IMPROVING MIX DESIGN AND CONSTRUCTION OF PERMEABLE FRICTION COURSE MIXTURES

A Dissertation

by

ALLEX EDUARDO ALVAREZ LUGO

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2009

Major Subject: Civil Engineering

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ABSTRACT

Improving Mix Design and Construction of Permeable Friction Course Mixtures.
(December 2009)
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Permeable friction course (PFC), or new generation open-graded friction course (OGFC) mixtures, are hot mix asphalt (HMA) characterized by high total air voids (AV) content (minimum 18 %) as compared to the most commonly used dense-graded HMA. The high AV content confers to PFC mixtures both high permeability and noise reduction effectiveness. These characteristics and the high values of surface friction exhibited by PFC mixtures, as compared to dense-graded HMA, lead to improvements in safety and the environment, which make PFC one of the safest, cleanest, and quietest alternatives currently available for surface paving. The main objective of this study was improving the current PFC mix design method and construction practices in terms of compaction control.

Corresponding results were integrated in an improved mix design method that is based on the guidelines of the current mix design method used by the Texas Department of Transportation. The improved mix design included modified computation of the inputs required to determine mixture density (or corresponding total AV content). These changes led to a proposed modification of the density specification for mix