggregate resulted in an increase in permeability (RW95 compared with PG95T).

Figure 5.51 presents the average spectra of sound absorption coefficients in one-third octave frequency bands for each mix, along with the curve for the reference DGAC mix. It can be seen that the acoustic absorption curve of mix PG475W is similar to that of mix RW475, and the acoustic absorption curve of mix AR475 is similar to that of mix AR475T, indicating that difference in aggregate types (shapes) does not significantly affect the sound absorption property of an open-graded mix with small size aggregates (4.75 mm NMAS). On the other hand, aggregate types (shapes) do appear to make a significant difference in the sound absorption property of an open-graded mix with larger aggregates (9.5 mm NMAS). It can be seen in the figure that mix AR95W (Watsonville aggregate) showed significantly lower peak acoustic absorption and a lower resonant frequency than mix AR95 (Syar aggregate), and that mix PG95T (Teichert aggregate) showed a slightly higher peak acoustic absorption than mix RW95 (Syar aggregate). The sound absorption curve of mix AR95W is very similar to those of mixes AR475 and AR475T, indicating that use of a less angular aggregate in a 9.5-mm OGFC mix can change its acoustic performance to match that of a 4.75-mm OGFC mix.

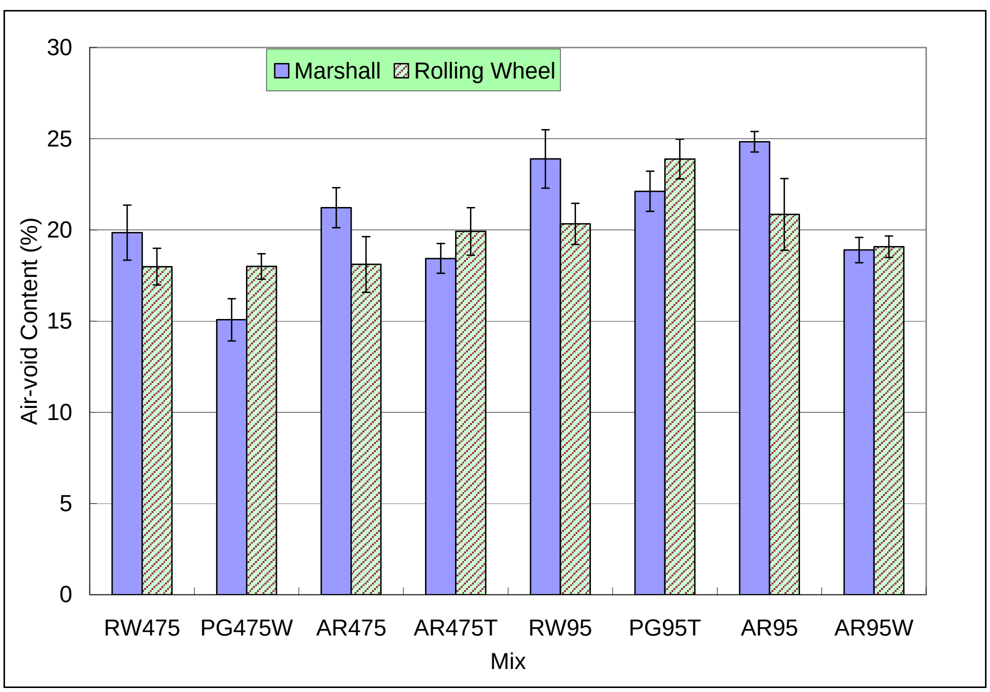


Figure 5.49: Air-void contents of mixes with various aggregate types, NMAS, and binders.
Notes: (1) All mixes made with Syar Lake Herman aggregate, except those ending in T have Teichert Jackson Road aggregate, and those ending in W have Graniterock Aromas aggregate. (2) Each pair of mixes from left to right is the same mix made once with Syar aggregate and second with T or W; for example, RW475 and PG475W are the same mix made with Syar and Graniterock Aromas aggregate respectively.

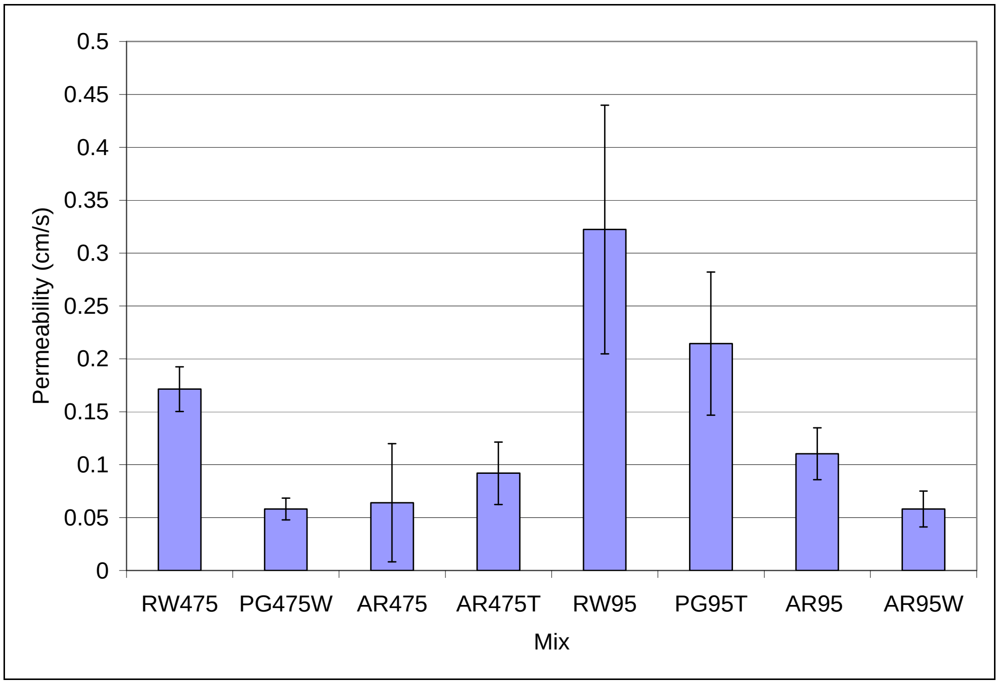


Figure 5.50: Permeability of mixes with various aggregate types, NMAS, and binders.
Notes: (1) All mixes made with Syar Lake Herman aggregate, except those ending in T have Teichert Jackson Road aggregate, and those ending in W have Graniterock Aromas aggregate. (2) Each pair of mixes from left to right is the same mix made once with Syar aggregate and second with T or W; for example, RW475 and PG475W are the same mix made with Syar and Graniterock Aromas aggregate respectively.

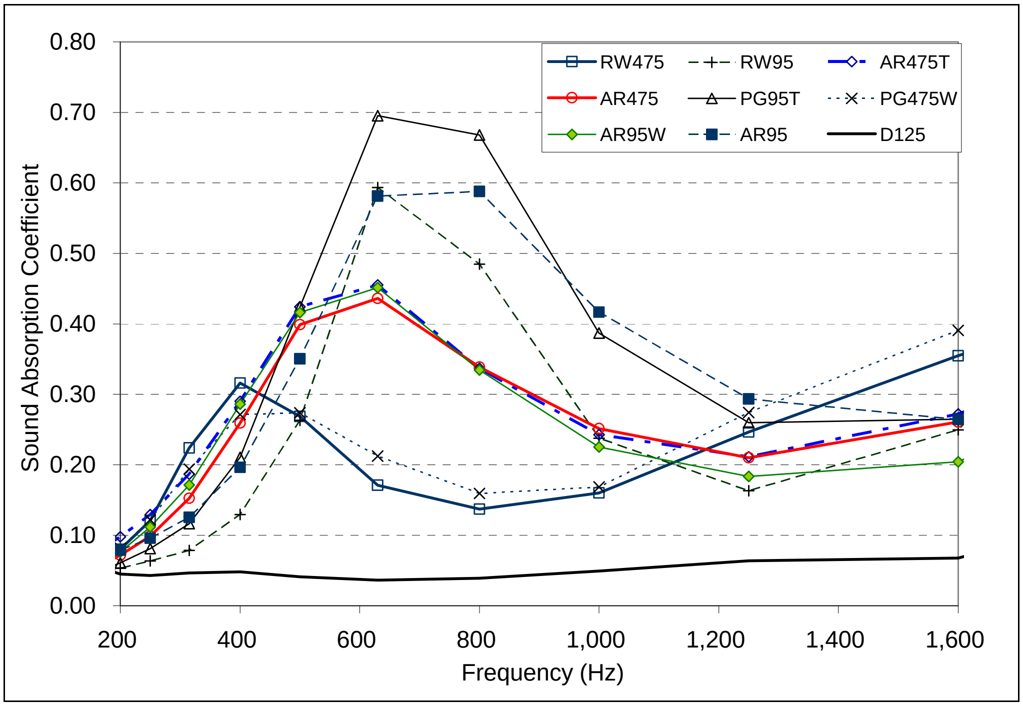


Figure 5.51: Spectra of sound absorption coefficients of mixes with various aggregate types, NMAS, and binders.

5.4.2 Acoustic Absorption

Figure 5.52 shows the overall acoustic absorption coefficient averaged from values between 200 Hz and 1,600 Hz, along with the average thickness of specimens used in the test. The plot shows that changing the aggregate shape and texture by changing the source from Syar to Teichert in an OGFC mix increased the mix's sound absorption capability, while changing the aggregate source from Syar to Watsonville in an OGFC mix reduced the mix's sound absorption capability for the 9.5-mm NMAS gradation, but had almost no effect for the 4.75-mm NMAS gradation.

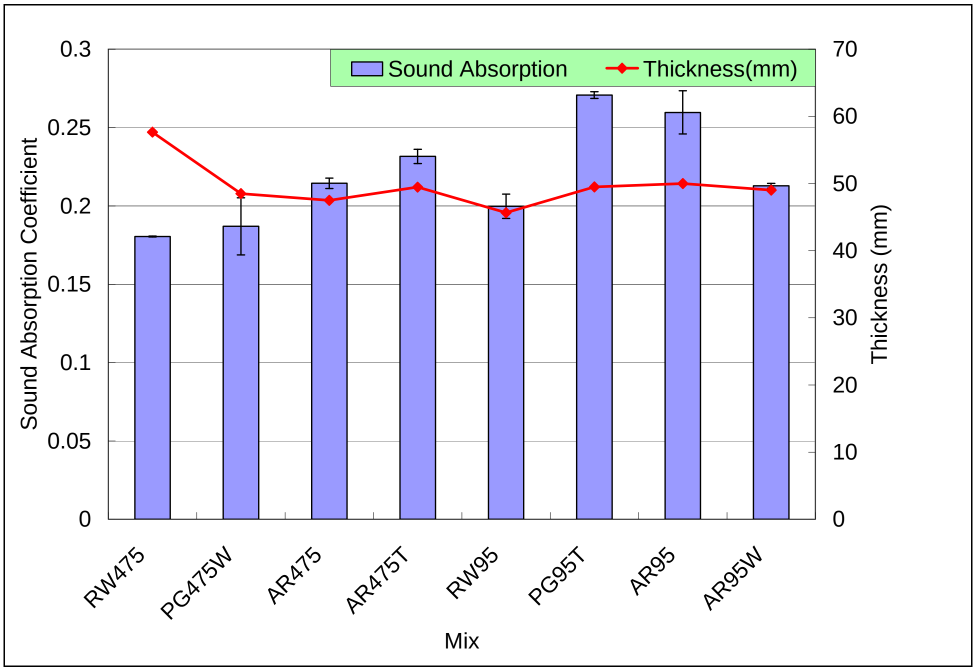


Figure 5.52: Average sound absorption coefficients of mixes with various aggregate types, NMAS, and binders.

5.4.3 Moisture Sensitivity

None of the mixes tested showed a TSR value higher than 70 percent. There was some effect of aggregate type on both dry and wet strength values, as well as tensile strength ratio (TSR). These results may come from differences in aggregate mineralogy or aggregate particle shapes, which cannot be further investigated in this study.

Figure 5.53 presents the rut depth curve from the HWTD for each mix designation. Each curve in the plot is the average of results from two replicates. It can be seen from the figure that the four mixes containing asphalt rubber (AR475, AR475T, AR95, and AR95W) performed much better than the other four mixes containing PG 64-16 binder (RW475, PG475W, RW95, and PG95T). Of the rubberized OGFC mixes, those containing Watsonville or Teichert aggregates performed slightly better than mixes containing Syar aggregates. Of the non-rubberized OGFC mixes, those containing Syar aggregates performed slightly better than mixes containing the other two aggregate types. The difference in HWTD test results caused by aggregate types, which is likely due to normal variability, however, is minor compared to the difference caused by binder type.

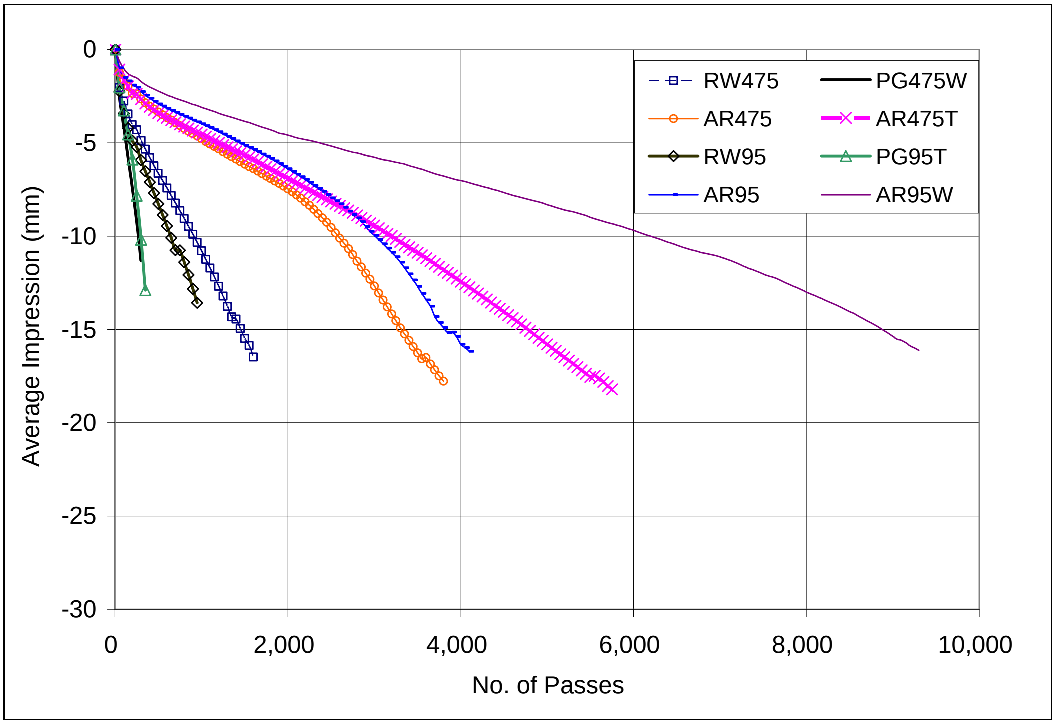


Figure 5.53: Rut depth curve of mixes with various aggregate types, NMAS, and binders from the HWTD test.

5.4.4 Resistance to Raveling

Figure 5.54 shows the average and range of one standard deviation of the Cantabro loss values from aged and unaged specimens. As can be seen, aggregate size played an important role in determining the mix's resistance to raveling. Mixes with 9.5-mm NMAS showed more material loss in the Cantabro test than mixes with 4.75-mm NMAS. Aggregate shape and angularity played a minor role in affecting mix resistance to raveling. The test data show that mixes containing Watsonville aggregates had slightly better raveling resistance than mixes containing Syar aggregates, likely due to lower air-void contents in the Watsonville mixes. The difference between the Teichert and Syar mixes varied with binder type. For mixes containing PG 64-16 binder, there was no significant difference; for mixes containing asphalt rubber binder, those containing Teichert aggregates showed less Cantabro loss than mixes containing Syar aggregates, although it is not clear why. The effects of aging were as expected, with aged specimens having a greater Cantabro loss than unaged specimens, except for the PG95T mix.

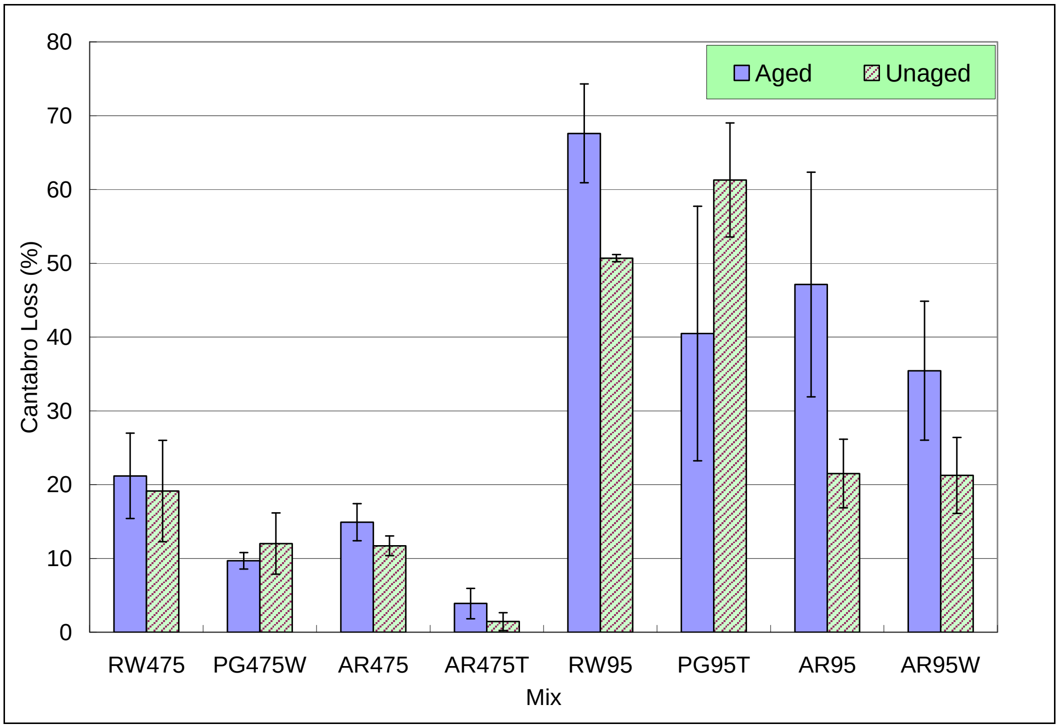


Figure 5.54: Cantabro loss results of aged and unaged mixes with various aggregate types, NMAS, and binders.

5.4.5 Friction

Figure 5.55 shows the average and range of one standard deviation of the British Pendulum Number (BPN) results for each mix. As can be seen, rubberized OGFC mixes generally had higher friction than non-rubberized OGFC mixes. Mixes containing the Watsonville aggregates showed higher BPN values than mixes containing the Syar aggregates although the surface texture measurements did not show them to be rougher, while mixes containing the Teichert aggregates had BPN values similar to mixes containing the Syar aggregates.

The results from the DFT, shown in Figure 5.56, indicated a higher friction for mix PG475W than that for RW475, but a lower friction for mix AR95W than that for mix AR95. It also shows similar friction curves for mixes containing Syar aggregates and Teichert aggregates.

Both the BPT and DFT tests show that the aggregate types included in this study may have some effect on the friction of an OGFC mix, but this effect can be confounded by binder type. This indicates that there is no conclusive evidence that differences in angularity and surface texture for these three aggregates have much effect on friction.

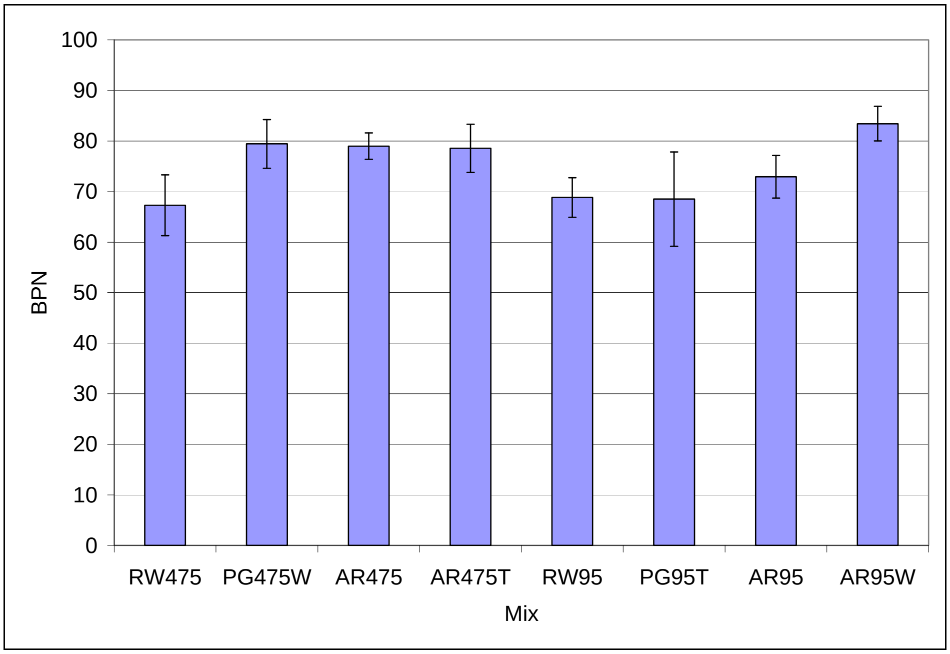


Figure 5.55: BPT results of mixes with various aggregate types, NMAS, and binders.

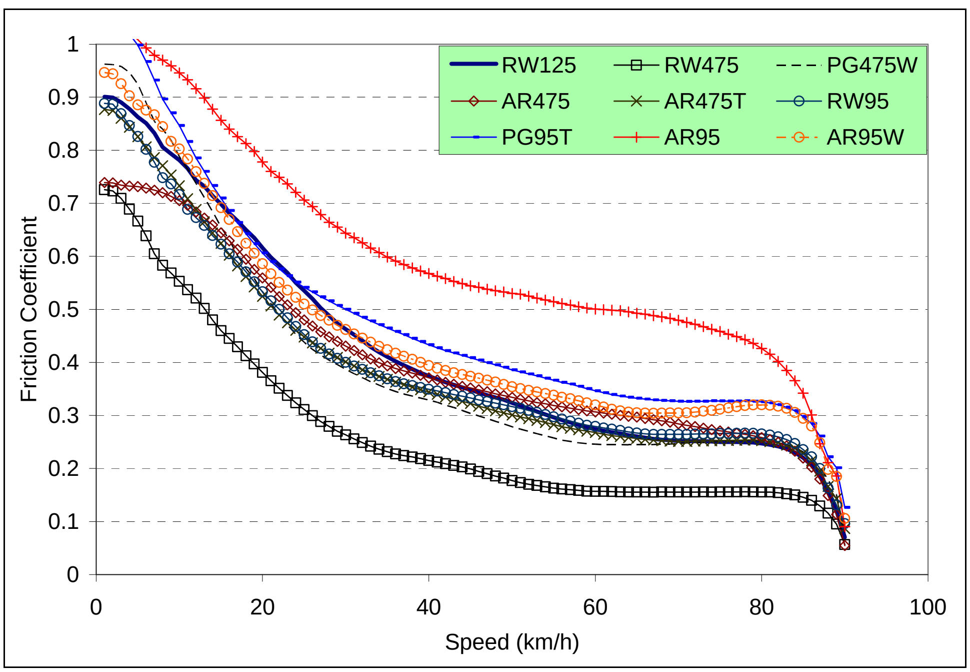


Figure 5.56: DFT results of mixes with various aggregate types, NMAS, and binders.

5.4.6 Texture

The surface profiles of five mixes are illustrated in Figure 5.57. The profiles of the other three mixes have been shown in previous sections. The mean profile depths (MPD) calculated from these profiles are summarized in Figure 5.58. As can be seen, no significant difference in MPD was detected between the mixes containing Syar and Teichert aggregates which have similar angularity for the 9.5 to 12.5-mm size fraction. On the other hand, for 4.75-mm NMAS mixes, use of the more spherical (at that size fraction) Watsonville aggregates provided a higher MPD than use of Syar aggregates. For 9.5-mm NMAS mixes, use of Watsonville aggregates instead of Syar aggregates had no effect on MPD, and both aggregates have similar angularity numbers for the 9.5 to 4.75-mm size fraction, although the Syar is slightly more angular.

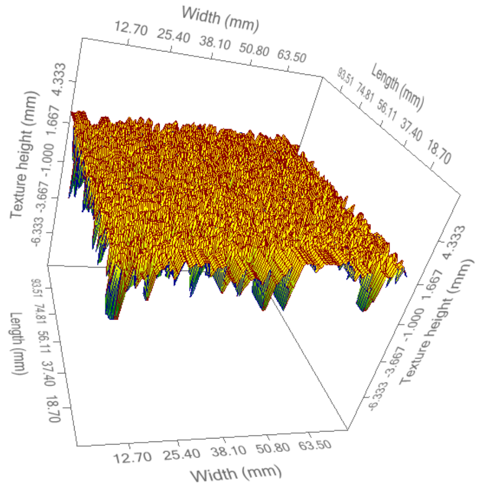
The above observations of differences in MPD among mixes with different aggregate types, aggregate sizes, and binder types are consistent with the relative ranking of the mixes based on friction measurement.

5.4.7 Resistance to Permanent Deformation

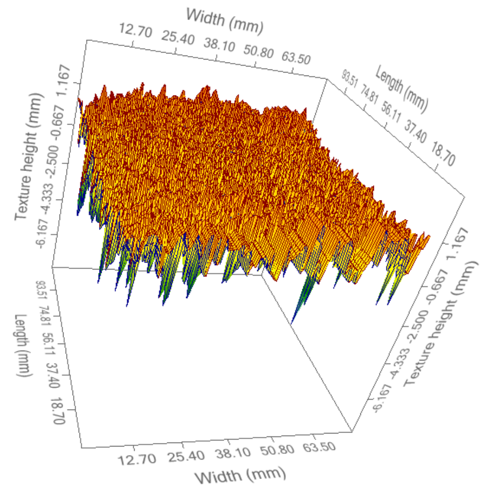
The initial shear modulus and cycles to failure (5 percent permanent shear strain) are shown in Figure 5.59 and Figure 5.60, respectively. As can be seen, aggregate type (shapes) generally did not have a significant effect on the shear resistance of OGFC mixes, except for the 4.75-mm NMAS mixes with PG 64-16 binder, where use of Watsonville rather than Syar aggregates increased both the initial shear modulus and the number of cycles to 5 percent permanent shear strain.

5.4.8 Resistance to Reflective Cracking

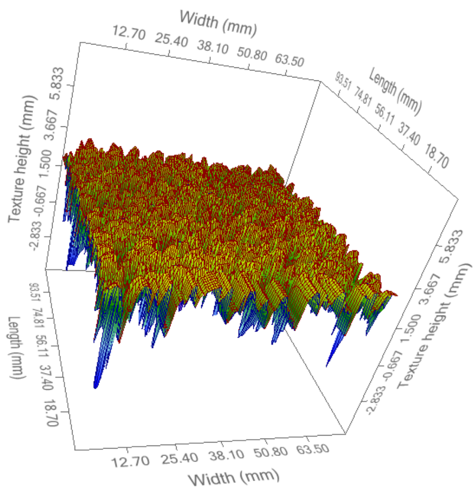
Figure 5.61 and Figure 5.62 summarize the Texas Overlay Tester results for each mix. Figure 5.61 shows that aggregate type did not make any significant difference in terms of the initial maximum load (or initial stiffness) of open-graded asphalt mixes. Mixes containing the Watsonville aggregates exhibited slightly better resistance to cracking than those containing Syar aggregates, while there was little difference between the mixes with Teichert aggregates and Syar aggregates in cracking resistance.



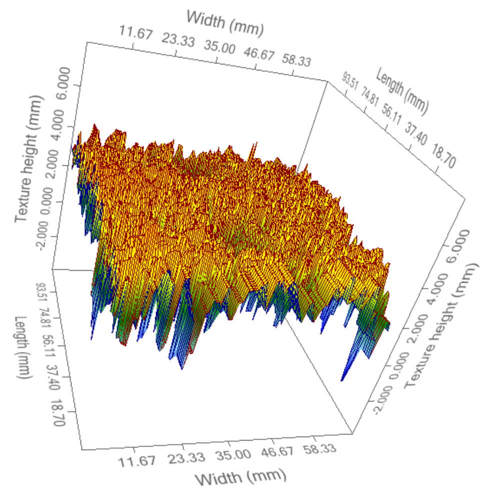
(a) PG475W



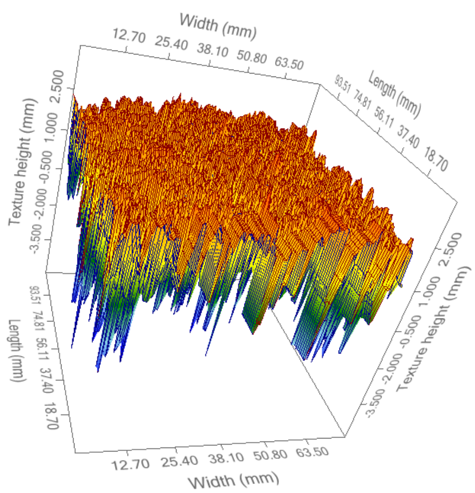
(b) AR475T



(c) PG95T



(d) AR95



(e) AR95W

Figure 5.57: Surface profiles of mixes with various aggregate types, NMAS, and binders.

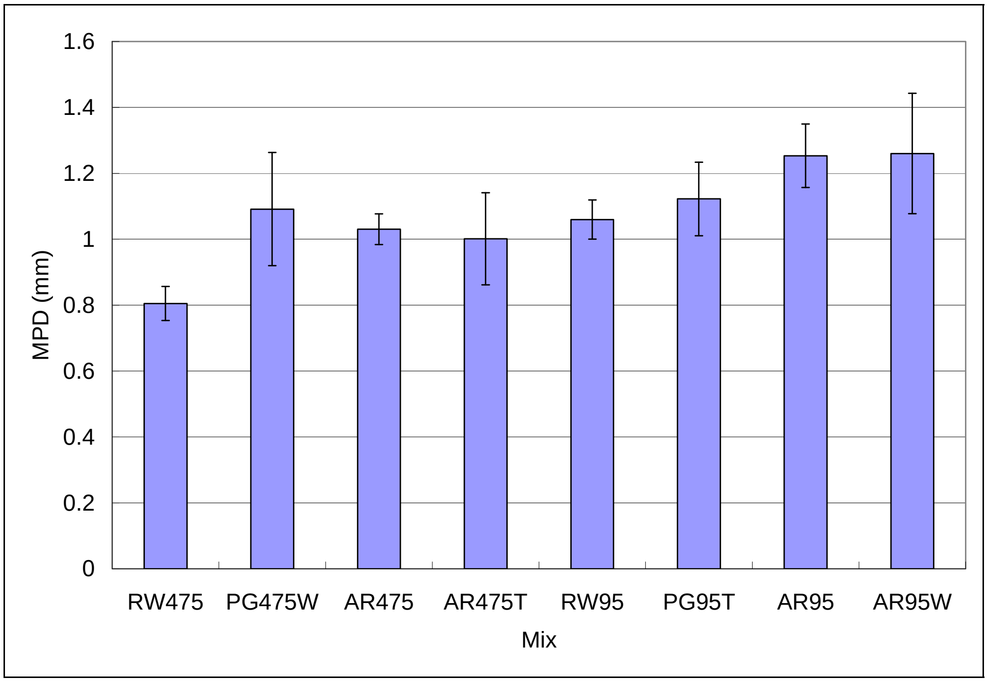


Figure 5.58: MPD of mixes with various aggregate types, NMAS, and binders.

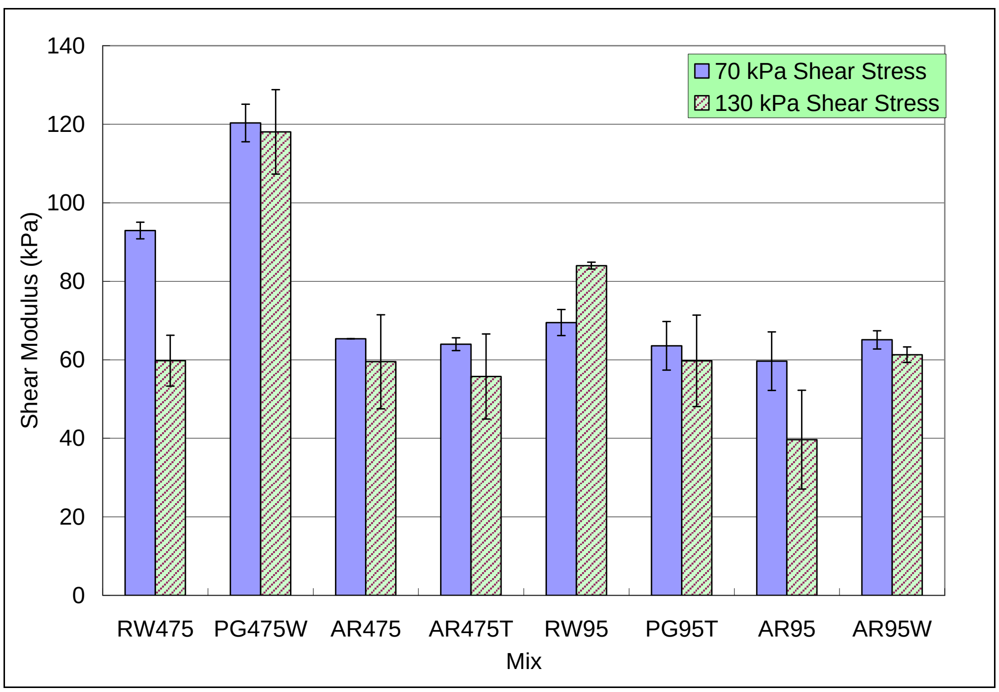


Figure 5.59: Initial shear modulus of mixes with various aggregate types, NMAS, and binders.

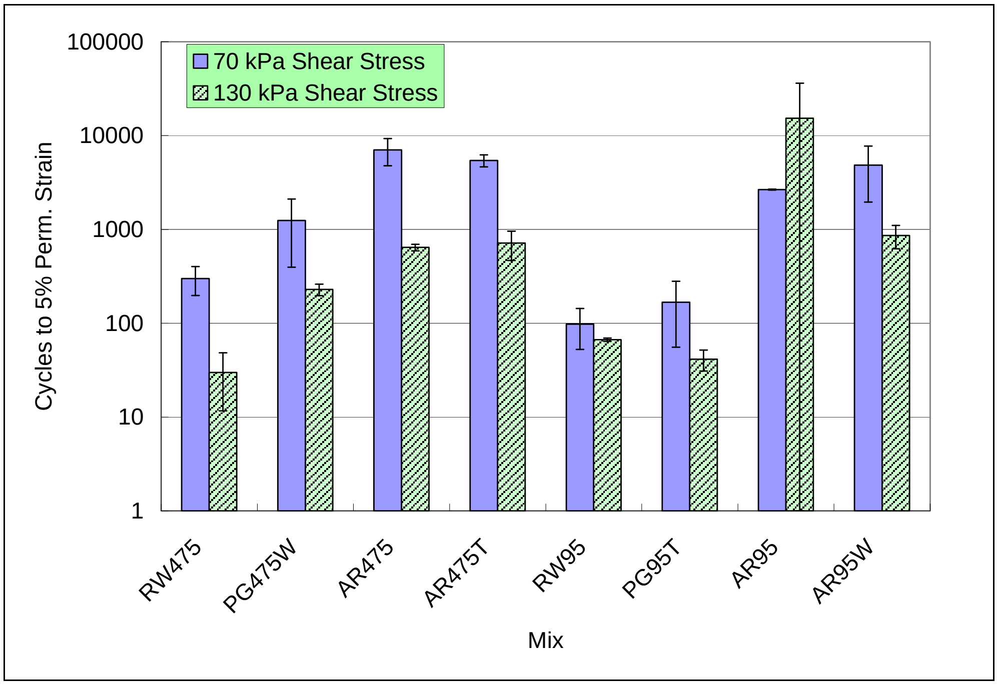


Figure 5.60: Cycles to 5 percent permanent shear strain of mixes with various aggregate types, NMAS, and binders.

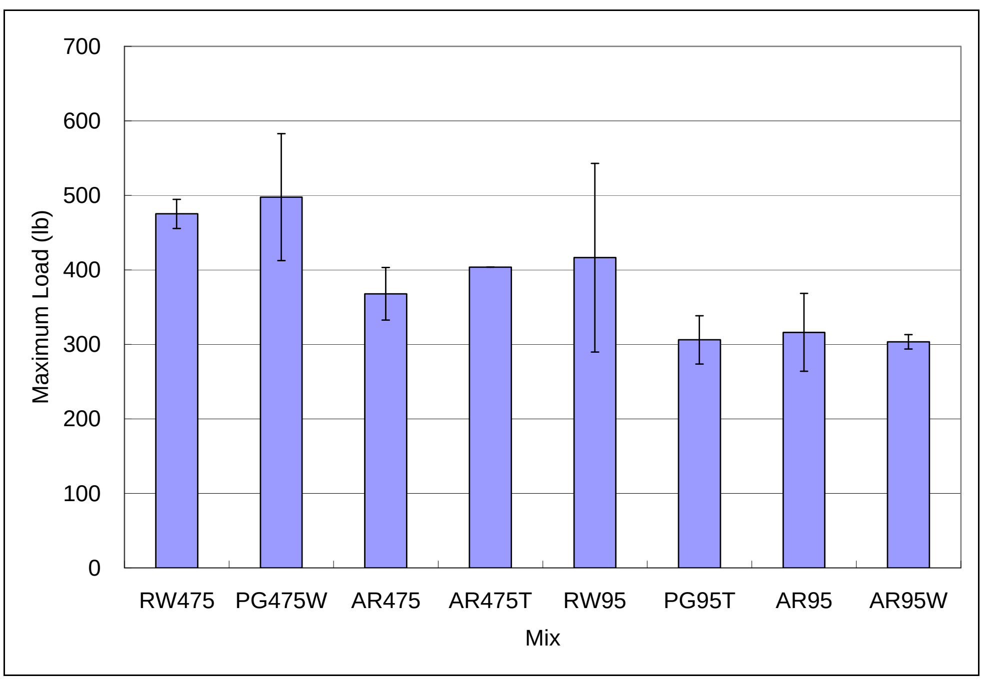


Figure 5.61: Maximum load of mixes with various aggregate types, NMAS, and binders.

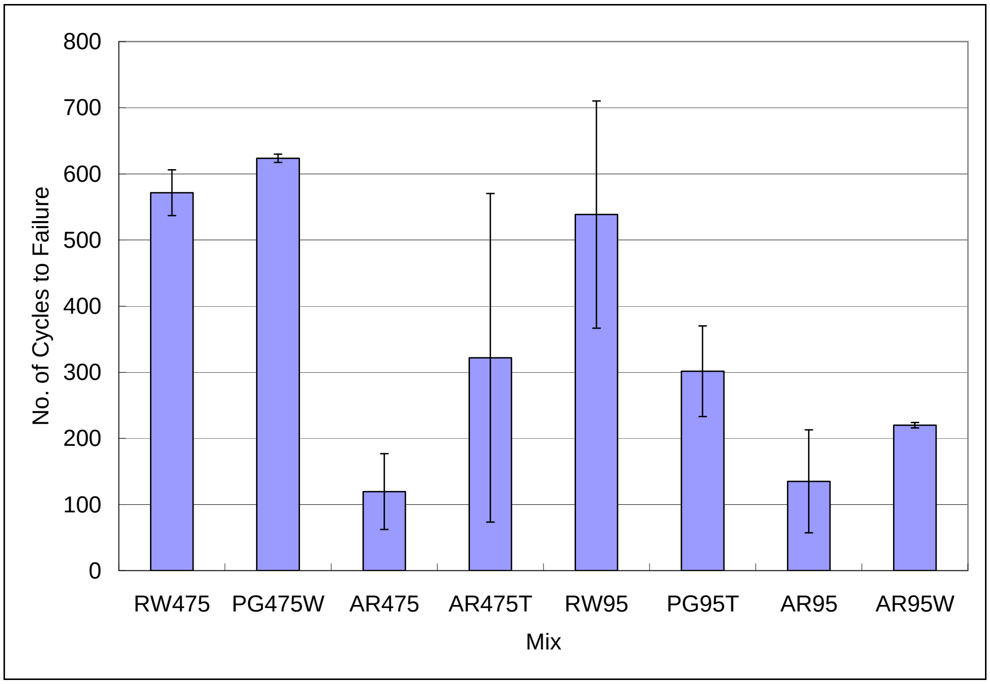


Figure 5.62: Number of cycles to failure of mixes with various aggregate types, NMAS, and binders.

5.4.9 Summary of Results from the Fourth Experiment

The objective of the fourth experiment was to investigate the effect of aggregate shape on noise reduction and durability. The more angular coarse aggregates provided some improvement for permeability and sound absorption, which will help with higher frequency noise. Otherwise there did not appear to be consistent and significant differences in overall performance between the different aggregate shapes. There did not appear to be consistent and important benefits from higher surface texture within the range included in this experiment. In summary, it appears that testing of individual mixes for key performance properties is important regardless of aggregate source.

5.5 Performance Comparison of Prospective Asphalt Surface Mixes

The fifth experiment was designed to compare the laboratory noise and durability performance of some asphalt surface mixes that have shown good performance in other states and countries (as described in Section 4.1) and the mixes developed in this study. Six prospective mixes were included in this experiment: AZ95, DL, SMA6P, SMA4P, G125, and E8, along with a reference DGAC mix, D125. Their laboratory test results are also compared to the performance of two of the 4.75 mm NMAS mixes included in the first four experiments, RW475 and AR475, since the 4.75 mm mixes also showed promising results.

5.5.1 Air-Void Content and Permeability

A nominal air-void content of 20 percent was specified in fabricating all specimens in this experiment except for the two stone mastic asphalt (SMA) mixes. The nominal air-void contents for SMA4P and SMA6P are

11 percent and 14 percent, respectively. Marshall specimens were not fabricated for the double-layer porous asphalt (DL), because the TSR and Cantabro tests were only conducted on the upper layer mix, E8.

Figure 5.63 shows the average air-void content, as well as the range of one standard deviation, for each mix from specimens compacted by the two methods. It can be seen that the average air-void contents of mixes AZ95, DL, G125, and E8 were around 20 percent, while those of mixes SMA6P and SMA4P were around 16 and 14 percent, respectively.

Figure 5.64 presents the permeability test results on slab specimens of the prospective mixes, and for comparison those from some mixes from previous experiments. As can be seen, the two SMA mixes have air-void contents (around 14 to 16 percent) between those of open-graded mixes and dense- or gap-graded mixes, and their permeabilities fall between as well. However, the permeabilities of the SMA mixes were significantly lower than those of open-graded mixes, and were only 10 times greater (one order of magnitude) larger than the permeability of a DGAC mix. This indicates that most air voids in the two SMA mixes are not interconnected. This observation is consistent with Danish experience *(28).*

The Georgia mix G125 and European mix E8 had similar permeabilities compared with those of mixes RW95 and RW125, while the Arizona mix AZ95 showed a much lower permeability. It should be remembered that the Arizona DOT mix design approach for AZ95 does not try to achieve a particularly high permeability.

The double layer porous asphalt, DL, showed a higher permeability than mix E8. Note that DL consists of a top layer of mix E8 and a bottom layer of mix E16, so adding a layer of coarse open-graded asphalt mix underneath a small size open-graded mix can significantly increase pavement surface permeability compared with the same total thickness of the smaller size aggregate mix.

5.5.2 Acoustic Absorption

Figure 5.65 presents the average spectra of sound absorption coefficients for the one-third octave frequency bands for each mix, along with the curve of the reference DGAC mix. The plot shows that the Arizona high-binder rubberized OGFC mix (AZ95) had a similar sound absorption curve to that of the asphalt rubber 4.75-mm NMAS mix AR475. SMA6P showed better sound absorption capability than SMA4P, indicating that inclusion of larger aggregates in the SMA mixes improves sound absorption. The sound absorption curves of the two small aggregate-size SMA mixes were higher than those of the DGAC mix (D125), but much flatter and lower than those of the open-graded mixes. The Georgia 12.5-mm OGFC mix (G125) had sound absorption characteristics similar to those of the European 8-mm NMAS OGFC mix (E8), while the double-layer porous asphalt mix (DL) showed the best noise absorption property among all the prospective mixes. The sound absorption of mixes DL, E8, and G125 was significantly higher than that of mixes AZ95, SMA4P, and SMA6P.

The overall absorption coefficient shown in Figure 5.66 indicates a ranking of various mixes that is the same as that discussed above.

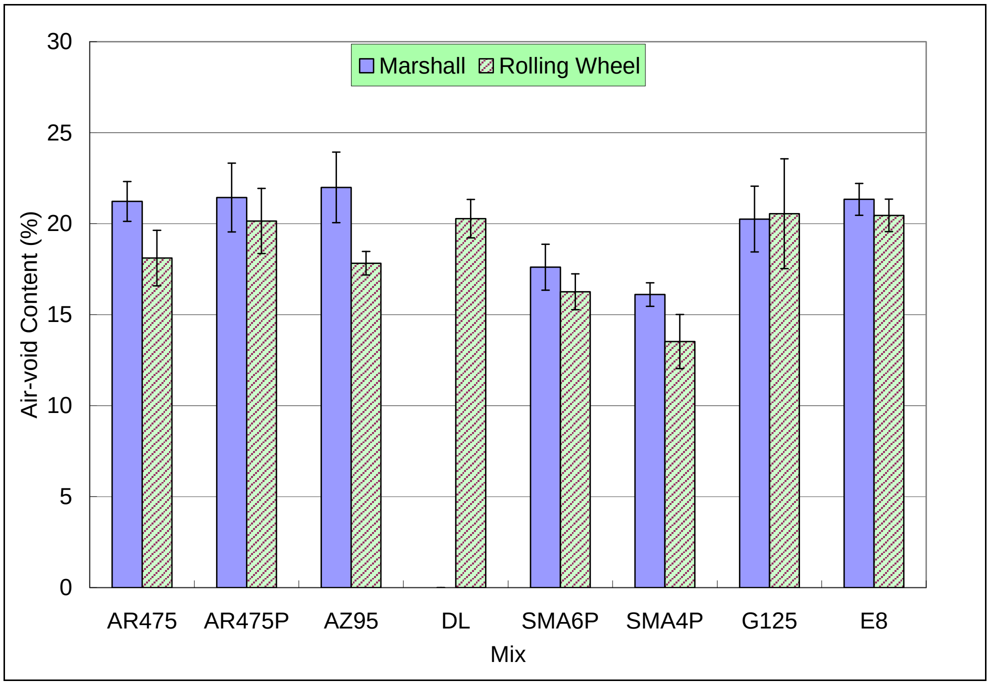


Figure 5.63: Air-void contents of various prospective mixes.

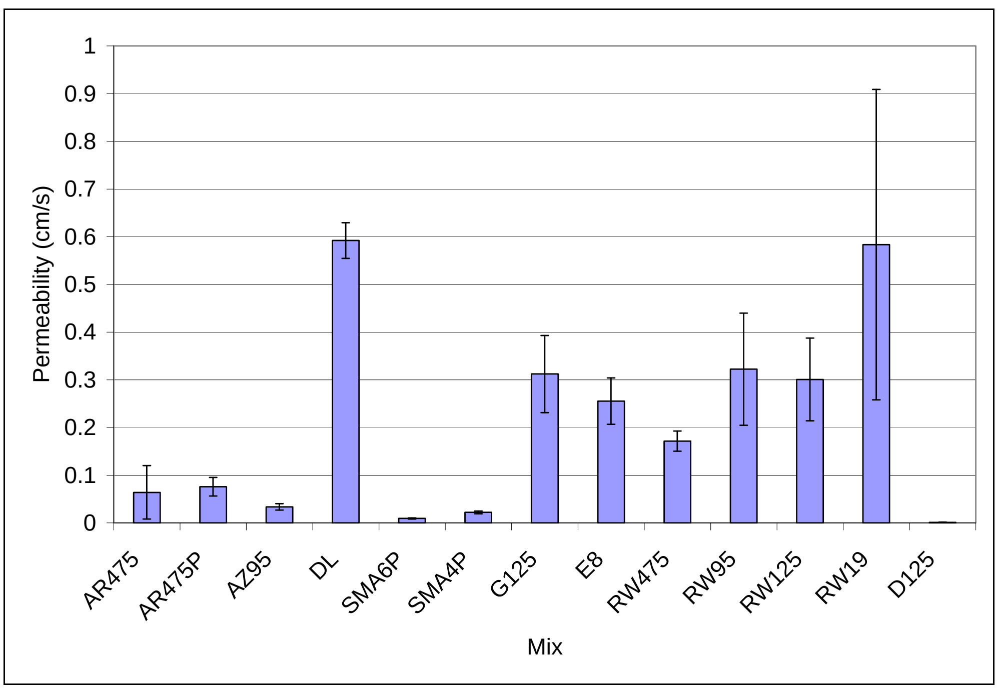


Figure 5.64: Permeability of various prospective mixes.
(Note: The permeability of the D125 mix is so low that it is difficult to see on the plot.)

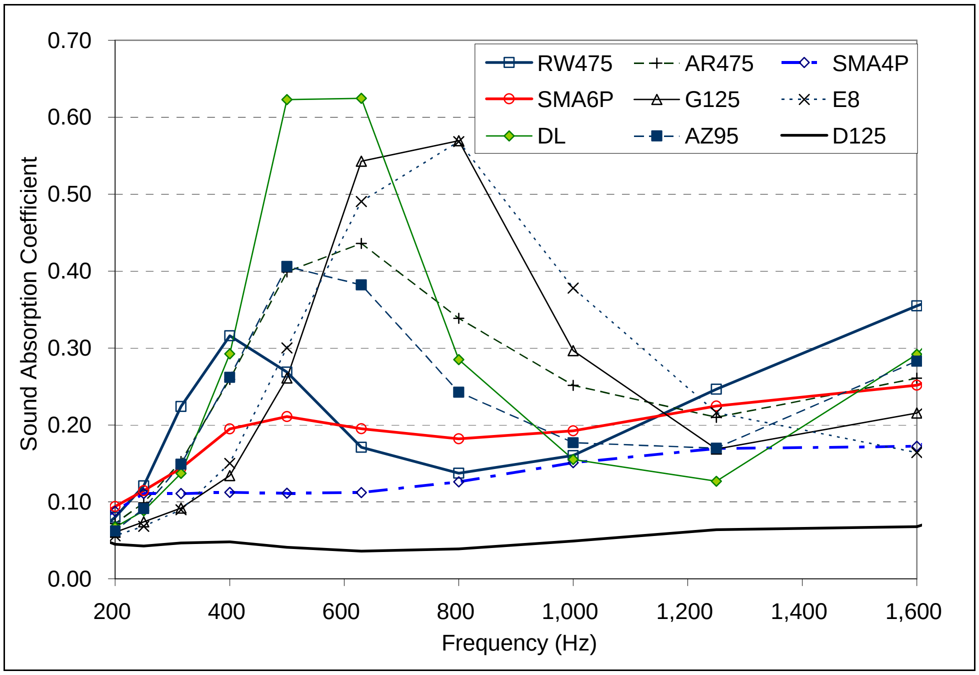


Figure 5.65: Spectra of sound absorption coefficients of various prospective mixes.

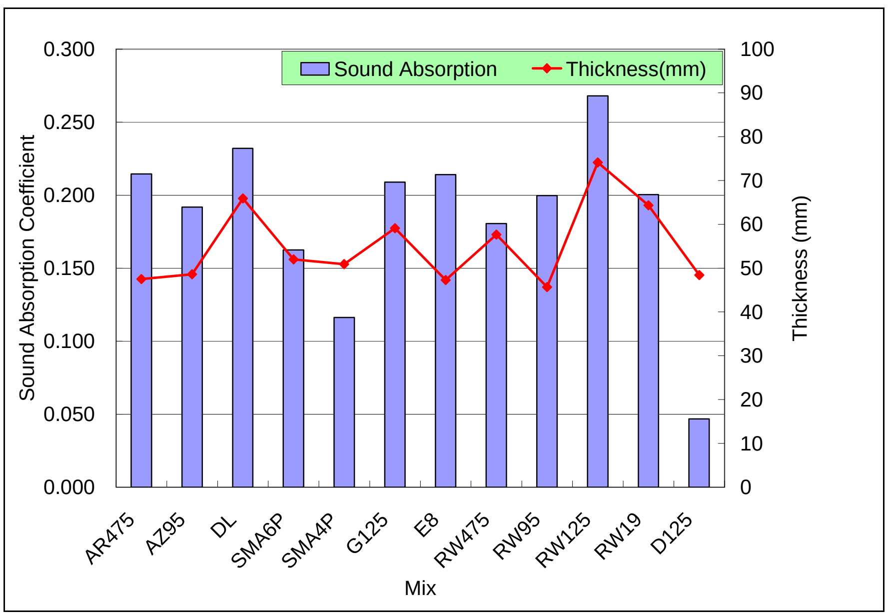


Figure 5.66: Average sound absorption coefficients of various mixes compared with new prospective mixes.

5.5.3 Moisture Sensitivity

Figure 5.67 and Figure 5.68 show the indirect tensile strength and tensile strength ratio (TSR) of the eight mixes. As can be seen, mixes with rubberized asphalt (AZ95) and PG 58-34 PM binder (SMA4P, SMA6P) had lower tensile strength in both dry and wet conditions than did mixes with conventional binder (RW475, E8), while the mix with PG 76-22 PM binder (G125) had similar tensile strength as mix RW475. The Georgia mix, G125, showed a higher TSR value than other mixes, likely due to the use of stiffer binder. Mixes AZ95, SMA4P, SMA6P, and E8 all had a TSR value less than 60 percent.

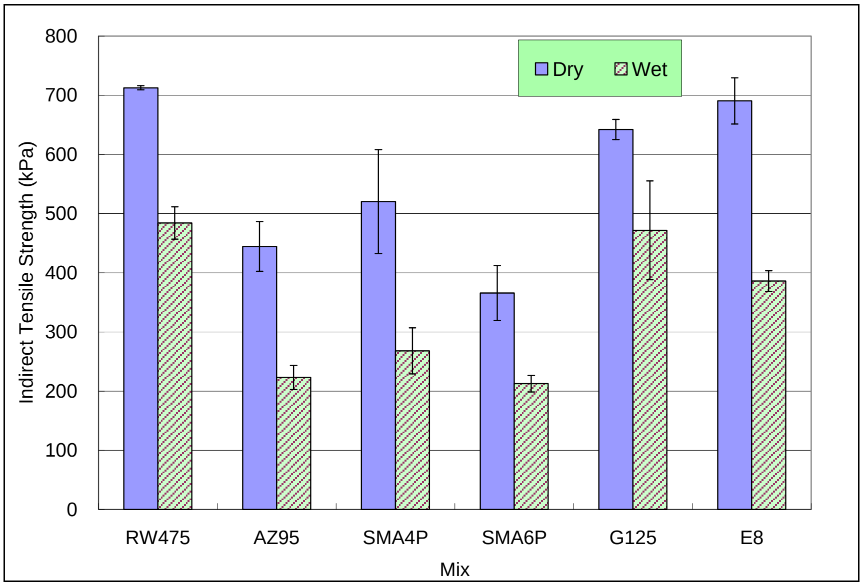


Figure 5.67: Indirect tensile strength of dry and moisture-conditioned specimens of various prospective mixes.

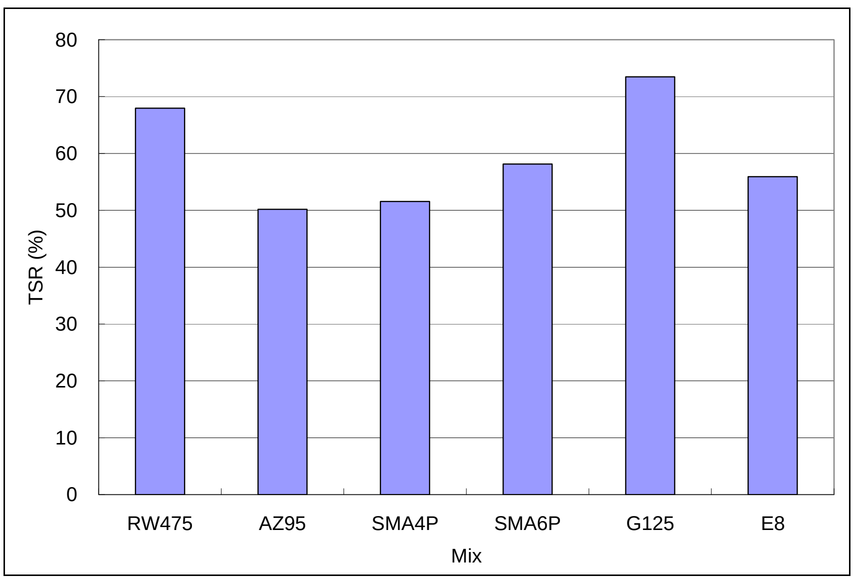


Figure 5.68: Indirect tensile strength ratio of various prospective mixes.

Figure 5.69 presents the rut depth curves from the HWTD of each mix designation. Each curve in the plot is the average of results from two replicates. The figure shows that mix E8 had very similar performance to that of mix RW475 in the HWTD test, likely because they contain the same asphalt binder (PG 64-16) and both have smaller aggregates. However, the double-layer porous asphalt (DL) showed much better performance than mix E8 although DL uses mix E8 as the top layer. Arizona mix AZ95 showed better resistance to moisture damage/premature failure than mixes SMA4P, SMA6P, and DL, while the Georgia mix G125 showed excellent performance in the HWTD test.

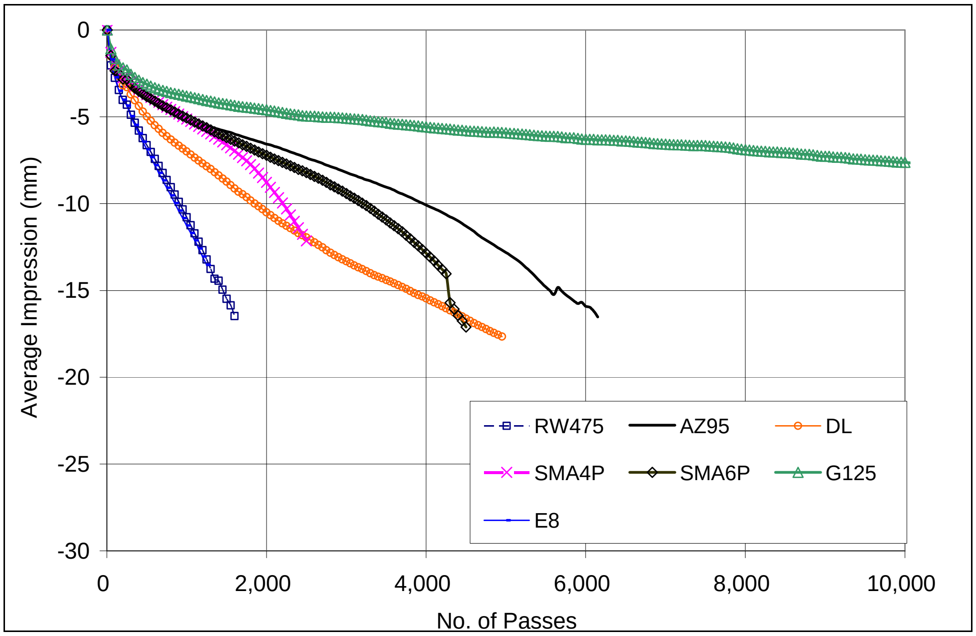


Figure 5.69: Rut depth curve of various prospective mixes from the HWTD test.

5.5.4 Resistance to Raveling

Figure 5.70 shows the average and range of one standard deviation for the Cantabro loss values from aged and unaged specimens. Mixes AZ95, SMA4P, and SMA6P all showed excellent resistance to raveling in the test, likely due to the use of small-sized aggregates and asphalt rubber binder or a soft binder (PG 58-34 PM). Mixes G125 and E8 however showed poor performance in the Cantabro test.

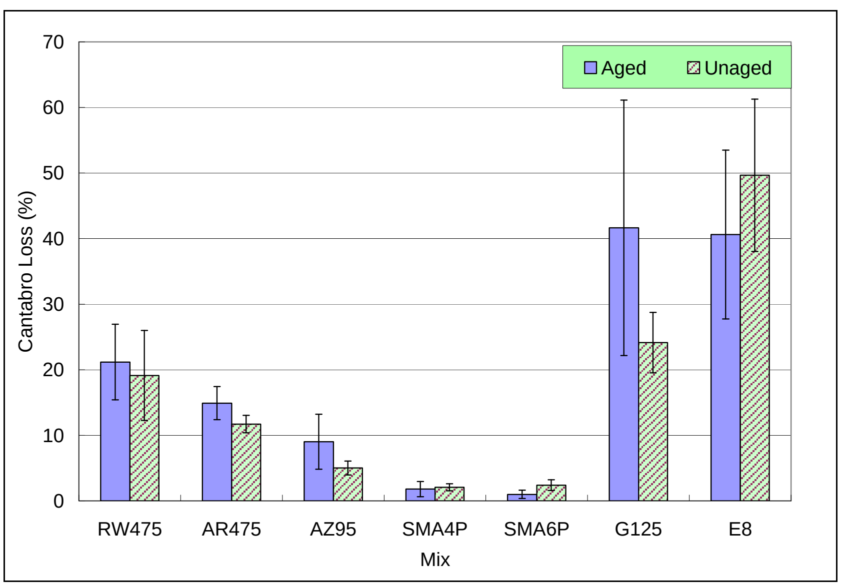


Figure 5.70: Cantabro loss results of various prospective mixes.

5.5.5 Friction

Figure 5.71 shows the average and range of one standard deviation for the British Pendulum Number (BPN) results for each mix. As can be seen, all the mixes had an average BPN close to or greater than the BPN (70) of a DGAC mix.

The results from the DFT, as shown in Figure 5.72, indicate that at a slip speed above 15 km/h, all the prospective mixes had a friction lower than that of a DGAC mix, but higher than that of mix RW475. The difference in friction among all the prospective mixes, however, is insignificant.

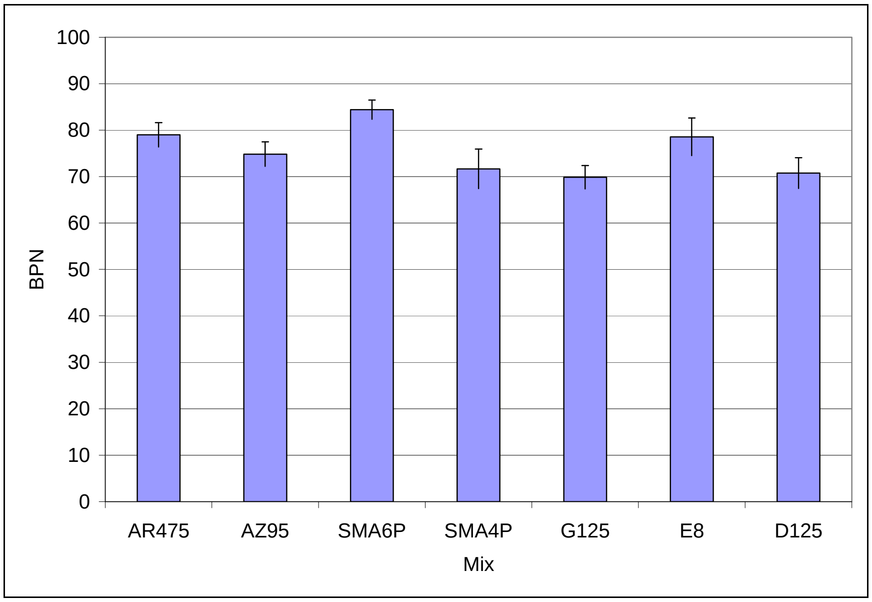


Figure 5.71: BPT results of various prospective mixes.

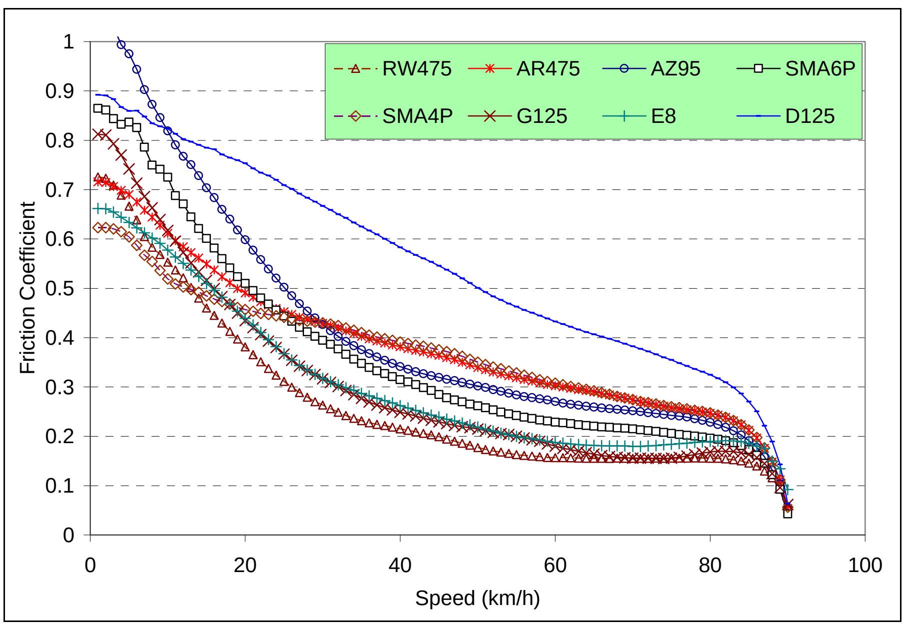
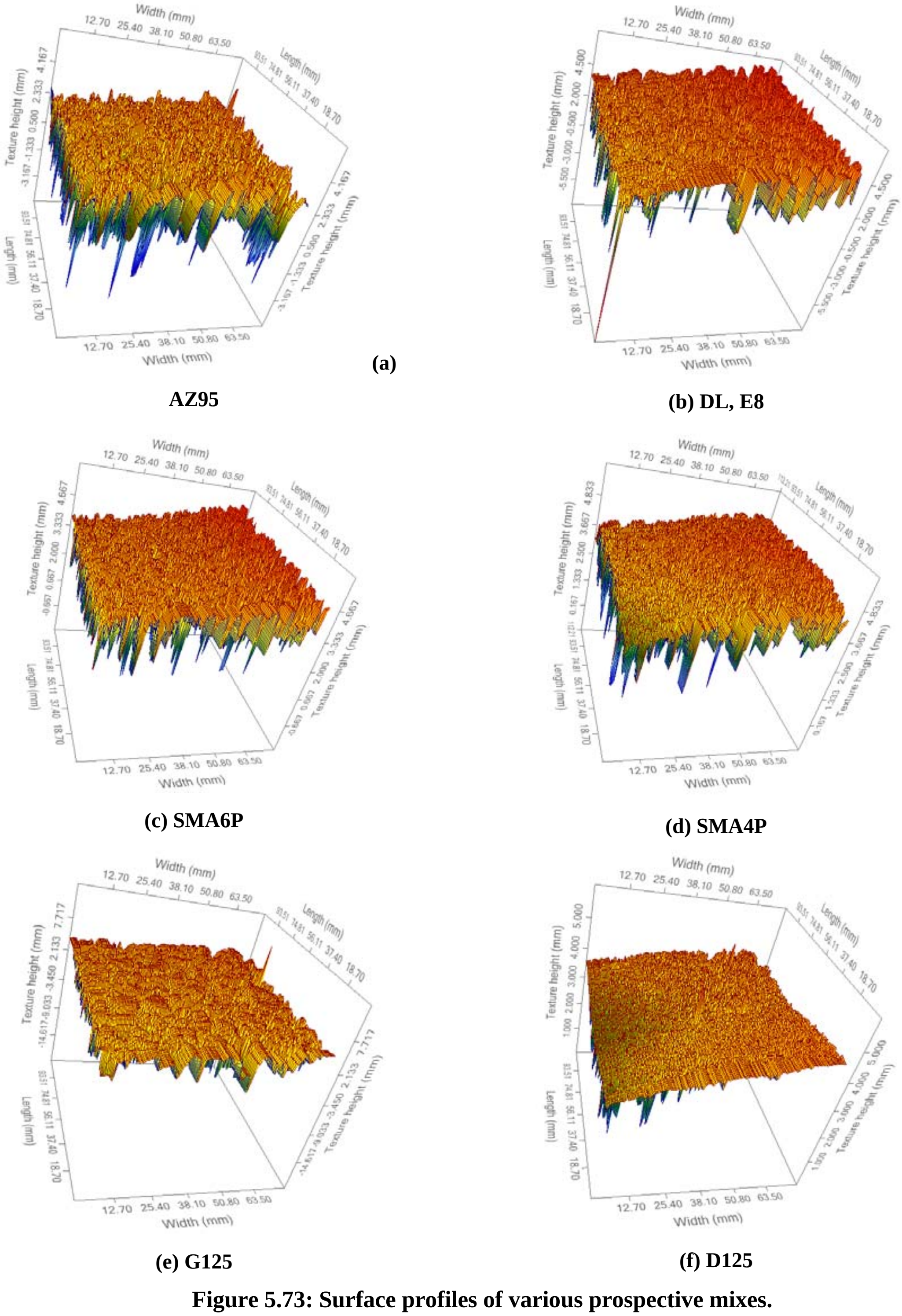


Figure 5.72: DFT results of various prospective mixes.

5.5.6 Texture

The surface profiles of six mixes are illustrated in Figure 5.73. The mean profile depths (MPD) calculated from these profiles are summarized in Figure 5.74. As can be seen, the two SMA mixes have higher MPD values than a DGAC mix (D125), but lower MPD values than all the open-graded mixes. The MPD of the Arizona mix, AZ95, and the Georgia mix, G125, were similar, and both were higher than those of the other open-graded mixes.



(a)

AZ95

(b) DL, E8

(c) SMA6P

(d) SMA4P

(e) G125

(f) D125

Figure 5.73: Surface profiles of various prospective mixes.

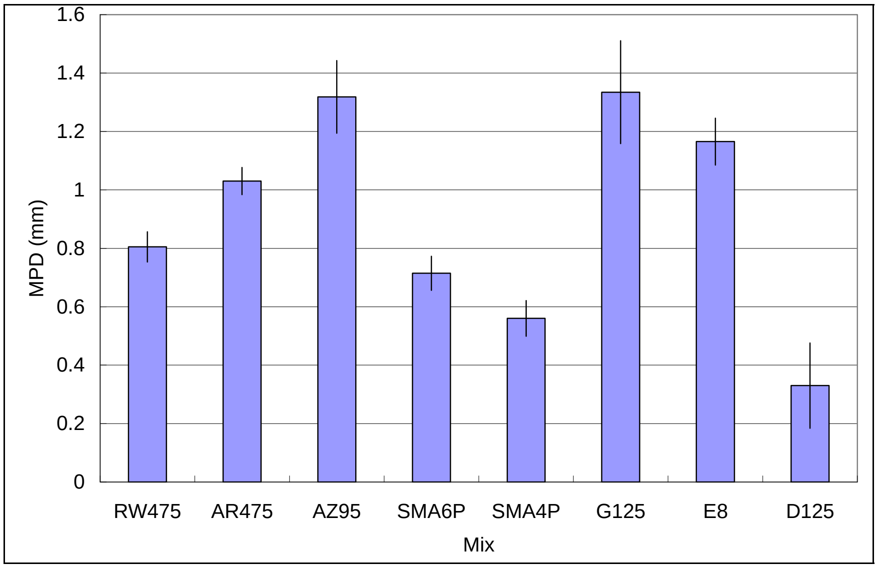


Figure 5.74: MPD of various prospective mixes.

5.5.7 Resistance to Permanent Deformation

The initial shear modulus and cycles to failure (5 percent permanent shear strain) are shown in Figure 5.75 and Figure 5.76, respectively. The reference DGAC mix, D125, showed the highest initial shear modulus and best resistance to permanent shear deformation. The two SMA mixes showed the lowest initial shear modulus and low resistance to permanent shear deformation, likely due to the use of a soft binder PG 58-34PM in the mixes. AZ95, the Arizona mix, showed a shear modulus and resistance to permanent deformation similar to those of mix AR475, while G125, the Georgia mix, showed higher shear modulus and better resistance to permanent deformation than mix AR475. DL, the double-layer porous asphalt, showed lower initial shear modulus and resistance to permanent shear deformation than mix E8.

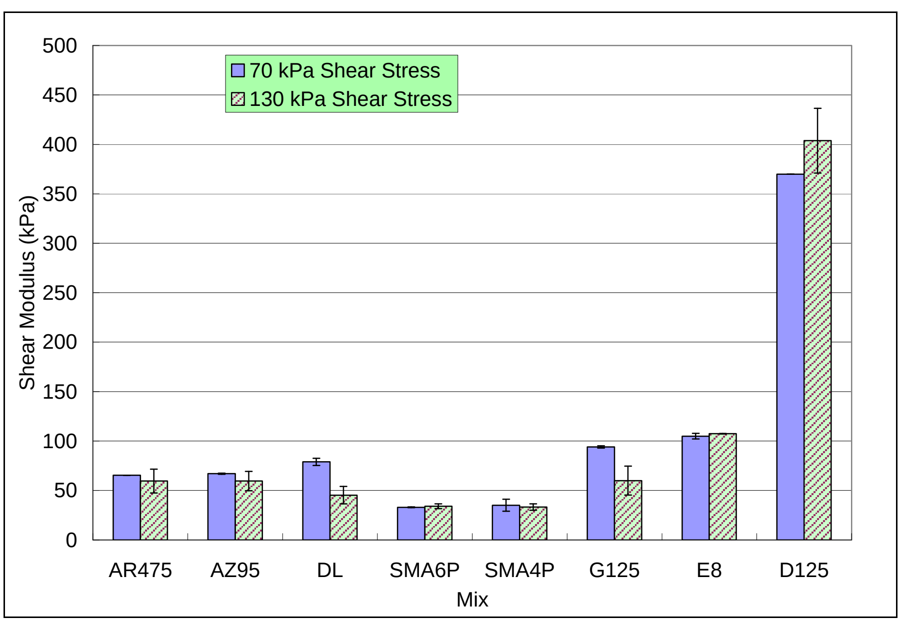


Figure 5.75: Initial shear modulus of various prospective mixes.

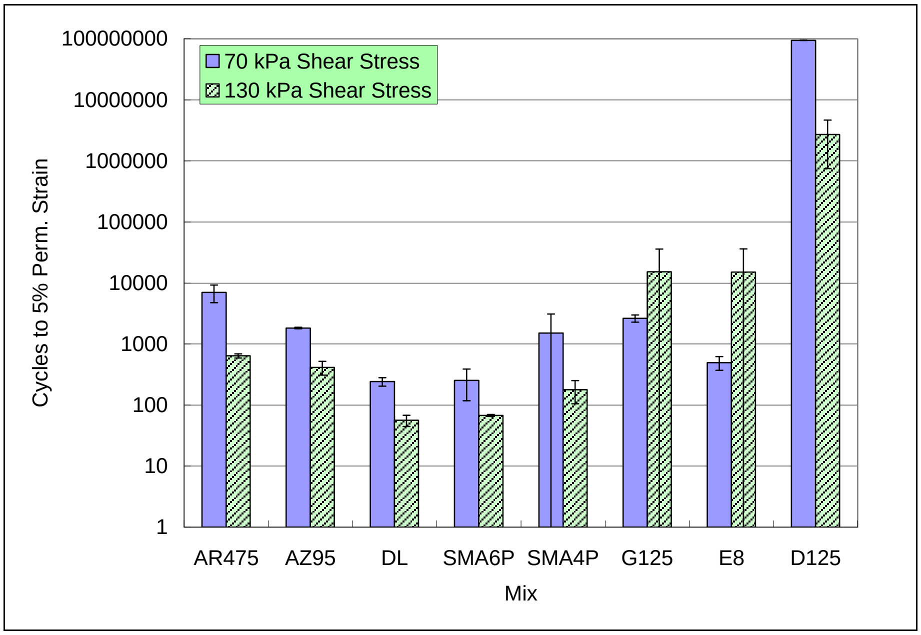


Figure 5.76: Cycles to 5 percent permanent shear strain of various prospective mixes.

5.5.8 Resistance to Reflective Cracking

Figure 5.77 and Figure 5.78 summarize the Texas Overlay Tester results. As can be seen, initial maximum load (or tensile stiffness) is negatively correlated to the number of cycles to failure. The DGAC mix (D125) had the highest initial stiffness but the lowest number of cycles to failure, while the SMA mixes (SMA4P, SMA6P) had the lowest initial stiffness but the best cracking resistance. The good cracking resistance of the SMAs is probably due to their low air-void contents and polymer-modified binders. Among the open-graded mixes, the Arizona mix AZ95 and the double-layer porous asphalt, DL, had similar cracking resistance, which was better than Georgia mix G125.

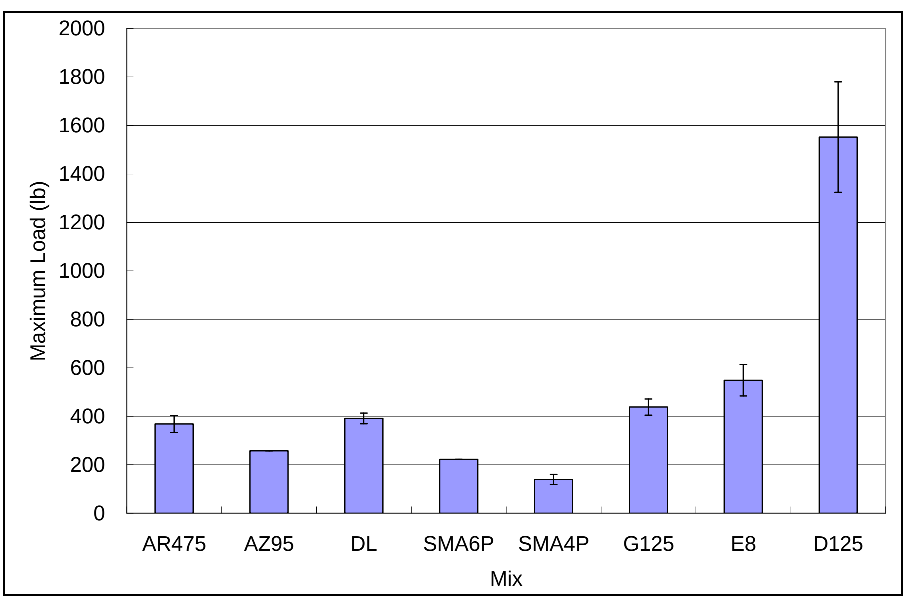


Figure 5.77: Maximum load of various prospective mixes.

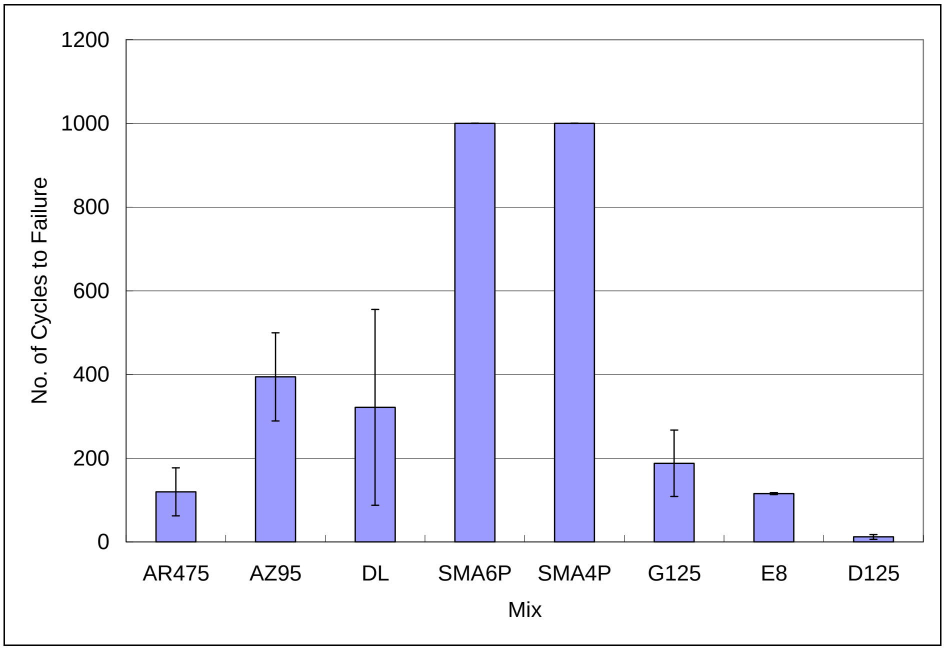


Figure 5.78: Number of cycles to failure of various prospective mixes. (The test cut off at 1,000 cycles).

5.5.9 Summary of Results from the Fifth Experiment

The objective of the fifth experiment was to compare the noise and durability performance of some asphalt surface mixes that have shown good performance in other states or countries and the new mixes developed in this study.

Property	Primary Observations
Permeability	Ranking best to worst: DL, RW19, RW95, G125, RW125, E8, RW475, AR475P, AR475, AZ95, SMA4P, SMA6P, D125
Raveling	Ranking best to worst (Cantabro): SMA4P, SMA6P, AZ95, AR475, RW475, G125, E8
Moisture sensitivity	Ranking best to worst (HWTD): G125, AZ95, SMA6P, SMA4P, DL, E8
Reflective cracking	Ranking best to worst (Texas Overlay Tester repetitions): SMA6P, SMA4P, AZ95, DL, G125, AR475, E8, D125
Rutting	Ranking best to worst (Repetitions to 5 percent shear strain): D125, E8, G125, AR475, AZ95, SMA4P, SMA6P, DL
Surface friction	No significant differences, all less than dense graded.
Noise-related properties	MPD ranking lowest to highest (high MPD correlated with high low frequency noise): D125, SMA4P, SMA6P, RW475, AR475, E8, AZ95, G125 Absorption ranking highest to lowest (high absorption correlated with low high frequency noise): RW125, DL, AR475, E8, G125, RW19, RW95, AZ95, RW475, SMA6P, SMA4P, D125

5.6 Discussion and Summary

In addition to the tests discussed in previous sections, a draindown test was also performed for all the mixes to check their potential for excessive binder draindown during construction. The draindown test was performed following ASTM D6390. In this test, a metal wire basket made of standard 6.3-mm sieve cloth is used to hold a freshly prepared loose mix at the mix production temperature for 1 hour, and the mass of drained material is used to calculate draindown. This procedure is repeated for another sample at 10°C above the mix production temperature. The maximum permissible draindown established in ASTM D7064 is 0.3 percent by total mixture mass. In this study, however, very little (near zero) binder draindown was measured for each mix following the ASTM D6390 procedure, likely due to the fact that the optimum binder contents of most mixes in this study were determined based on other versions of the draindown test (e.g., CTM 368 and GDT 114) so that draindown was not an issue for the mixes tested.

The test results in rank order for all mixes included in the study for permeability, sound absorption, Cantabro mass loss, MPD, and DFT are shown in Figure 5.79 through Figure 5.83 for reference for the following summary.

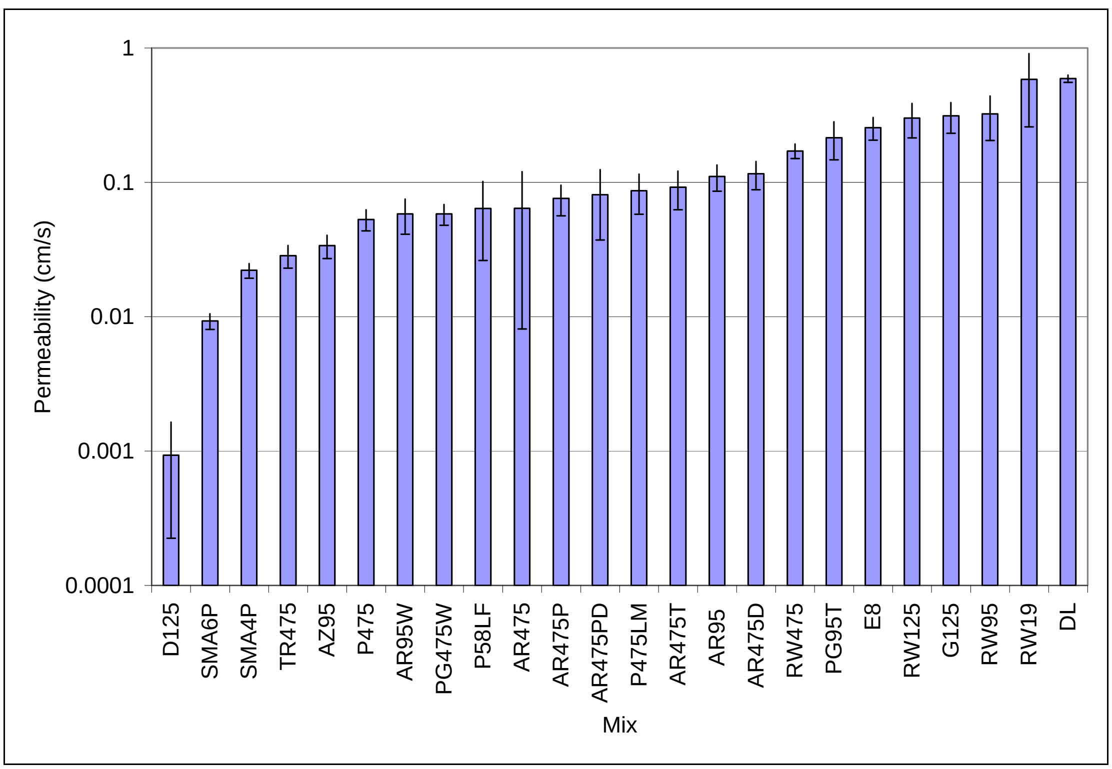


Figure 5.79: Permeability test results in rank order for all mixes.

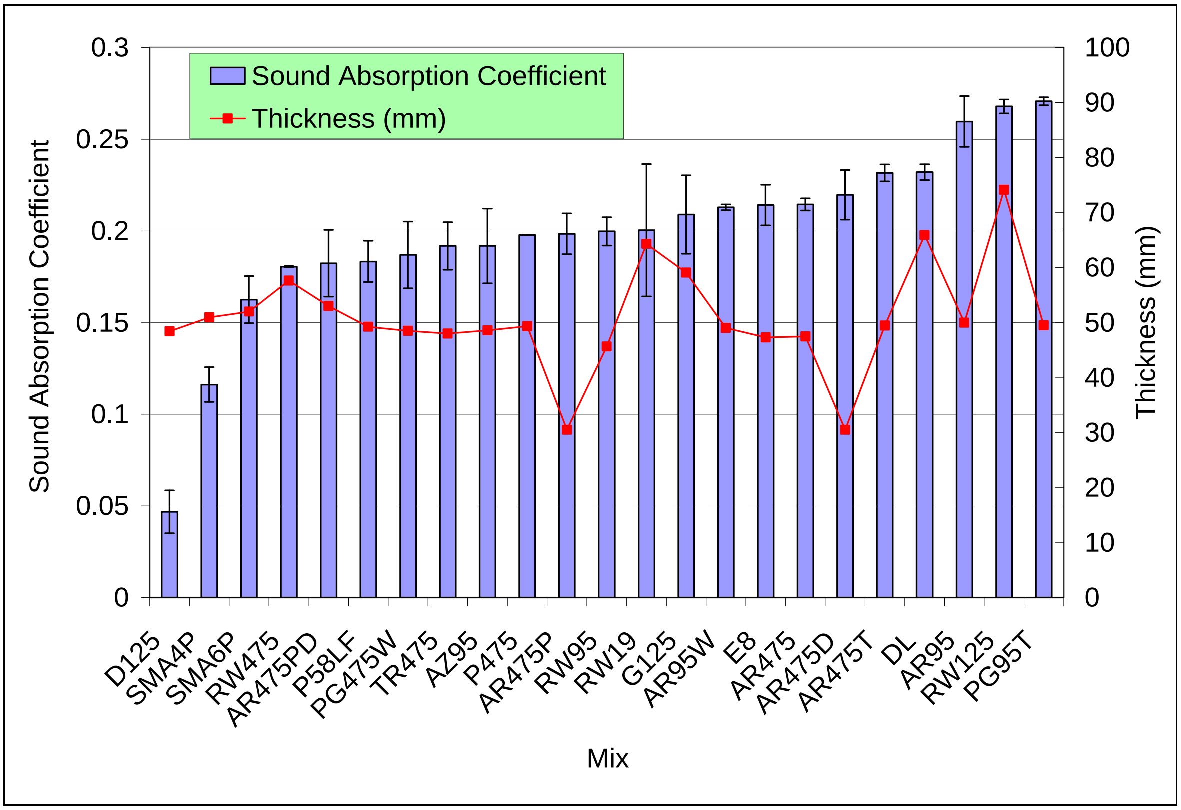


Figure 5.80: Average sound absorption coefficient in rank order for all mixes.

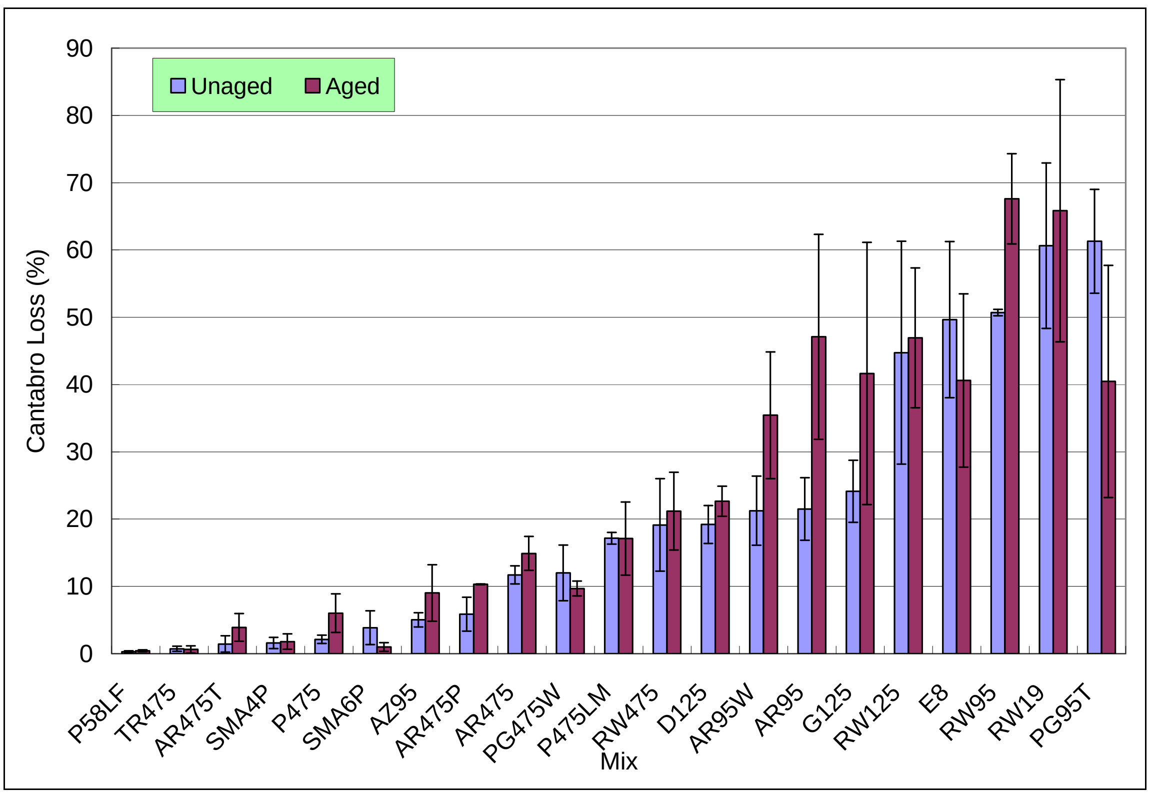


Figure 5.81: Average Cantabro mass loss results in rank order for all mixes.

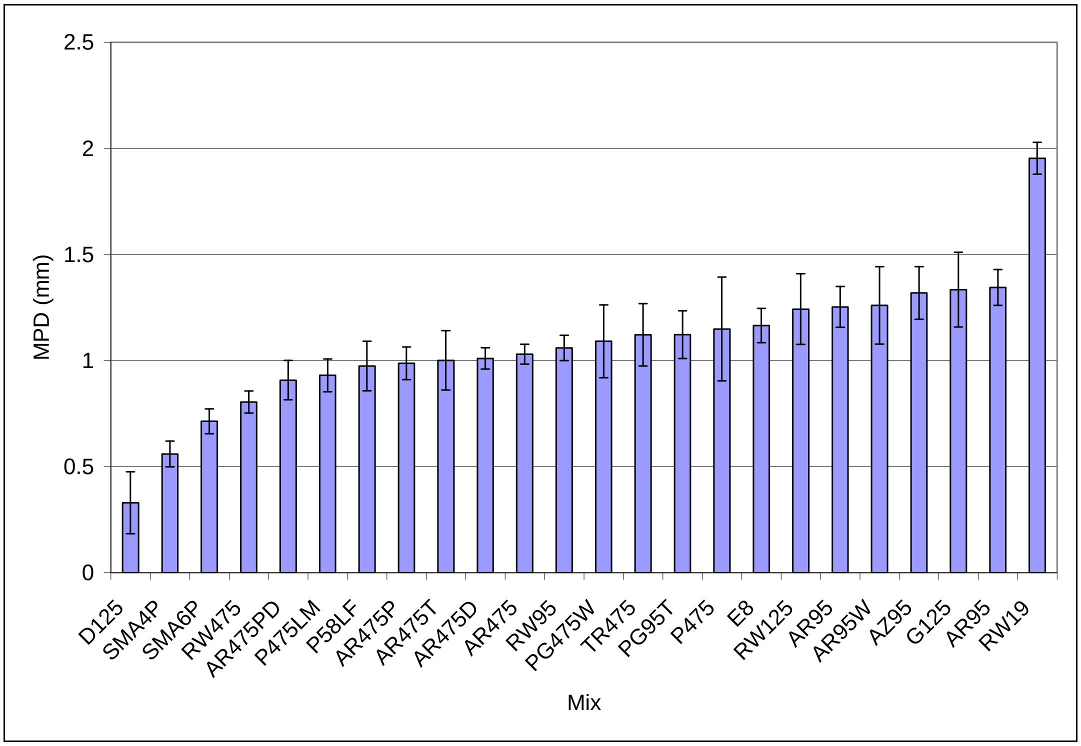


Figure 5.82: Average mean profile depth (MPD) in rank order for all mixes.

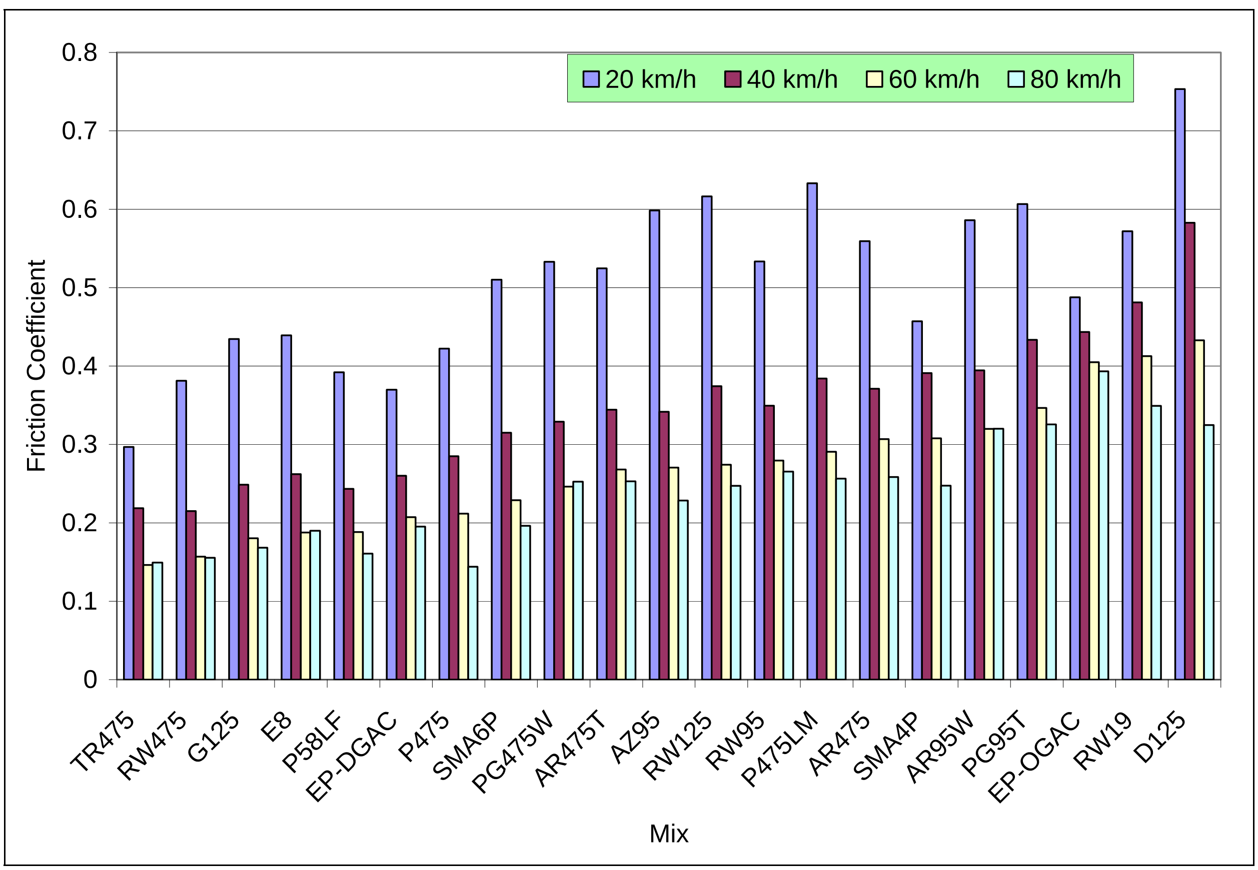


Figure 5.83: Average DFT test results at four slip speeds in rank order for all mixes.

Currently most OGFC mixes used in California and the rest of the United States contain aggregates with 9.5-mm or 12.5-mm NMAS. When an unmodified binder is used, such mixes exhibit significant material loss in the Cantabro test, indicating high potential for raveling in the field. Using asphalt rubber or polymer-modified binder helps to reduce the raveling potential. Reducing the NMAS from 9.5 and 12.5 mm to a smaller sizes (i.e., 4.75 mm), coupled with the use of asphalt rubber or polymer-modified binders appears to significantly reduce the raveling potential of an OGFC mix, and consequently to reduce the low frequency tire/pavement noise generated by tire vibration on a raveled pavement surface.

The trade off is that reducing the NMAS from 9.5–12.5 mm to 4.75 mm does not significantly change the rutting resistance and can improve the mix resistance to reflective cracking, but it also reduces the permeability and sound absorption capability of a mix, which will increase the higher frequency tire/pavement noise caused by the air pumping phenomenon. Two other concerns with using small aggregate size OGFC mixes are the reduction of surface friction and the higher potential for void clogging. A question that remains is, "What is the minimum permeability required initially for an open-graded mix at different locations in the state network", which will be a function of the number of lanes and the rainfall events? The initial literature survey for the UCPRC/Caltrans tire/pavement noise study (PPRC SPE 4.16 *[1])* found a few standards, although their basis was not available in the specifications as follows:

> *A permeability value in the range of 0.01 to 0.4 cm/sec is specified for open-graded mixes by European standards for porous asphalt* (Citation 25 in Reference 1). *The requirement for in-situ permeability of open-graded mixes in Switzerland is 0.11 cm/sec (15 l/min)* (Citation 26 in Reference 1). *No permeability requirements for open-graded mixes could be found in the literature from the United States.*

It is possible that state transportation departments in the U.S. do not set standards for fear of liability, in that the public may take the permeability as a warrant, although any open-graded mix will have much greater permeability than a dense-graded asphalt surface. All of the open-graded mixes included in this study had permeabilities greater than 0.01 cm/s, while the dense-graded control mix and the SMAs did not.

Results from the first experiment showed that although the British Pendulum Test indicated a high BPN (over 60) on the 4.75-mm OGFC mix, the DFT test revealed a reduction of about 40 percent of the surface friction at a slip speed over 20 km/h when the NMAS was reduced from 9.5 mm to 4.75 mm. Test results from the third experiment, however, showed that this reduction in friction can be potentially compensated for by addition of a few oversized aggregates into the small aggregate size OGFC mixes.

Clogging was not evaluated in this study due to the lack of an appropriate test method. Based on the literature, double-layer porous asphalt (DLPA) has less clogging potential than single-layer OGFC mixes because the large voids in its bottom layer allow water to transport dust and debris away from pavements. The DLPA evaluated in this study used an 8-mm NMAS open-graded mix as the top layer, and exhibited good overall performance. Based on the test results on the small size aggregate open-graded mix in this study, a 4.75-mm OGFC may be used as the upper layer of DLPA so that its clogging potential can be reduced. This needs further study in the laboratory or in the field.

Using polymer-modified or asphalt rubber binders in OGFC mixes may reduce their permeability because there are fewer interconnected air voids than in untreated conventional OGFC mixes. For the 4.75-mm NMAS OGFC in this study, using asphalt rubber binder reduced the mix's permeability to one-third of the value of the same mix containing conventional binder. This permeability, however, is still 100 times greater than that of conventional DGAC mixes. Although using polymer-modified or rubberized binders reduces permeability, the acoustic absorption was slightly increased instead. This indicates that the reduction in permeability was not great enough for them to lose their open-graded nature. Another possible reason that has been postulated by Biligiri is that the more viscous behavior (as measured by phase angle) of rubberized asphalt binder mixes would provide more noise-dampening effect, leading to less tire/pavement surface noise *(34)*, although another study showed little overall difference in acoustical absorption between rubberized and conventional binder open-graded mixes *(21)*.

Other benefits of using asphalt rubber binder included improvement of mix resistance to moisture damage/premature failure, raveling, and rutting. According to Texas Overlay Tester results, mix resistance to reflective cracking was reduced by introducing asphalt rubber into the surface asphalt mixes, a finding that ran contrary to most experience where asphalt rubber mixes were compared with conventional binder mixes—although those previous experiences were based on comparison of dense- and gap-graded mixes. However, it was not a critical performance index because the main purpose of asphalt surface mix was to improve the functional performance of the pavement surface, not the structural performance. Cracking resistance should be mainly provided by the underlying pavement layers. Use of open-graded mixes placed on thick sprayed asphalt tack coats, creating bonded wearing courses, may both seal the surface of the pavement and provide the benefits of an open-graded mix.

The use of hydrated lime can slightly improve the resistance to raveling of an open-graded mix, but it did not improve the resistance to moisture/premature failure, as evaluated by the TSR test and the HWTD test. In this study, hydrated lime was added to a mix by first mixing lime slurry with aggregates, and then after drying, mixing the coated aggregates with asphalt binder. The benefit of hydrated lime in OGFC mixes was largely undetected in this laboratory study. Whether the TSR test and the HWTD test can sufficiently characterize an OGFC mix's resistance to moisture damage/premature failure is out of the scope of this study. Test section or field study is needed to further verify the effect of hydrated lime on OGFC mixes.

The third experiment in this study investigated the effect of smaller air-void content and inclusion of oversized aggregates on the performance of small aggregate size OGFC mixes. The intended low air-void content was 15 percent, but neither the Marshall compaction nor the rolling wheel compaction reached this level of density, even with additional material and increased compaction. It was difficult to compact an open-graded asphalt mix to an air-void content level of 15 percent or lower. The lowest air-void content level reached for the 4.75-mm mix in this study was about 16 percent (mix TR475 in the second experiment). Reducing the air-void content by 2 or 3 percent from 20 percent, however, can increase mix durability in terms of raveling and reflective cracking without significantly affecting the permeability and overall acoustic absorption. Including some oversized aggregates in the 4.75-mm NMAS open-graded mix (in this study the percentage of aggregates retained on the No. 4 [4.75-mm] sieve was increased from 9 to 35) with asphalt rubber binder only slightly increased permeability, and did not provide any acoustic benefit in terms of noise absorption. It improved pavement friction and slightly reduced mix resistance to permanent deformation and cracking.

Aggregate type (shape) may affect the acoustic performance of an open-graded mix with 9.5 mm NMAS, indicating that there are ranges of permeabilities and absorption values in the field with current Caltrans mix designs, that are in part a function of the characteristics of aggregate from different sources. Aggregates with less angular and smoother particles generally tend to orient themselves well during compaction so that air-void content, permeability, and acoustic absorption are reduced. The aggregate shape effect on noise performance at high frequencies as estimated by the correlated sound absorption test, however, was less significant in mixes with small aggregate sizes. The effect of aggregate type (shape) on the durability of an open-graded asphalt mix was minor.

A few prospective asphalt surface mixes for noise reduction were evaluated in this study. The small aggregate size SMA mixes recently developed in Europe showed low permeability and sound absorption despite a high air-void content. Arizona rubberized OGFC mix with high-binder content showed permeability, sound absorption curve, shear modulus, and resistance to permanent deformation results similar to those of a 4.75-mm rubberized OGFC mix. The double-layer porous asphalt mix showed the best noise absorption property among all the prospective mixes included in this study, and showed increased pavement surface permeability, noise absorption, and resistance to premature failure. The Georgia 12.5-mm OGFC mix had significantly higher sound absorption than the Arizona mix and SMA mixes. It also showed excellent performance (resistance to moisture damage and rutting) in the HWTD test, and higher shear modulus and better resistance to permanent deformation than the Arizona mix. The double-layer porous asphalt and Georgia mix are worthy of further study in field test sections.

6 CONCLUSIONS

This report summarizes the work completed under project PPRC SPE 4.20. The main objective of the project was to evaluate the properties and performance of various asphalt surface mixes through laboratory tests and to determine the best asphalt surface mixes in terms of overall performance (i.e., sound absorption, durability, permeability, and friction) that can be tested in field sections and using the Heavy Vehicle Simulator.

The following conclusions were obtained regarding mix design for noise reduction and durability improvement:

- Reducing the NMAS of open-graded mixes from 9.5 (3/8 in.) or 12.5 mm (1/2 in.) to smaller sizes (e.g., 4.75 mm [No. 4 sieve]), together with the use of asphalt rubber or polymer-modified binders, can significantly reduce raveling potential, and therefore increase the longevity of tire/pavement noise reduction benefits. On the other hand, reduction of aggregate sizes causes some reduction in the permeability and sound absorption capabilities of a mix, although this is a small trade-off since the permeabilities of the open-graded mixes with 4.75 mm aggregates are still substantially greater than those of dense- and gap-graded mixes. Reducing the aggregate size of open-graded mixes does not significantly change rutting resistance but it can improve the mix's resistance to reflective cracking. The reduced aggregate size mixes appear to cause some reduction in friction due to use of small aggregates, which it appears can be compensated for by introduction of some oversized aggregates in the mix.
- Using polymer-modified or asphalt rubber binders in OGFC mixes may reduce the mix permeability, but a slight increase was measured in acoustic absorption, which may be due to the more viscous nature of these binders (as measured by phase angle), although this possible explanation was not evaluated in this study. Using asphalt rubber binder also improves mix resistance to moisture damage/premature failure, raveling, and rutting.
- Hydrated lime, added in lime slurry form, did not improve the resistance of an open-graded mix to moisture/premature failure, as evaluated by the TSR test or HWTD test. The potential benefit of hydrated lime in OGFC mixes was largely undetected in this laboratory study.
- It was difficult to compact an open-graded asphalt mix to an air-void content level of 15 percent or lower for the gradations included in this study. Compacting mixes to an air-void content of 17 or 18 percent instead of 20 percent was found to increase mix durability in terms of raveling and reflective cracking without significantly affecting permeability and overall acoustic absorption.
- Including some oversized aggregates in the 4.75-mm NMAS open-graded mix with asphalt rubber binder improves pavement friction and slightly increases permeability, but does not provide any acoustic benefit in terms of noise absorption.
- Although there was some change in permeability and acoustic absorption with changes in aggregate shape and surface texture, there did not appear to be consistent and significant differences in overall performance

between the different aggregate shapes. The higher surface textures in the range included in this experiment did not appear to bring expected consistent and significant benefits in terms of rutting performance in the HWTD, permeability, or other performance properties. In summary, it appears that testing of individual mixes for key performance properties is more important, rather than using assumptions regarding performance based on aggregate source or estimated shape and texture from visual observation.

- The small aggregate size SMA mixes recently developed in Europe showed permeability and sound absorption properties consistent with their air-void contents (14 to 16 percent), which were in between those of dense- and gap-graded mixes (5 to 8 percent) and open-graded mixes (15 to 22 percent). However, their permeabilities and sound absorption properties were closer to those of the lower air-void content mixes, indicating that their air-voids were not particularly well connected.
- The Arizona rubberized 9.5-mm NMAS OGFC mix, which has a higher binder content than Caltrans 9.5-mm NMAS OGFC, showed permeability, sound absorption curve, shear modulus, and resistance to permanent deformation properties similar to those of the 4.75-mm rubberized OGFC mix. However, its macrotexture is significantly greater than the 4.75-mm rubberized OGFC mix, indicating that overall, the latter mix would provide better performance as a noise-reducing layer.
- The double-layer porous asphalt mix showed noise absorption results better than all the newly developed mixes included in this study (about 0.22 sound absorption coefficient), and second highest of all the mixes included in the study. It was also the most permeable of all the mixes included in the study and showed good resistance to premature failure.
- The Georgia 12.5-mm OGFC mix in this study had significantly higher sound absorption than the Arizona mix, and the SMA mixes showed better durability than the Arizona mix. However, it had relatively high macrotexture, which may indicate a propensity for low frequency noise.

The following conclusions were obtained regarding performance evaluation and test procedures:

- For open-graded mixes with large aggregate sizes (i.e., 19-mm NMAS), permeability should be not evaluated on 100-mm or 150-mm diameter cores using the laboratory flexible wall permeameter because the results are not similar to the tests performed on slabs, which are a more realistic simulation of field permeability.
- The acoustic absorption coefficient as measured by the impedance tube test can clearly distinguish mixes with different air-void structures (e.g., DGAC, SMA, and OGFC). For large aggregate OGFC mixes (i.e., 19-mm NMAS), a 100-mm diameter specimen is too small for the impedance tube test to correctly characterize the mix sound absorption. Use of the acoustic absorption coefficient to predict the tire/pavement noise in the field is still under research, although a correlation, but not a causal relationship, has been identified with high frequency tire/pavement noise.

- The current indirect tensile strength ratio (TSR) test recommended in the ASTM D7064 may not be appropriate for evaluating the moisture sensitivity of OGFC mixes. The 24-hour conditioning at 60°C is not suitable because OGFC mixes, without appropriate constraint, tend to creep significantly under this condition. At the least, an appropriate constraining procedure should be specified clearly in the test specification.
- Most open-graded mixes failed quickly in the standard RSST-CH test using 150-mm diameter, 50-mm thick cylindrical specimens. A possible reason is that specimens with these standard dimensions may not produce results representative of the same mixes in the field. Further research is needed to identify appropriate sizes for open-graded mix specimens for the simple shear test.
- Friction measurements of OGFC mix specimens taken with the British Pendulum Tester (BPT) are sensitive to operators and test locations, and often show poor repeatability. The British Pendulum Number (BPN) values generally do not distinguish various mixes. The DFT better distinguishes various mixes in terms of friction.

7 RECOMMENDATIONS

Based on this study's findings and conclusions, two series of recommendations are given below, one regarding asphalt surface mix design and another for further evaluating mixes in field or HVS test sections.

7.1 Recommended Specifications for Asphalt Surface Mix Design

In "Section 39 Hot Mix Asphalt" of the current Caltrans Standard Specifications there are special provisions specifying open-graded friction course (OGFC), which includes hot-mix asphalt (open graded), rubberized hot-mix asphalt (open-graded) (RHMA-O), and rubberized hot-mix asphalt (open-graded high binder) (RHMA-O-HB). Three aggregate gradation types for OGFC are specified: 1-in. (25-mm), 1/2-in. (12.5-mm), and 3/8-in. (9.5-mm), identified by nominal maximum aggregate size. The optimum asphalt binder content is determined following California Test 368, which is solely based on drainage of binder. Compaction of OGFC is achieved with two coverages of steel-tired, two-axle tandem rollers in vibrator-off mode. Selection of asphalt binder type for OGFC is specified in *Caltrans Design Information Bulletin Number 86,* as shown in the table below *(29):*

Table 7.1: Selection of Asphalt Binder Grade in California *(29)*

Binder / Climatic Region	Conventional Hot Mixed Asphalt				Rubberized Asphalt
	Dense Graded HMA		Open Graded		Base Stock for Gap and Open Graded
	Typical	Special[1]	Placement Temperature >70°F	Placement Temperature <70°F	
South Coast Central Coast Inland Valleys	PG 64-10	PG 70-10 PG 64-28 PM	PG 64-10	PG 58-34 PM	PG 64-16
North Coast	PG 64-16	PG 64-28 PM	PG 64-16	PG 58-34 PM	PG 64-16
Low Mountain South Mountain	PG 64-16	PG 64-28 PM	PG 64-16	PG 58-34 PM	PG 64-16
High Mountain High Desert	PG 64-28	PG 58-34 PM[2]	PG 64-28	PG 58-34 PM	PG 58-22
Desert	PG 70-10	PG 64-28 PM	PG 70-10	PG 58-34 PM or PG 64-28PM[3]	PG 64-16

Notes:
1. PG 76-22PM may be specified for conventional dense graded hot mixed asphalt for special conditions in all climatic region when specifically requested by the District Materials Engineer.
2. PG 64-28 may be specified when specifically requested by the District Materials Engineer.
3. Consult the District Materials Engineer for which binder grade to use.

The current Caltrans specifications for OGFC were mainly developed for improving pavement surface friction and permeability, and did not take tire/pavement noise into consideration. Although the current standard test CT 368 is based on the strategy of providing an OGFC mix with sufficient asphalt film thickness to provide good durability and avoid excessive asphalt drainage, it does not include any procedures to explicitly evaluate mix performance in the laboratory. Following a recent National Center for Asphalt Technology (NCAT) effort that had proposed a more comprehensive design approach for OGFC mixes, Caltrans recently developed a work plan *(35)* to make major revisions to the current CT 368 by including the principles described in the NCAT approach and incorporating findings from the multilab test study.

The objectives of the study presented in this report did not include development of a comprehensive design specification for asphalt surface mixes that have not only good friction and permeability performance, but also good noise reduction capability. This work will need more time and resources than those available to this study. The work in this study, however, was based on current specifications and knowledge of OGFC, including CT 368, Caltrans OGFC specifications, the NCAT comprehensive design approach for OGFC, and noise-related tests. Findings from this study, therefore, can shed light on how to improve current Caltrans OGFC design for a more durable and quieter asphalt surface mix.

Based on test results from this study and findings from the three-year field performance survey of asphalt surface mixes in California, the following recommendations are provided for design of quieter and more durable asphalt surfaces:

- Large aggregate size should not be used in the mix due to higher raveling potential in the field within two to five years after construction. To ensure low tire vibration–generated noise and air-pumping noise, a durable smooth surface is needed, which can be better achieved by use of small-size aggregates in the mix. The Caltrans ½ inch (12.5-mm) open-graded aggregate gradation should be avoided in areas where traffic noise is a concern (the current specification requires use of the 3/8 inch [9.5 mm] gradation unless justification is provided for using the larger NMAS).
- Hydrated lime does not show much benefit in OGFC mixes in terms of improvement of durability (moisture resistance and rutting resistance), so it is not recommended to add hydrated lime in OGFC mixes if further field evaluation reveals similar conclusions.
- Polymer-modified or asphalt rubber (wet process) binders are preferred rather than unmodified binders. Unmodified binders should not be used in 9.5-mm OGFC due to high potential for raveling.
- The draindown test specified in CT 368 seems appropriate for limiting the amount of drainage during mix production and construction, not only for 9.5-mm and 12.5-mm OGFC, but also for 4.75-mm OGFC. This test can be used to determine a preliminary optimum binder content for evaluation in other tests.

- Mixes with the preliminary optimum binder content determined in CT 368 should be evaluated for other properties. The final optimum binder content should be determined based on test results for permeability, acoustic absorption (where it is an issue), raveling, moisture damage/premature failure (optional), friction, and resistance to reflective cracking (where it is an issue).
- Two types of specimens are needed for evaluation of other properties: cylindrical specimens and slab specimens. Cylindrical specimens compacted by Marshall or Superpave gyratory compactor are recommended for use in permeability, acoustic absorption, and raveling (Cantabro) tests, while slab specimens are recommended for use in HWTD (moisture damage/premature failure), friction, and resistance to reflective cracking tests. Hveem kneading compaction is not recommended for preparing OGFC specimens.
- For open-graded mixes with NMAS of 12.5 mm or less, permeability can be evaluated on 100-mm or 150-mm diameter cores using a laboratory flexible wall permeameter following ASTM PS129. However, slab permeability as measured by NCAT field permeameter is preferred.
- The acoustic absorption coefficient can be measured by the impedance tube test. For large aggregate OGFC mixes (i.e., 19-mm NMAS), larger size specimens (diameter greater than 100 mm) are needed. A procedure for evaluating the noise potential of open-graded asphalt mixes in the laboratory is being investigated as a master's degree project at the University of California Pavement Research Center, based on macrotexture measurements to assess low frequency noise and air permeability tests to assess high frequency noise.
- The current indirect tensile strength ratio (TSR) test specified in ASTM D7064 is not recommended for evaluating moisture sensitivity of OGFC mixes. Instead, the HWTD test should be used to evaluate the premature failure/moisture damage/rutting potential.
- Friction should be measured with a Dynamic Friction Tester (DFT) instead of the British Pendulum Tester (BPT). This means slab specimens should be prepared in the laboratory for use with the DFT.

7.2 Recommendations for Field and HVS Test Sections

The following recommendations are provided for further mix evaluation in the field or on HVS test sections:

- Three rubberized or polymer-modified 4.75-mm NMAS mixes (AR475, AR475P, and P475) and one Georgia OGFC mix (G125) are recommended for long-term performance evaluation in field test sections. These mixes should be compared with current Caltrans mixes produced using the same aggregates in the test sections. It is recommended that additional evaluation of the double-layer porous asphalt be postponed in California for several years until more performance information is available from Europe.
- Mixes with small aggregate sizes and asphalt rubber or polymer-modified binder (e.g., AR475, AR475P, and P475) are recommended for resistance-to-rutting and moisture damage evaluation in HVS test sections.

REFERENCES

1. Ongel, J. Harvey, E. Kohler, Q. Lu, and B. Steven. 2008. *Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphaltic Pavement Surface Types: First- and Second-Year Results.* Report prepared by University of California Pavement Research Center for the Caltrans Department of Research and Innovation. UCPRC-RR-2007-03.
2. Q. Lu, E. Kohler, J. Harvey, A. Ongel. 2009. *Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Three-Year Results*. Report prepared by University of California Pavement Research Center for the Caltrans Department of Research and Innovation. UCPRC-RR-2009-01.
3. Ongel, A., J. Harvey, and E. Kohler. *State of the Practice in 2006 for Open-graded Asphalt Mix Design.* December 2007. Technical memorandum prepared by UCPRC for the Caltrans Department of Research and Innovation. UCPRC-TM-2008-07.
4. Hanson, D.I., James, R.S., and NeSmith, C. 2004a. *Tire/Pavement Noise Study*. National Center for Asphalt Technology, Report No. 04-02.
5. Hanson, D.I., and James, R.S. 2004b. *Colorado DOT Tire/Pavement Noise Study*. The Colorado Department of Transportation, Report No. CDOT-DTD-R-2004-5.
6. Hanson, D.I., and Waller, B. 2006. 2005 *Colorado DOT Tire/Pavement Noise Study*. The Colorado Department of Transportation, Report No. CDOT-2006-18.
7. Hanson, D.I., and James, R.S. 2004. *Nevada DOT Tire/Pavement Noise Study*. National Center for Asphalt Technology.
8. Anderson, K.W., Pierce, L.M., Uhlmeyer, J.S., and Weston, J. 2008. *Evaluation of Long-Term Pavement Performance and Noise Characteristics of Open-Graded Friction Courses.* The Washington State Department of Transportation, Report No. WA-RD 683.1.
9. Illingworth & Rodkin, Inc. 2005. *7th Year Summary Report: I-80 Davis OGAC Pavement Noise Study–Traffic Noise Levels Associated with Aging Open Grade Asphalt Concrete Overlay.* A report prepared by the Illingworth & Rodkin, Inc., for the California Department of Transportation, Division of Environmental Analysis.
10. McDaniel, R.S., Thornton, W.D., and Dominguez, J.G. 2004. *Field Evaluation of Porous Asphalt Pavement.* The Institute for Safe, Quiet and Durable Highways, Report No. SQDH 2004-3.
11. Chiba, M., Maruyama, K., and Tako, J. 2008. "Sustainability of Noise Reduction and Winder Skid Resistance on Porous Asphalt Pavements." *Proceedings of the International ISAP Symposium on Asphalt Pavements and Environment,* August 2008, Zurich, Switzerland.
12. Santagata, F., Canestrari, F., Pasquini, E., Ayr, U., and Pisciotta, M. 2008. *Acoustic Characterization of Different Road Materials.* Proceedings of the International ISAP Symposium on Asphalt Pavements and Environment, August 2008, Zurich, Switzerland.

13. Huddleston, U.J., Zhou, H., and Hicks, R.G. 1991. "Performance Evaluation of Open-Graded Asphalt Concrete Mixtures Used in Oregon.*" Journal of AAPT,* Vol. 60, pp 19–43.
14. Martinez, F.C., and Poecker, R.A. 2006. *Evaluation of Deicer Applications on Open Graded Pavement.* A report prepared for the Oregon Department of Transportation and FHWA, Report No. FHWA-OR-RD-06-12.
15. Birgisson, B., Roque, R., Varadhan, A., Thai, T., and Jaiswal, L. 2006. *Evaluation of Thick Open Graded and Bonded Friction Courses for Florida.* University of Florida, Department of Civil and Coastal Engineering, Report No. 4504968-12 (00026875).
16. Chiba, M., Maruyama, K., and Tako, J. 2008. Sustainability of Noise Reduction and Winder Skid Resistance on Porous Asphalt Pavements. Proceedings of the International ISAP Symposium on Asphalt Pavements and Environment, August 2008, Zurich, Switzerland.
17. Gibbs, D., Iwasaki, R., Bernhard, R., Bledsoe, J., Carlson, D., Corbisier, C., Fults, K., Hearne, T., McMullen, J.K., Newcomb, D., Roberts, J., Rochat, J., Scofield, L., and Swanlund, M. 2005. *Quiet pavement systems in Europe.* Office of International Programs, Office of Policy, Federal Highway Administration, U.S. Department of Transportation, American Association of State Highway and Transportation Officials, Federal Highway Administration, Report No. FHWA-PL-05-011, HPIP/05-05(3M)EW, 50p.
18. Newcomb, D., and L. Scofield. 2004. *Quiet Pavements Raise the Roof in Europe.* Scanning Tour Reveals European Practice for Noise Mitigation. Hot Mix Asphalt Technology Magazine, National Asphalt Pavement Association, Lanham, Maryland, September/October 2004. pp 22-28.
19. Huurman, R., Molenaar, A., van Reisen, F., Hofman, R., Schreyer, J., Steinhauer, B., and van Bochove, G. 2008. *Accelerated Testing of Double Layer Porous Asphalt Wearing Courses.* Proceedings, Third International Conference on Accelerated Pavement Testing, Madrid, Spain.
20. Molenaar, A., A. Meerkerk, M. Miradi, and T. van der Steen. 2006. *Performance of Porous Asphalt Concrete.* Journal of the Association of Asphalt Paving Technologists. Volume: 75, pp 1,053–1,094.
21. Ongel, A. and E. Kohler. *Acoustical Absorption of Open-Graded, Gap-Graded, and Dense-Graded Asphalt Pavements.* 2007. Report prepared by UCPRC for the Caltrans Department of Research and Innovation. UCPRC-TM-2007-13.
22. Ongel, A., J.T. Harvey, E. Kohler, Q. Lu, B.D. Steven, and C.L. Monismith. 2008. *Summary Report: Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphalt Pavement Surface Types: First- and Second-Year Results.* Report prepared by University of California Pavement Research Center for the Caltrans Department of Research and Innovation. UCPRC-SR-2008-01.

23. D. Watson, A. Johnson, and D. Jared. 1998. “Georgia Department of Transportation’s Progress in Open-Graded Friction Course Development.” *Transportation Research Record 1616*. Transportation Research Board: Washington, D.C.
24. Fitts, G. (2002). “The New and Improved Open Graded Friction Course Mixes.” *Asphalt*, pp.17–18.
25. Morris, G.R., and D.D. Carlson. 2002. *The Arizona Asphalt-Rubber Project Review. Part 1, Evaluation of A-R Pavements Constructed Before 1992.* Arizona Department of Transportation and the Rubber Pavements Association. *www.asphaltrubber.org/ari/Performance/The_Arizona_10_Year_A-R_Project_Review.pdf,* accessed on March 20th, 2009.
26. Hamzah, M.O., and Hardiman. 2005. “Characterization of the Clogging Behavior of Double Layer Porous Asphalt.” *Journal of the Eastern Asia Society for Transportation Studies*, Vol. 6, pp. 968–980.
27. J. Raaberg, E. Nielsen, and H. Bendtsen. 2006. *Noise reducing SMA pavements: Mix design for Silence - F2*. VI Technical Note 39. Road Directorate/Danish Road Institute Hedehusene, Denmark.
28. Bendtsen, H. 2009. *European Experiment: Thin Quieter Pavements on Low Volume Roads*. (CD-ROM). Transportation Research Board of the National Academies, Washington, D.C.
29. Leja, M. 2006. *Selecting Asphalt Binder Type. Design Information Bulletin Number 86.* California Department of Transportation, Pavement Standards Team & Division of Design, Office of Pavement Design, Sacramento, California.
30. Al-Rousan, T., E. Masad, L. Myers, and C. Speigelman. 2005. “New Methodology for Shape Classification of Aggregates.” *Transportation Research Record*: Journal of the Transportation Research Record, No. 1913. Transportation Research Board of the National Academies, Washington, D.C., pp. 11–23.
31. Nodes, J. 2009. Asphalt Rubber Mixture Design. *www.asphaltrubber.org/ari,* accessed July 1st, 2009.
32. Alvarez, A.E., A. Epps Martin, C. K. Estakhri, J.W. Button, C.J. Glover, and S.H. Jung. 2006. *Synthesis of Current Practice on the Design, Construction, and Maintenance of Porous Friction Courses*. Technical Report. 0-5262-1. Texas Transportation Institute, Texas A&M University, College Station, TX.
33. Kandhal, P. S., and R. B. Mallick. 1999. *Design of New-Generation Open-Graded Friction Course*. NCAT Report 99-03. National Center for Asphalt Technology, Auburn University, Alabama.
34. Biligiri, K. P. 2008. Asphalt mixtures' properties indicative of tire/pavement noise. Doctoral thesis, Arizona State University.
35. California Department of Transportation (Caltrans). 2009. “Work Plan for the Development of a Test Method for Open-Graded Friction Course Used in California.” Office of Flexible Pavement Materials, Materials Engineering and Testing Services-MS #5, Division of Engineering Services, Sacramento, California.

APPENDICES

APPENDIX A: MIXES INCLUDED IN THE STUDY

Table A.1: Aggregate Gradations of Mixes Included in the Study

Mix ID	Description	Percent Passing (mm)										NMAS*
		19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	(mm)
RW19	¾ in. (19 mm) open-graded mix with conventional binder	95	54	36	20	15	10	7	5	4	2	19
RW125	Caltrans ½ in. (12.5 mm) open-graded mix with conventional binder	100	97.5	83.5	32.5	12.5	5	5	4	3	1.5	12.5
RW95	Caltrans 3/8 in. (9.5 mm) open-graded mix with conventional binder	100	100	95	32.5	12.5	5	5	4	3	1.5	9.5
RW475	No. 4 (4.75 mm) open-graded mix with conventional binder	100	100	100	91	14	12	10	8	7	6	4.75
AZ95	No. 4 (4.75 mm) open-graded mix with rubberized binder	100	100	100	40	9	5	4	3	2	2	9.5
E8	No. 4 (4.75 mm) open-graded mix with modified (polymers and rubber) binder	100	100	100	29	9	8	8	8	8	8	8
E16	No. 4 (4.75 mm) open-graded mix with polymer-modified binder, lime treatment and fibers	100	62	28	8	7	6	5	5	5	5	16
SMA6P	No. 4 (4.75 mm) open-graded mix with polymer-modified binder	100	100	100	76	33	14	12	10	9	8.5	6+
G125	Same as AR475, except Teichert aggregate source[3]	100	92.5	65	20	7.5	5	5	4	3	3	12.5
SMA4P	Same as RW475 except Graniterock aggregate source[3]	100	100	100	84	41	18	15	12	10	8	4+
D125	Same as RW95 except Graniterock aggregate source[3]	100	97.5	87.5	62.5	46	35	22.5	16	9	5	12.5
AR475, AR475D	Same as RW95 except Teichert aggregate source[3]	100	100	100	91	14	12	10	8	7	6	4.75
TR475	Same as RW475 except lime treated	100	100	100	91	14	12	10	8	7	6	4.75
P58LF	3/8 inch (9.5 mm) open-graded mix with rubberized binder	100	100	100	91	14	12	10	8	7	6	4.75
P475	Same as AR95 except gradation changed (P) and more compaction (PD)	100	100	100	91	14	12	10	8	7	6	4.75
AR475T	Arizona high-binder content open-graded rubberized mix	100	100	100	91	14	12	10	8	7	6	4.75
PG475W	European 8 mm open-graded mix, top layer of double layer porous asphalt	100	100	100	91	14	12	10	8	7	6	4.75
AR95W	European 16 mm open-graded mix, bottom layer of double layer porous asphalt	100	100	95	32.5	12.5	5	5	4	3	1.5	9.5
PG95T	Stone mastic asphalt 6 mm maximum aggregate size and polymer-modified binder	100	100	95	32.5	12.5	5	5	4	3	1.5	9.5
P475LM	Georgia DOT ½ in. (12.5 mm) open-graded mix with polymer-modified binder, lime treatment, and fibers	100	100	100	91	14	12	10	8	7	6	4.75
AR95	Stone mastic asphalt 4 mm maximum aggregate size and polymer-modified binder	100	100	95	32.5	12.5	5	5	4	3	1.5	9.5
AR475P, AR475PD	Caltrans ½ in. (12.5 mm) dense-graded hot-mix asphalt with conventional binder	100	100	100	65	14	12	10	7	6	5	4.75+

*NMAS: Nominal maximum aggregate size

Table A.2: Characteristics of Mixes Included in the Study

Mix ID*	Binder Content (%)	Binder Type	Fiber**	Hydrated Lime	Mixing Temperature (ºC)	Compaction Temperature (ºC)	Fineness Modulus	Cc**	Cu**
RW19	5.0	PG 64-16	None	0	135	125	6.08	0.70	2.14
RW125	5.9	PG 64-16	None	0	135	125	5.55	1.38	3.72
RW95	5.9	PG 64-16	None	0	135	125	5.43	1.47	3.48
RW475	7.9	PG 64-16	None	0	135	125	4.58	0.91	1.60
AZ95	9.2	Asphalt rubber	None	1.0%	163	149	5.37	1.03	2.60
E8	6.4	PG 64-16	0.25% CF	1.5%	135	125	5.30	1.37	2.75
E16	4.6	PG 64-16	0.25% CF	1.5%	135	125	6.36	1.45	2.36
SMA6P	6.5	PG 58-34PM	0.25% CF	0	155	138	4.46	0.61	1.93
G125	6.3	PG 76-22PM	0.4% MF	1.4%	165	160	5.91	1.32	3.16
SMA4P	6.7	PG 58-34PM	0.25% CF	0	155	138	4.20	0.80	2.89
D125	6.0	PG 64-16	None	0	144	125	4.22	1.19	25.60
AR475, AR475D	9.5	Asphalt rubber	None	0	163	149	4.58	0.91	1.60
TR475	9.5	PG 76-22TR	None	0	163	149	4.58	0.91	1.60
P58LF	7.9	PG 58-34PM	0.3% CF	1.5%	155	138	4.58	0.91	1.60
P475	7.9	PG 76-22PM	None	0	163	149	4.58	0.91	1.60
AR475T	9.5	Asphalt rubber	None	0	163	149	4.58	0.91	1.60
PG475W	7.9	PG 64-16	None	0	135	125	4.58	0.91	1.60
AR95W	7.1	Asphalt rubber	None	0	163	149	5.43	1.47	3.48
PG95T	5.9	PG 64-16	None	0	135	125	5.43	1.47	3.48
P475LM	7.9	PG 64-16	None	1.5%	135	125	4.58	0.91	1.60
AR95	7.1	Asphalt rubber	None	0	163	149	5.43	1.47	3.48
AR475P, AR475PD	8.4	Asphalt rubber	None	0	163	149	4.86	0.91	1.91

* See Table A.1 for mix descriptions.
** CF: Cellulose Fiber; MF: Mineral Fiber; C_c: coefficient of curvature; C_u: coefficient of uniformity

APPENDIX B: TEST RESULTS FOR OBC FOLLOWING CTM 368

Table B.1: Test Results for OBC Following CTM 368

Mix Type	Aggregate Mass (g)	Binder Content (%)	Binder Used (g)	Thimble Mass (g)	Mass of Thimble with Residual Asphalt (g)	Asphalt Drainage (g)
RW475	1468.4	6.13	90.0	2046.8	2047.6	0.8
	1467.2	6.07	89.0	2046.8	2048.1	1.3
	1466.6	6.87	100.7	2046.9	2048.7	1.8
	1465.6	6.77	99.2	2046.7	2049.0	2.3
	1472.5	7.46	109.9	2046.8	2049.2	2.4
	1469.9	7.47	109.8	2047.0	2049.9	2.9
	1470.7	7.47	109.9	2046.5	2049.6	3.1
	1471.0	8.17	120.2	2046.8	2050.6	3.8
	1472.8	8.17	120.3	2046.4	2050.5	4.1
	1465.6	8.24	120.7	2046.9	2051.9	5.0
	1465.1	8.87	130.0	2046.3	2052.8	6.5
	1470.0	8.82	129.7	2046.9	2054.5	7.6
	1471.6	8.87	130.5	2046.9	2054.9	8.0
RW95	1476.4	5.40	79.7	2046.6	2049.1	2.5
	1475.5	5.39	79.5	2047.0	2049.8	2.8
	1480.1	6.07	89.8	2046.5	2050.2	3.7
	1478.6	6.21	91.8	2046.4	2050.6	4.2
	1475.8	5.52	81.4	2046.5	2050.7	4.2
	1482.0	6.07	90.0	2046.3	2051.0	4.7
	1476.4	6.91	102.0	2046.9	2051.7	4.8
	1477.9	6.83	101.0	2046.5	2052.0	5.5
	1476.4	6.94	102.5	2046.7	2053.2	6.5
RW125	1475.3	5.50	81.1	2054.3	2056.4	2.1
	1478.9	4.69	69.3	2054.2	2056.4	2.2
	1474.4	5.39	79.5	2046.3	2048.9	2.6
	1475.5	5.37	79.2	2046.0	2049.4	3.4
	1471.8	6.07	89.3	2046.2	2049.8	3.6
	1473.6	4.63	68.3	2054.3	2058.0	3.7
	1474.7	6.10	89.9	2046.4	2051.0	4.6
	1479.8	6.07	89.8	2046.2	2051.2	5.0
	1476.6	6.77	100.0	2046.0	2053.2	7.2
	1472.3	6.77	99.7	2046.3	2054.5	8.2
	1472.0	7.15	105.3	2046.2	2055.6	9.4
RW19	1476.4	4.67	68.9	2046.9	2048.6	1.7
	1473.4	4.67	68.8	2046.9	2049.3	2.4
	1463.0	4.78	69.9	2046.8	2050.4	3.6
	1474.1	5.38	79.3	2046.9	2052.2	5.3
	1478.0	5.37	79.3	2046.9	2052.7	5.8
	1480.2	5.84	86.4	2046.7	2055.4	8.7
	1472.3	6.07	89.3	2046.8	2056.0	9.2
	1474.9	6.07	89.5	2046.8	2057.4	10.6

Mix Type	Aggregate Mass (g)	Binder Content (%)	Binder Used (g)	Thimble Mass (g)	Mass of Thimble with Residual Asphalt (g)	Asphalt Drainage (g)
	1472.2	6.07	89.3	2046.7	2059.3	12.6
AR475P	1474.3	6.00	88.4	2047.6	2048.8	1.2
	1472.1	6.70	98.7	2047.6	2049.8	2.2
	1472.3	7.38	108.7	2047.5	2052.8	5.3
	1474.7	8.10	119.4	2047.6	2056.3	8.7
	1473.6	6.01	88.6	2047.6	2049.5	1.9
	1472.3	6.70	98.6	2047.6	2051.8	4.2
	1474.5	7.39	109.0	2048.2	2052.5	4.3
	1475.1	8.09	119.4	2047.7	2057.1	9.4
	1471.5	6.01	88.4	2048.2	2049.8	1.6
	1474.8	6.71	99.0	2048.3	2050.4	2.1
	1474.6	7.38	108.8	2048.4	2050.9	2.5
	1471.9	8.28	121.8	2048.5	2054.3	5.8

APPENDIX C: SELECTION OF COMPACTION METHODS FOR SPECIMEN FABRICATION

This section investigates the impact of compaction methods on the performance of quiet (porous) asphalt mixes to provide information necessary for determining the compaction methods appropriate for fabricating open-graded asphalt specimens in the laboratory.

Experimental Design

In this study of compaction methods, the four mix designs included in the first experiment of the main study were selected for comparison. Four compaction methods were selected and compared: Hveem kneading compaction, Superpave gyratory compaction, Marshall impact compaction, and rolling wheel compaction. In this study, the mix properties that are critical to pavement surface performance were evaluated, including permeability, acoustic absorption, moisture sensitivity, and resistance to raveling.

For each of the four mixtures, cylindrical specimens were fabricated with each of the four compaction methods, which led to a total of 16 different types of specimens. The cylinders from the rolling wheel compaction were cored from larger compacted slab specimens, while the Superpave Gyratory, Hveem, and Marshall specimens were tested with their as-compacted shapes. Air-void content, permeability, acoustical absorption, moisture sensitivity, and resistance to raveling (Cantabro loss) were measured on each type of specimens, using the test methods described in Section 4.4. Three replicates were used in each test, and the same specimens tested for permeability were used later in the impedance tube test for sound absorption. A total of 240 specimens were fabricated and tested.

Results and Discussion

<u>Air-Void Content</u>

The nominal air-void content of all specimens was selected at 20 percent. Based on this value and the nominal specimen sizes (100 mm diameter and 63.5 mm thickness), the amount of loose mix was weighed and compacted by different methods. In the Hveem kneading and the rolling wheel compactions, specimens were compacted to a predefined volume, so the obtained air-void contents should be near 20 percent. In the Marshall and Superpave gyratory compactions, however, only the number of blows or gyrations was specified. The obtained air-void content, therefore, may vary from 20 percent significantly, depending on the structure of aggregates in a mixture and the amount of compaction energy provided by the specific compaction procedure.

The average thickness of each type of specimen is shown in Figure C.1. As expected, specimens compacted by the Hveem kneading and rolling wheel methods had an average thickness close to 63.5 mm (in the range of 62 mm to 64 mm). The Marshall-compacted specimens also had an average thickness close to the nominal value (63.5 mm). On the other hand, the Superpave gyratory–compacted specimens are generally thicker than 63.5 mm. This indicates that the 50 blows (on each side) Marshall compaction provided densification under compaction action similar to the rolling wheel and Hveem kneading compactions, while the 50 gyrations gyratory compaction was less efficient than the other three compaction methods, particularly for the 9.5-mm and 12.5-mm mixes.

Figure C.2 shows the average air-void content of the 16 types of specimens. Specimens with a NMAS of 19 mm generally had smaller measured air-void contents than specimens with a NMAS of 4.75 mm, 9.5 mm, or 12.5 mm. This is due to the very rough surface of the 19-mm mixture, which is comparable to the specimen sizes. The large surface voids were mostly not included in the measured air-void contents in the CoreLok method due to the penetration of the bag film into the voids under vacuum. Excluding the 19-mm specimens, it can be seen that the Hveem kneading compacted specimens had an average air-void content close to 20 percent, which is expected. For the Marshall-compacted specimens, the air-void contents were close to 20 percent, except for the 4.75-mm specimens, which were slightly lower. For the gyratory-compacted specimens, the air-void contents were close to 20 percent for the 4.75-mm mixture, but higher than 20 percent for the 9.5-mm and 12.5-mm mixtures. For the rolling wheel–compacted specimens, the air-void contents were slightly less than 20 percent for the 9.5-mm and 12.5-mm mixtures and about 2.5 percent less for the 4.75-mm mixture. This was likely due to slight overcompaction in the center of the slab, from which the cylindrical specimens were cored, when 30 wheel passes were applied.

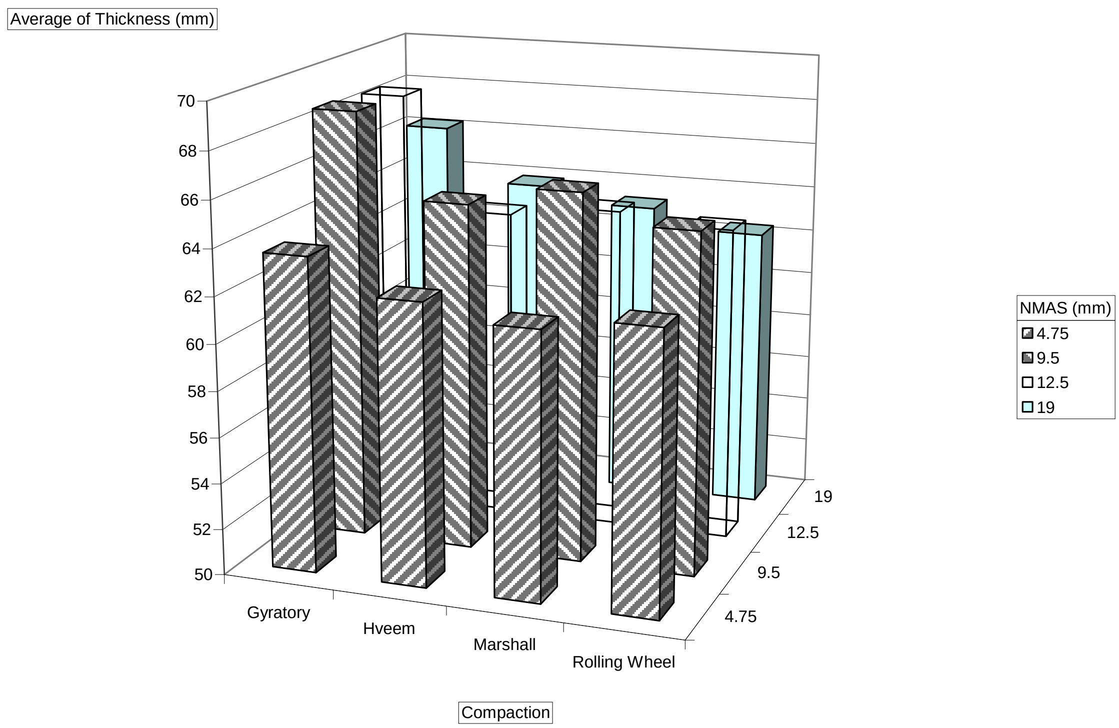


Figure C.1: Average thicknesses of specimens versus NMAS and compaction methods.

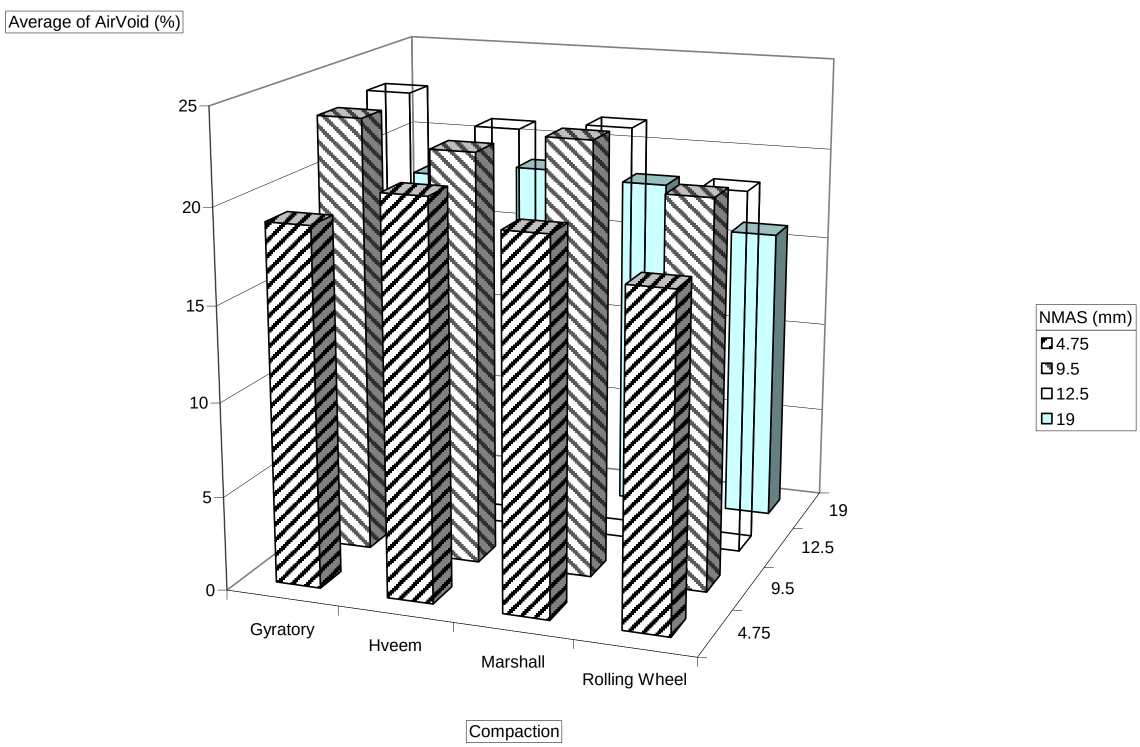


Figure C.2: Average air-void contents of specimens versus NMAS and compaction methods.

Permeability

Specimens of similar air-void contents were selected for the permeability test. The measured permeability was corrected to a value corresponding to a standard water temperature 20°C, using the correction factors specified in ASTM PS129.

The average permeability for each type of compaction on 100-mm diameter specimens is shown in Figure C.3. The figure shows that the permeability measured from the 19-mm NMAS specimens was smaller than the values measured from the 9.5-mm and 12.5-mm NMAS specimens. Generally a mixture with coarser gradation should have more connected voids, and therefore have higher permeability. The permeability measured on the slab specimens before coring using a Gilson AP-1B permeameter (an on-site falling head permeameter used in the field) did show greater permeability for the 19-mm NMAS material, as shown in Figure C.4. The low values measured from the 19-mm NMAS 100-mm diameter specimens were likely due to the relatively small sizes of the specimen compared to the maximum aggregate size, which made the side effect (e.g., penetration of confining membrane into voids) important.

It can be seen that there was no significant difference of permeability among specimens compacted by the four compaction methods for the 9.5-mm and 12.5-mm NMAS mixtures. For the 4.75-mm NMAS mixture, the cores from the rolling wheel compaction produced less permeable specimens than the other three compaction methods. Because specimens of similar air-void contents were used in the permeability test, this difference indicates that rolling wheel compaction creates fewer interconnected voids in the 4.75-mm NMAS mix than the other three compaction methods. The rolling wheel likely produces greater aggregate orientation for the open-graded mixes in the large slab mold, while the mold walls constrain aggregate orientation in the 100-mm molds.

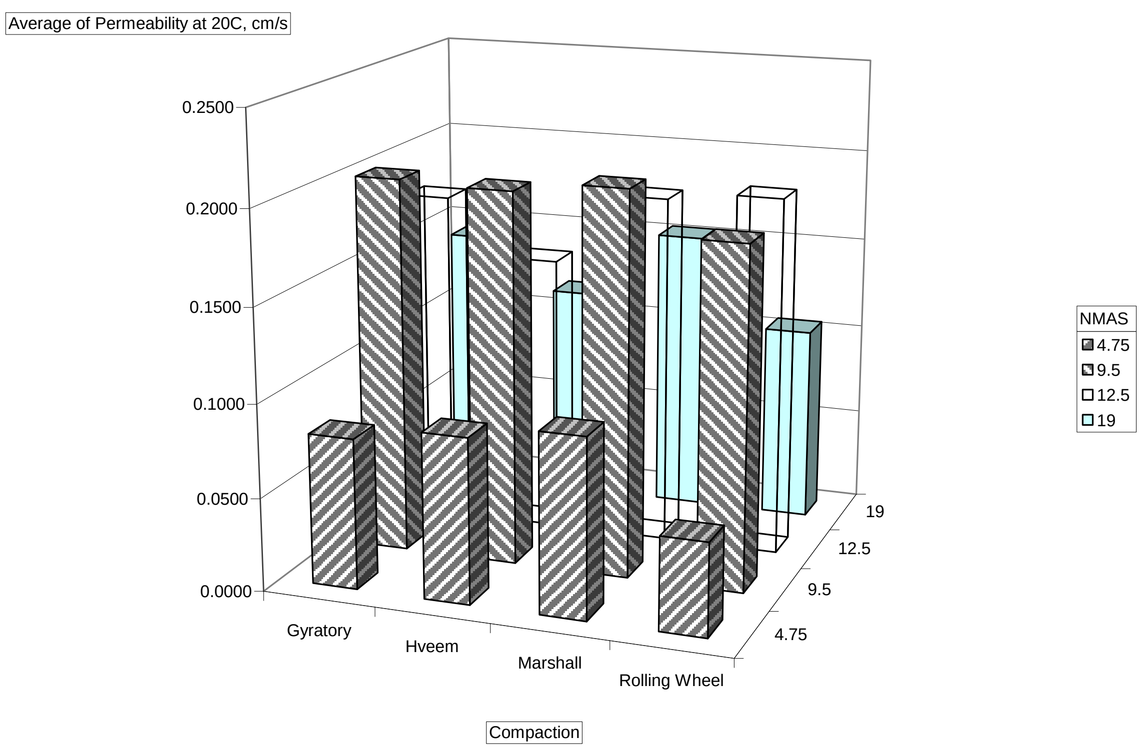


Figure C.3: Average permeability versus NMAS and compaction methods.

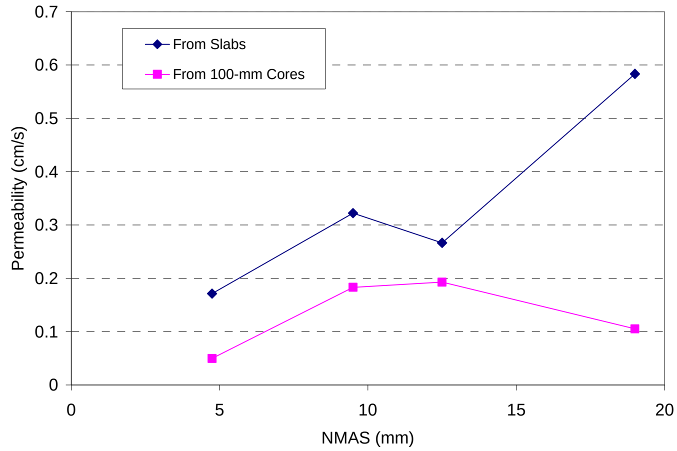


Figure C.4: Permeability measured from rolling wheel–compacted slabs and cores taken from those slabs.

Acoustic Absorption

The result of a sound absorption test is a vector containing the absorption coefficient in the one-third octave frequency bands from 100 to 2,000 Hz. Each absorption coefficient value ranges from 0 to 1 depending on the fraction of the sound energy that at any given frequency is reflected back ($\alpha = 0$) or absorbed ($\alpha = 1$). The frequency at which the maximum absorption occurs is known as the resonant frequency. In this study, there are generally two peaks in every absorption curve measured from every mixture, as shown in Figure C.5.

Figure C.5 presents the average absorption curve in the one-third octave frequency bands for each of the 16 different types of specimens. As can be seen, the resonant frequencies are generally similar for specimens of the same NMAS even with compaction by different methods, except that the Marshall-compacted specimens showed slightly higher resonant frequencies than the specimens compacted by the other three methods for the 4.75-mm and 12.5-mm NMAS mixtures, and that the rolling wheel–compacted specimens showed slightly higher resonant frequencies than the specimens compacted by the other three methods for the 9.5-mm and 19-mm NMAS mixtures. The maximum absorption coefficients were similar among the four compaction methods for the 9.5-mm and 12.5-mm NMAS mixtures, but those for the 4.75-mm and 19-mm NMAS, specimens compacted by the rolling wheel compactor are significantly lower than specimens compacted by the other three compaction methods.

In summary, from the acoustic absorption consideration, specimens compacted by the gyratory, Marshall, and kneading methods were similar to the rolling wheel–compacted specimens for mixtures with NMAS no larger than 12.5 mm, except that for small aggregate size (4.75-mm NMAS) mixtures, the Marshall compaction might lead to higher absorption than the rolling wheel compaction. For the mixture with large size aggregates (19-mm NMAS), the rolling wheel–compacted specimens had significantly different acoustic absorption characteristics than specimens compacted by the other three methods.

To compare the sound absorption of mixtures with different NMAS, the measured absorption coefficients between 200 and 1,700 Hz were averaged to cover the absorption effects at all available frequencies. Absorption at frequencies below 200 Hz and above 1,700 Hz were not included because leakage through the annulus around the specimen, or blow-by, may have affected some of the test results at low frequencies, while the absorption above 1,700 Hz might not be accurate either due to the geometry of the impedance tube used.

Figure C.6 shows the averaged average absorption of each type of specimen. Generally there was no significant difference between gyratory, Marshall, and kneading compaction methods for mixtures with NMAS no larger than 12.5 mm, except that Marshall compaction led to higher absorption for the 4.75-mm NMAS mixture. For the four mixtures, the 9.5-mm and 12.5-mm NMAS specimens showed higher absorption than the 4.75-mm and 19-mm NMAS specimens. This ranking is similar to the ranking based on permeability (Figure C.3), which indicates the existence of correlation between sound absorption and permeability.

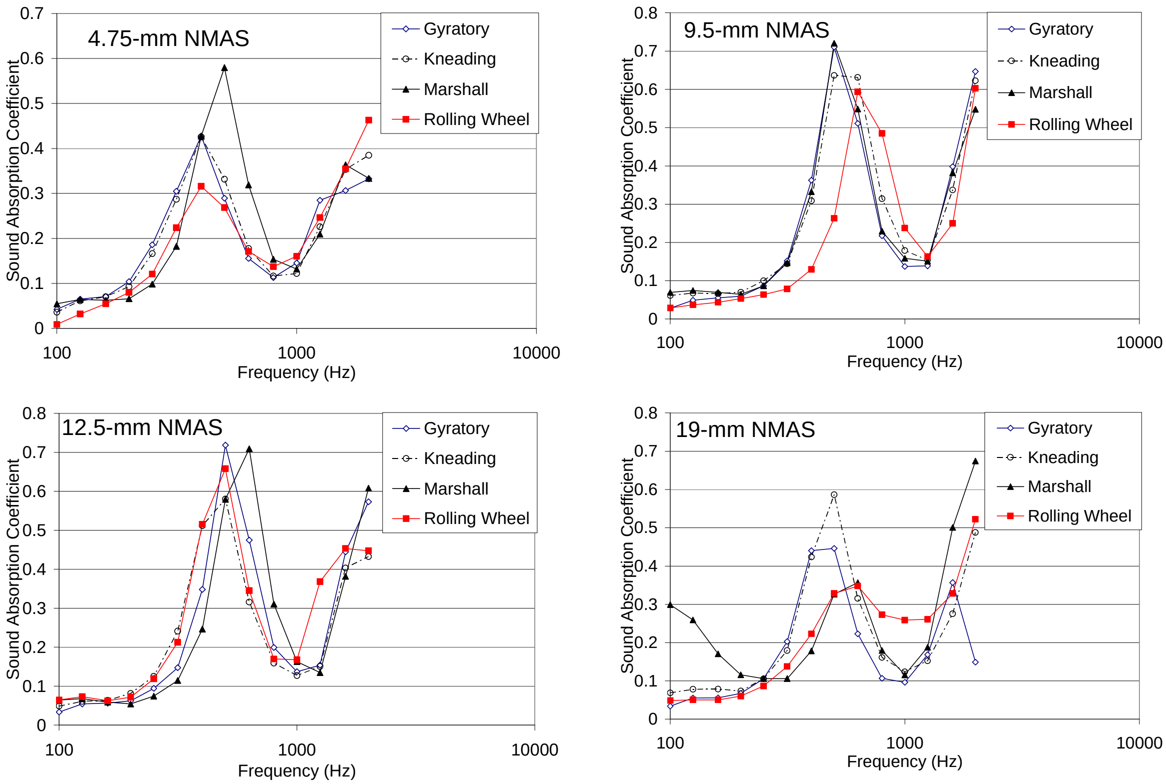


Figure C.5: Absorption coefficients at 1/3-octave frequency bands for mixtures with various aggregate sizes.

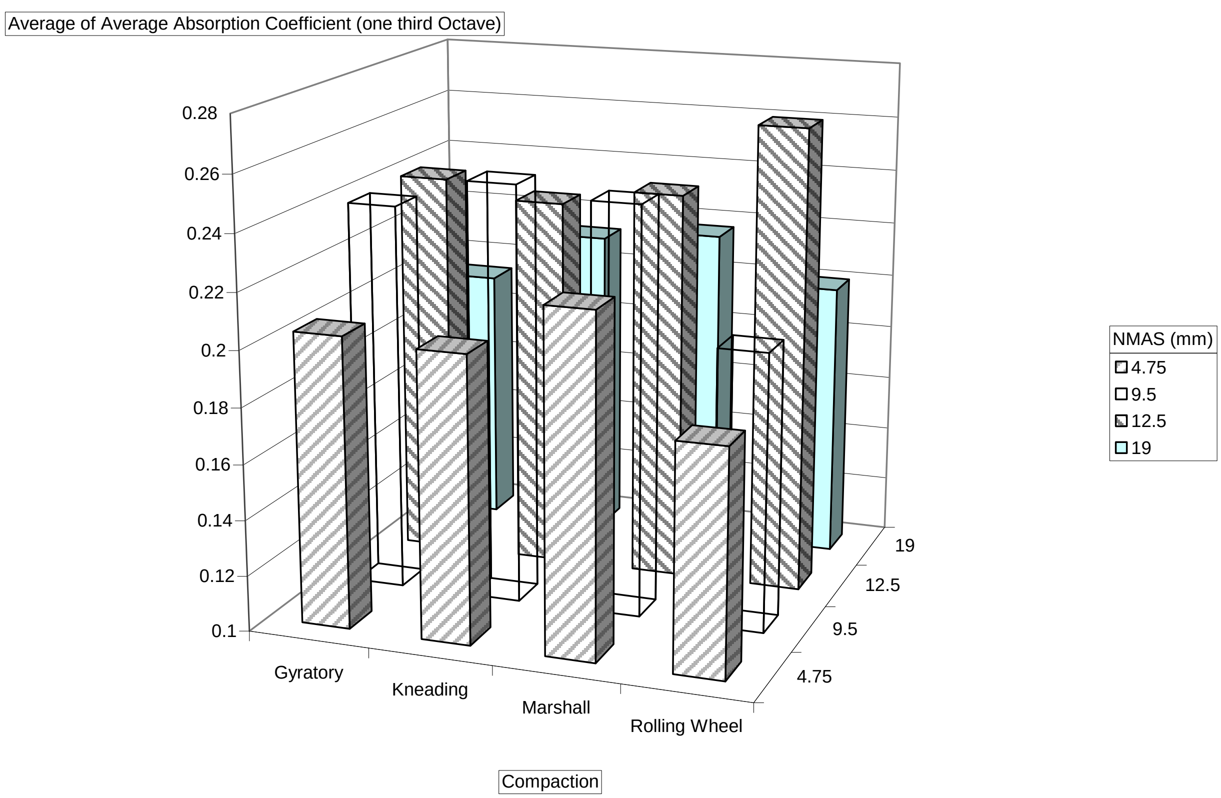


Figure C.6: Average absorption coefficient versus NMAS and compaction methods.

Moisture Susceptibility

Specimens of similar air-void contents were selected in the moisture susceptibility test. The average indirect tensile strengths of the 16 types of specimens with and without moisture conditioning are shown in Figure C.7. It can be seen that for the unconditioned specimens, the indirect tensile strength ("dry strength") was generally higher for specimens from gyratory and Marshall compaction than those from the rolling wheel compaction. The kneading compaction was similar to the rolling wheel compaction in terms of dry strength for mixtures with 4.75-mm or 19-mm NMAS, but produced higher strength for mixtures with 9.5-mm and 12.5-mm NMAS. One potential reason for the relatively lower strength of the rolling wheel compacted specimens is that they were cored from slabs so that their sides have cut aggregate faces. Specimens compacted by other methods, on the other hand, have intact molded surfaces.

For the moisture-conditioned specimens, the indirect tensile strength ("wet strength") was generally still higher for specimens from gyratory and Marshall compactions than those from the rolling wheel compaction, but generally lower for specimens from the kneading compaction.

The tensile strength ratio (TSR) is shown in Figure C.8. Specimens compacted by the rolling wheel compactor generally show higher TSR values than specimens compacted by other methods. Gyratory-compacted and Marshall-compacted specimens had similar TSR values for all sizes of aggregate gradations. The kneading compacted specimens showed similar TSR values to the gyratory- and Marshall-compacted specimens for the 4.75-mm and 19-mm NMAS mixtures, but showed lower TSR values than other compaction methods for the 9.5-mm and 12.5-mm NMAS mixtures.

The TSR values show that mixtures with 4.75-mm and 19-mm NMAS seem to have better resistance to moisture damage than mixtures with 9.5-mm and 12.5-mm NMAS. None of the four mixtures, however, can retain tensile strength over 80 percent, as recommended in ASTM D7064. Visual examination of the broken faces of conditioned specimens did not reveal any stripping in the mix. The reduction in strength after moisture conditioning, therefore, may be attributed to the possible weakening of binder by moisture and/or change of aggregate skeleton structure due to the freeze-thaw cycle. The 24-hour conditioning at 60°C may introduce significant creep deformation in the porous mix even without water. This was verified by a small-scale experiment in the laboratory, in which additional rolling wheel–compacted 12.5-mm NMAS specimens were conditioned at 60°C for 24 hours without water and then tested for the indirect tensile strength. It was found that the strength was about 75 percent of that of unconditioned specimens. The applicability to open-graded mixes of the current test procedure for moisture susceptibility, therefore, needs further investigation.

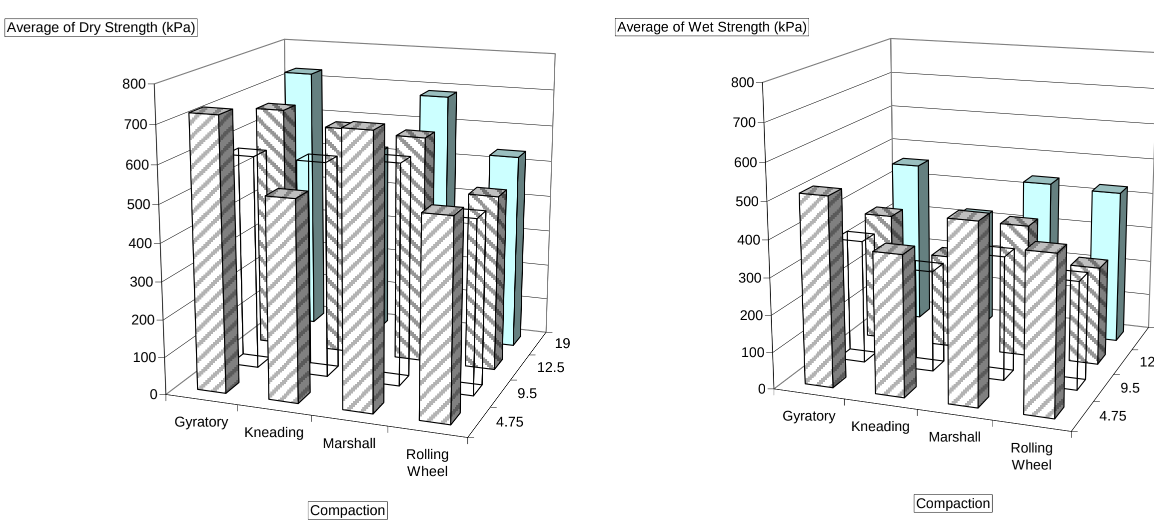


Figure C.7: Average indirect tensile strength of unconditioned and conditioned specimens.

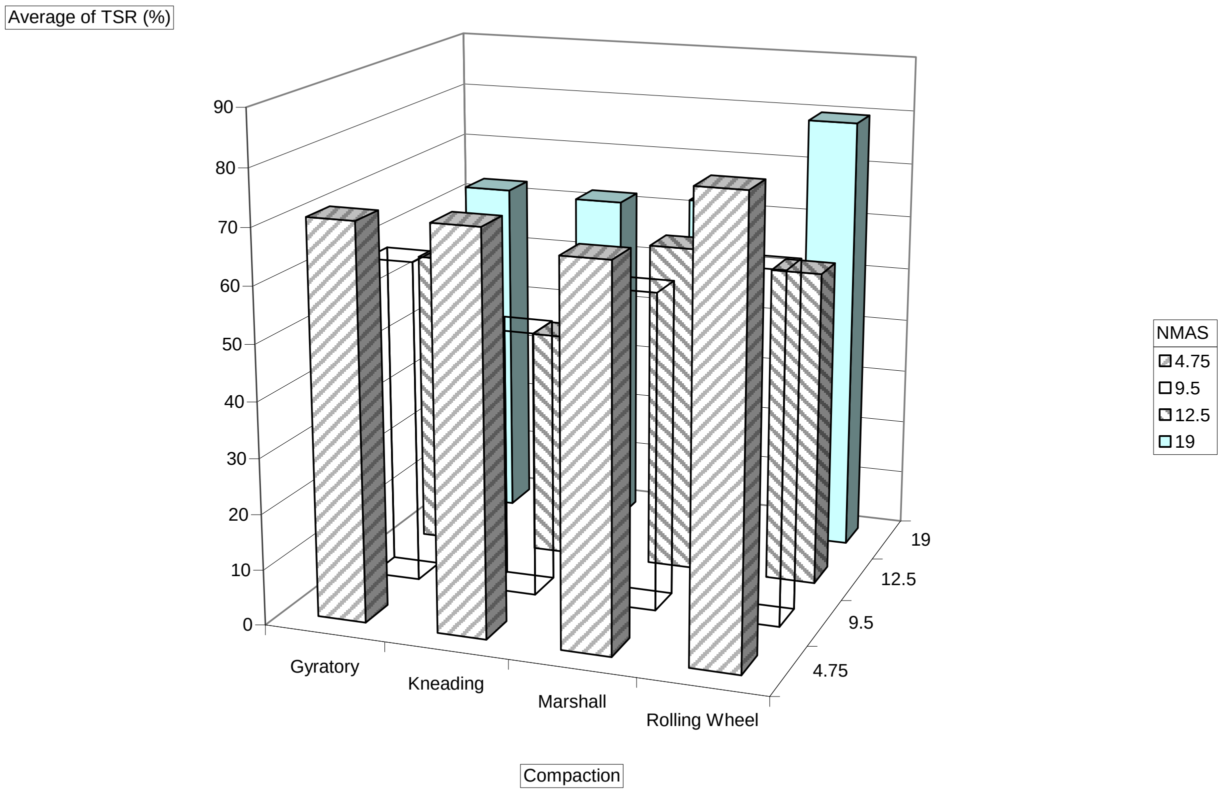


Figure C.8: Tensile strength ratio versus NMAS and compaction methods.

<u>Resistance to Raveling</u>

Resistance to raveling was evaluated by the Cantabro test. The average Cantabro loss values of unaged specimens are shown in Figure C.9. The average air-void content of each type of specimen used in the test was very similar to the value shown in Figure C.2. As can be seen from Figure C.9, the amount of mass loss in the Cantabro test is highly correlated to aggregate size. The general trend is that larger NMAS leads to more material loss in the test. The Cantabro loss of mixture with 19-mm NMAS is high for all compaction methods, with the rolling wheel compaction producing specimens with the highest mass loss. For mixtures with 9.5-mm and 12.5-mm NMAS, gyratory-compacted specimens showed the highest mass loss among four compaction methods. This is likely due to the relatively higher air-void contents in these specimens, as shown in Figure C.2. This again verifies that less compaction energy is provided for the 9.5-mm and 12.5-mm mixtures in the Superpave gyratory compaction than in other compaction methods, as pointed out in earlier. There is no statistically significant difference among the other three compaction methods. For the mixture with 4.75-mm NMAS, there was no statistically significant difference among all four compaction methods.

Figure C.10 shows the average Cantabro loss values of aged specimens. Generally, aging makes asphalt binder more brittle, and therefore leads to more material loss in the Cantabro test. This can be observed by comparing the data in Figure C.9 and Figure C.10. Statistical analysis shows that after seven-day aging at 60°C, Superpave gyratory–compacted specimens had more material loss than the rolling wheel–compacted specimens, while specimens compacted by kneading and Marshall compaction methods had statistically similar material loss when compared to the rolling wheel–compacted specimens.

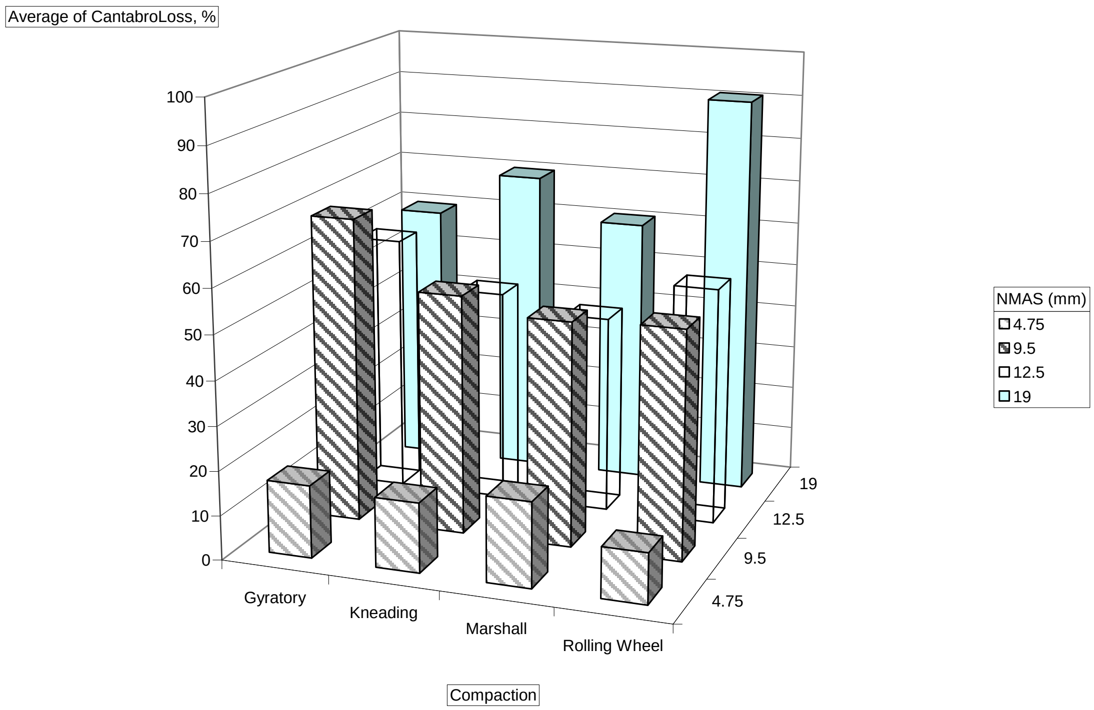


Figure C.9: Average Cantabro loss from unaged specimens versus NMAS and compaction methods.

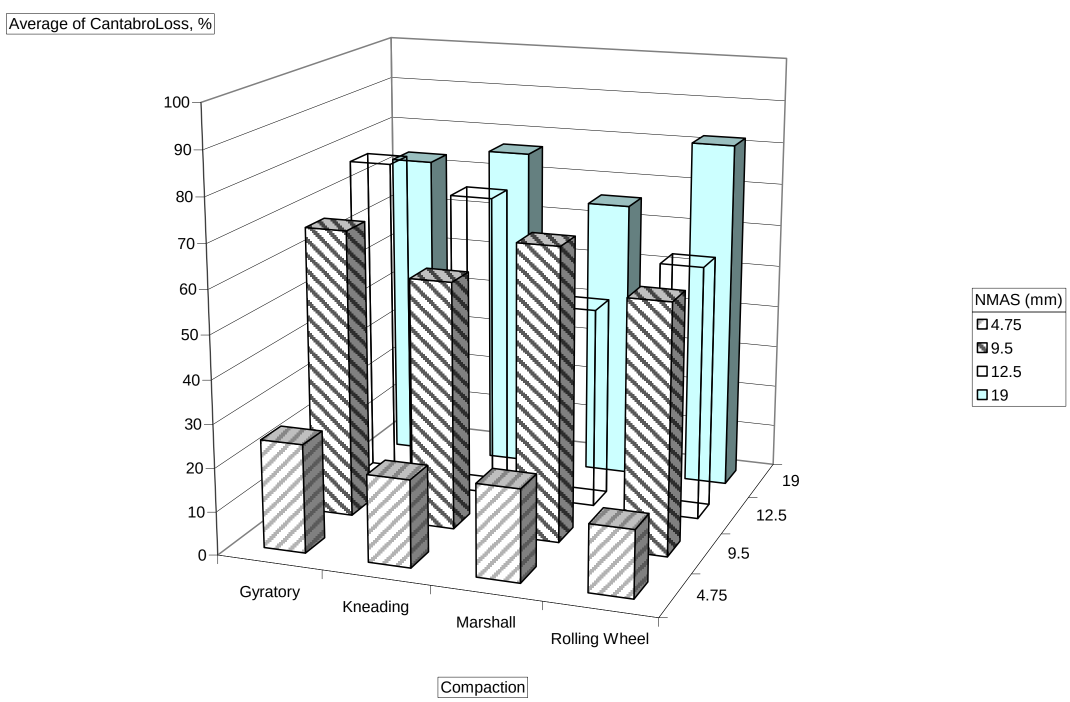


Figure C.10: Average Cantabro loss from aged specimens versus NMAS and compaction methods.

Discussion

Results of the study show that compaction effect varies with aggregate gradation and the performance index being evaluated. Depending on the type of mixture and the performance index to be evaluated, different compaction methods may be chosen in the laboratory to better represent the mixture placed in the field. Other considerations may also need to be taken into account when selecting the compaction method in the laboratory.

In general, the rolling wheel compaction is expected to provide aggregate orientations and air-void distributions closest to field compaction, because the rolling wheel method uses a larger compacted slab, while the aggregates in the other three methods are constrained next to the mold walls. This is an expectation based on previous dense-graded studies, although it is unverified for open-graded mixes. The Hveem kneading compactor compacts a mix by a ram foot with a small bottom area, which may create a stress concentration in aggregate particles high enough to break the aggregate. This is particularly true for porous mixes because their gradations contain mainly large aggregate particles. In fact, breaking and crushing of surface aggregate were frequently observed in the Hveem kneading compaction in this study. The Marshall method may produce similar breakage for certain aggregates because of the impact loading.

There are also practical considerations. For example, unlike dense-graded mixes, porous mixes cannot be extruded from a mold shortly after compaction, otherwise the compacted specimen will collapse under gravity. When multiple specimens need to be fabricated in a batch, which is a typical case, it is better to have multiple molds to prevent a long waiting period. The high cost of gyratory compaction molds may then prevent the use of this compaction method in a laboratory with a limited budget.

The rolling wheel compactor is expected to produce results closest to field compaction, however for routine mix design, the current configuration and process for rolling wheel compaction used by the UCPRC is not considered practical for routine use in open-graded mix design. Based on the findings in this comparison study, the preliminary recommendation is that a laboratory compaction method for routine mix design use be selected for porous mixes based on the nominal maximum aggregate size. For mixes with small aggregates (4.75 mm or less), Marshall, gyratory, or Hveem kneading compaction can be used. For mixes with medium or large aggregates (9.5 mm or more), Marshall or gyratory compaction can be considered, while Hveem compaction should be avoided due to aggregate breakage. For gyratory compaction on mixes with medium-sized (9.5 mm and 12.5 mm) aggregates, a fixed specimen height might be specified instead of a fixed number of gyrations.

These results indicate that selection of laboratory compaction for open-graded mix design needs further investigation, or at least it must be understood that the methods will produce different results for different tests, and for a given test depending on a number of mix design factors.

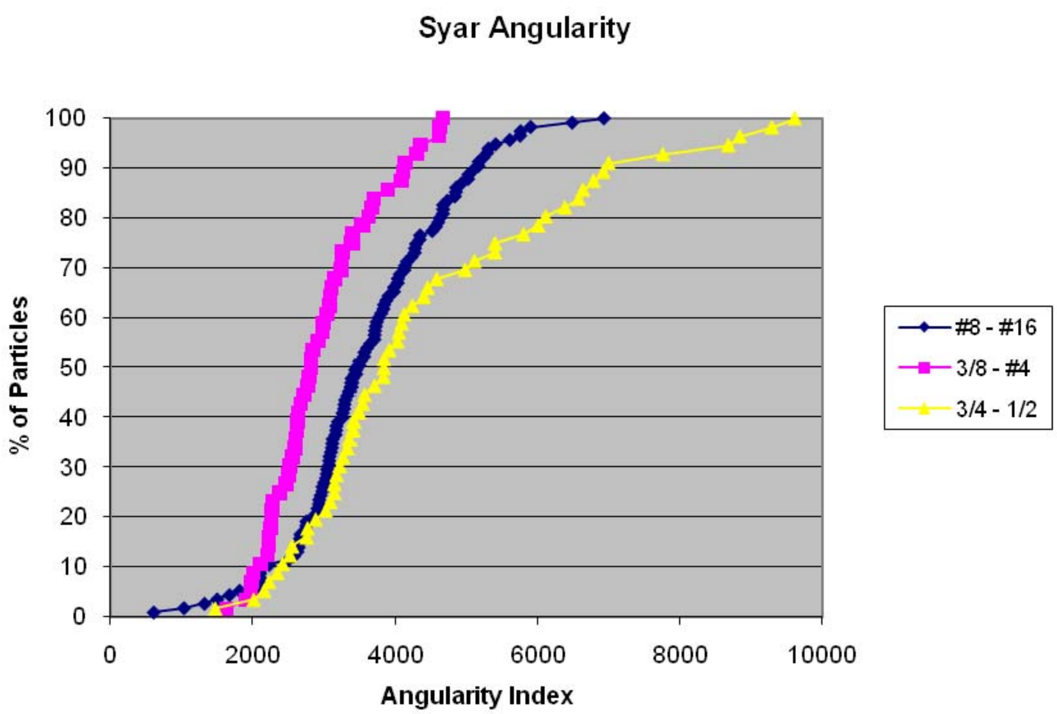
APPENDIX D: AGGREGATE SHAPE ANALYSIS RESULTS FROM TEXAS TRANSPORTATION INSTITUTE

Table D.1: Summary of Aggregate Shape Analysis Results

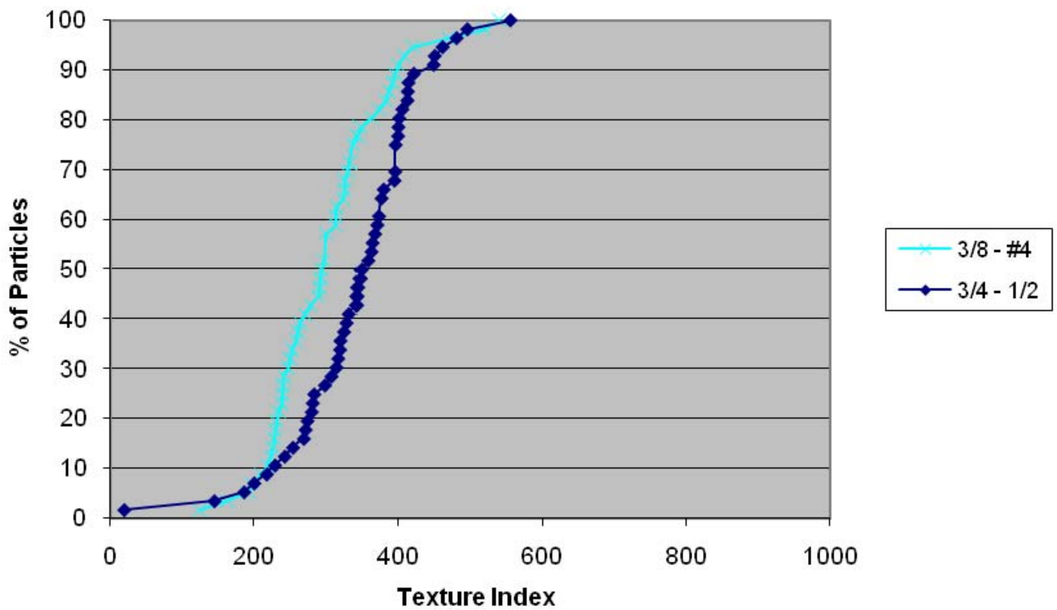
	Size	No. of Particles	Angularity Average	Texture Average	2D Form Average
Syar	1/2" - 3/8"	56	4442.96	341.89	
	3/8" - No. 4	56	2976.67	301.24	
	No. 8 - No. 16	115	3630.61		7.99
Teichert	1/2" - 3/8"	56	4361.27	419.43	
	3/8" - No. 4	56	3091.71	383.67	
	No. 8 - No. 16	115	3787.65		8.18
Graniterock (Watsonville)	1/2" - 3/8"	56	2728.48	356.71	
	3/8" - No. 4	56	2889.11	293.91	
	No. 8 - No. 16	118	3745.27		7.48

Note: a higher angularity average value indicates more angularity; a higher texture average value indicates coarser texture; a higher 2D form average value indiates that a particle is more like a square and less like a sphere. Details of the meanings of the parameters in the above table can be found in Reference (30).

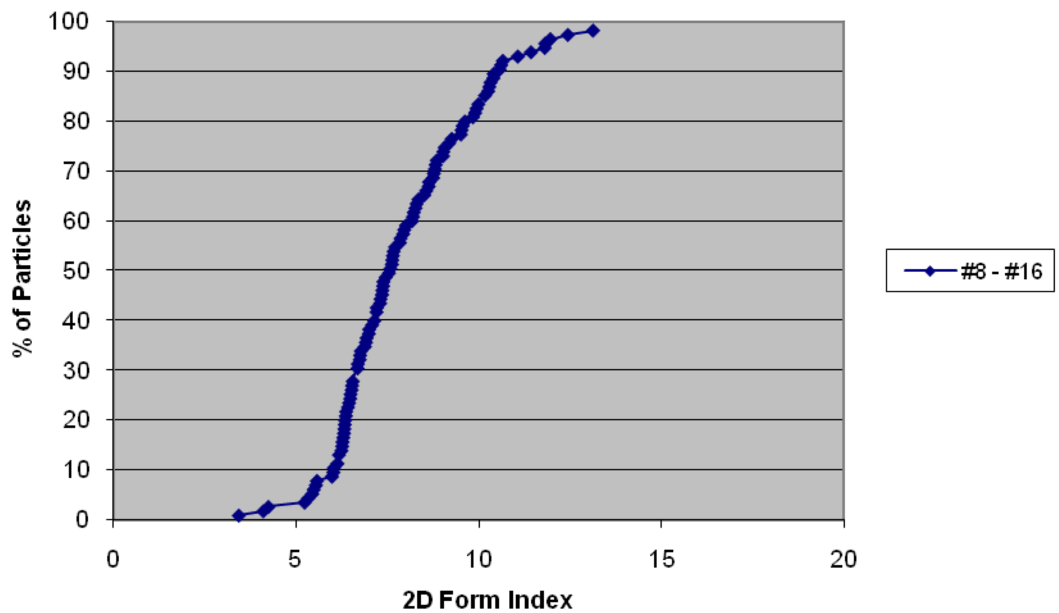
The following figures show the cumulative distributions of angularity index, texture index, and 2D form index of the three aggregate types.

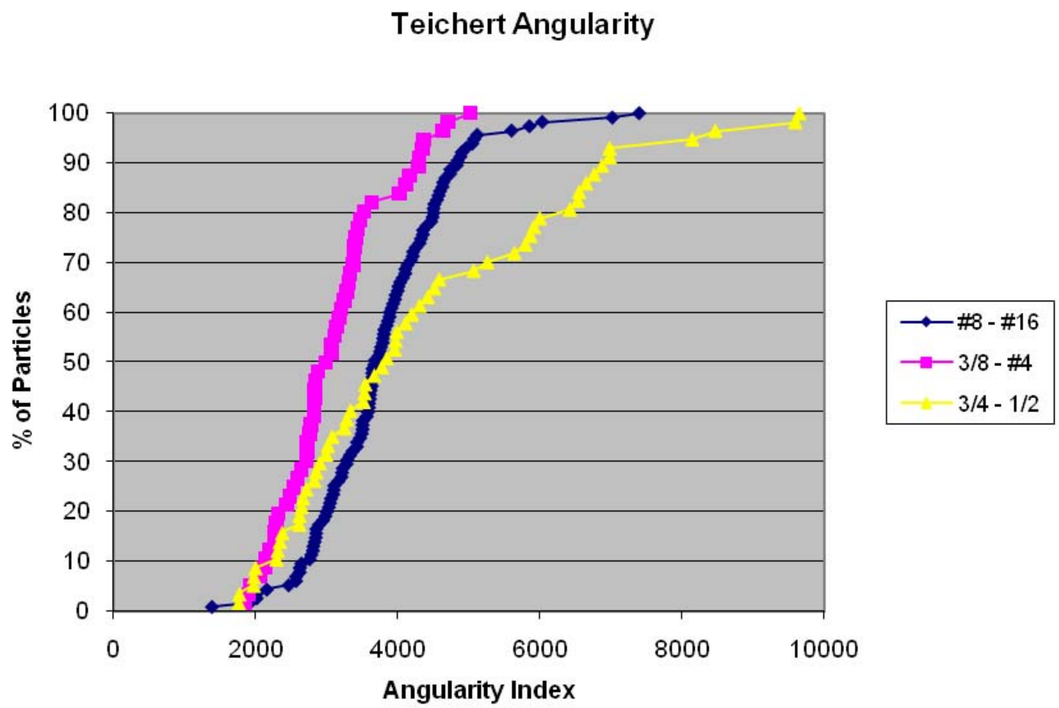


Syar Texture

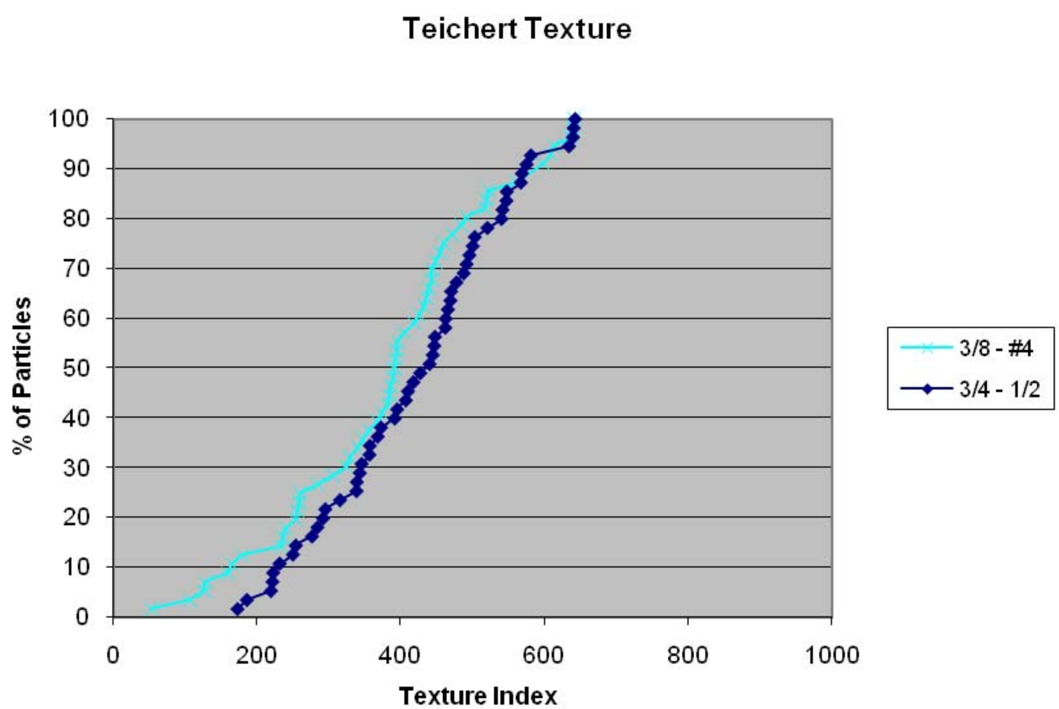


Syar 2D Form

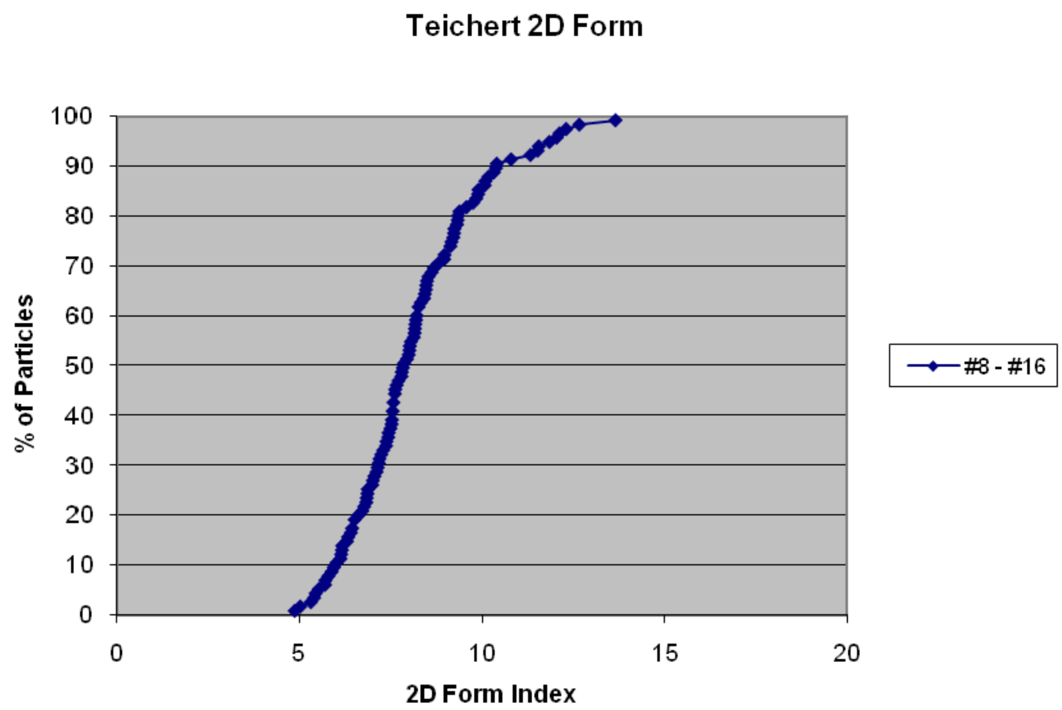




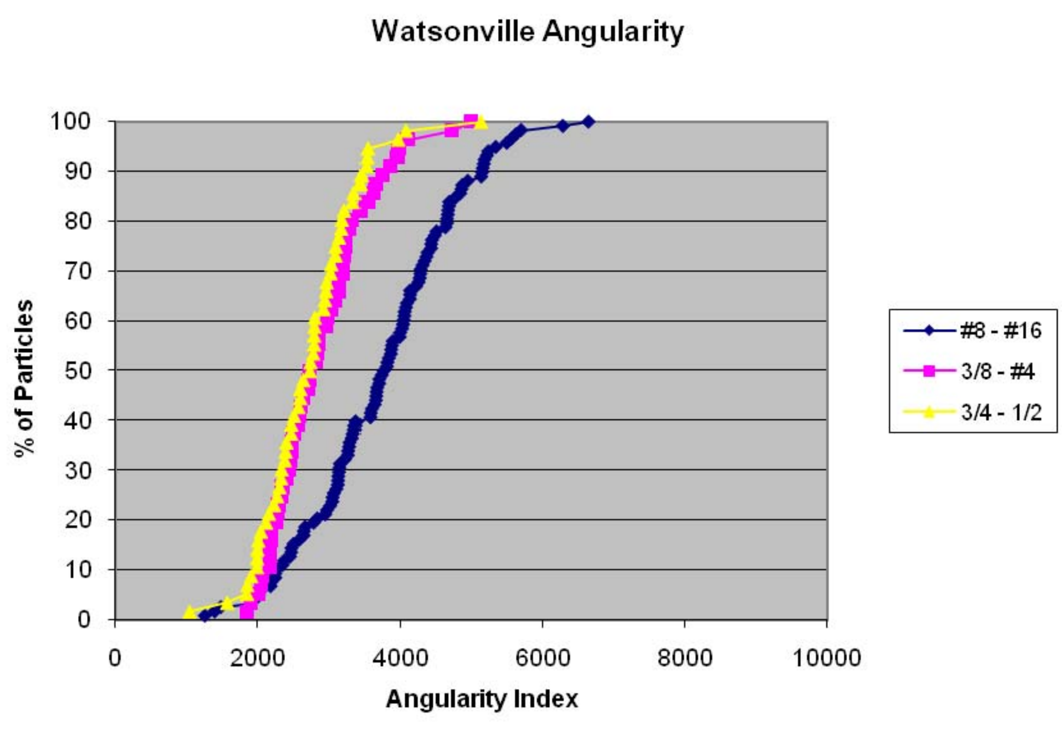
Teichert Angularity
% of Particles
Angularity Index
0
10
20
30
40
50
60
70
80
90
100
0
2000
4000
6000
8000
10000
#8 - #16
3/8 - #4
3/4 - 1/2



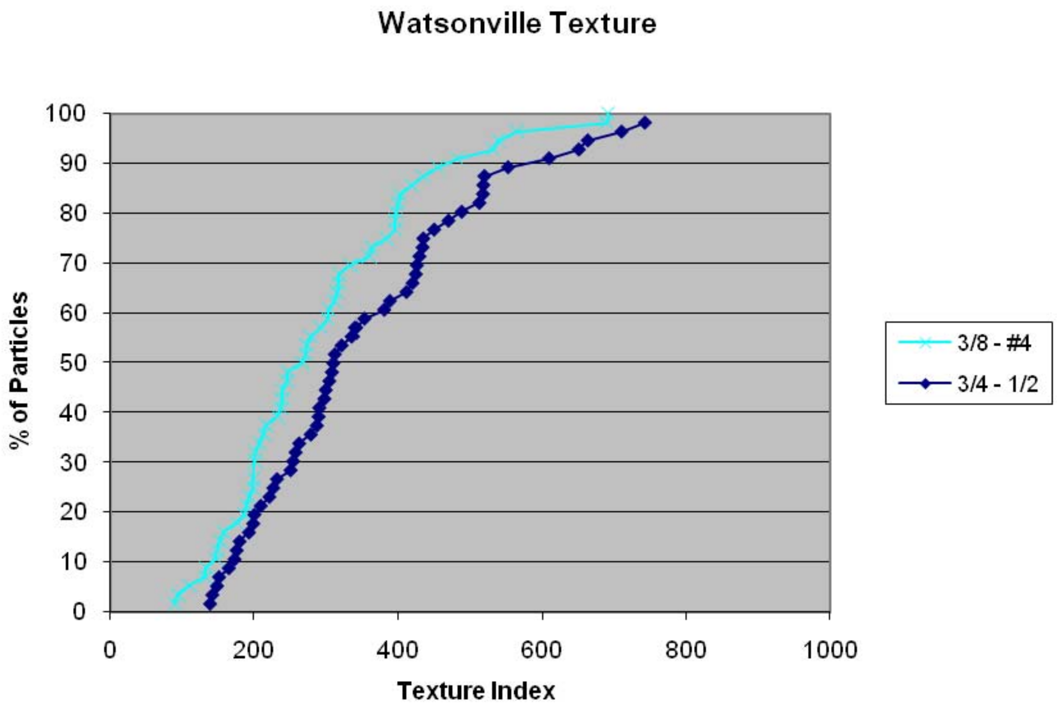
Teichert Texture
% of Particles
Texture Index
0
10
20
30
40
50
60
70
80
90
100
0
200
400
600
800
1000
3/8 - #4
3/4 - 1/2



Teichert 2D Form
100
90
80
70
60
50
40
30
20
10
0
% of Particles
0
5
10
15
20
2D Form Index
#8 - #16



Watsonville Angularity
100
90
80
70
60
50
40
30
20
10
0
% of Particles
0
2000
4000
6000
8000
10000
Angularity Index
#8 - #16
3/8 - #4
3/4 - 1/2


Watsonville Texture
100
90
80
70
60
50
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% of Particles
0
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400
600
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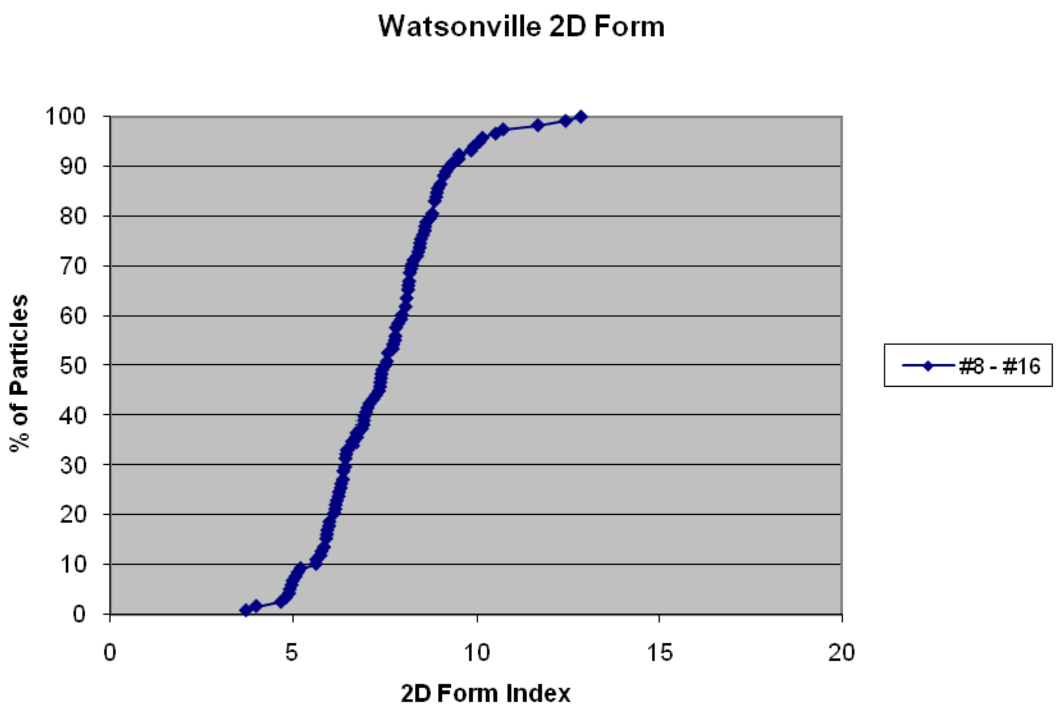
Texture Index
3/8 - #4
3/4 - 1/2


Watsonville 2D Form
100
90
80
70
60
50
40
30
20
10
0
% of Particles
0
5
10
15
20
2D Form Index
#8 - #16

APPENDIX E: SURFACE PHOTOS OF MIXES INCLUDED IN THE STUDY

(*Note:* Each black or white square in the photos represents a length of 10 mm.)

(a) RW475

(b) RW95

(c) RW125

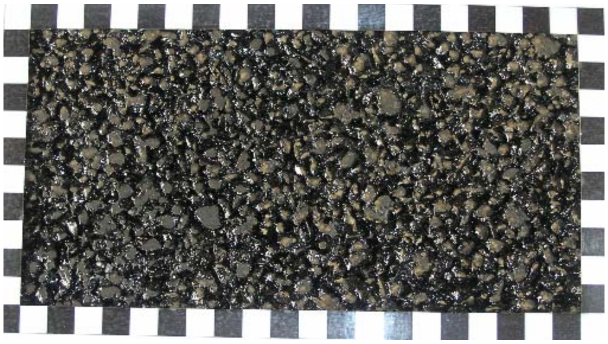
(d) RW19

(e) AR475

(f) P475

(g) P475LM

(h) P58LF



(i) TR475

(j) AR475D

(k) AR475PD

(l) AR475P

(m) PG475W

(n) AR475T

(o) PG95T

(p) AR95

(q) AR95W

(r) AZ95

(s) DL

(t) SMA6P

(u) SMA4P

(v) G125

(w) E8

(x) D125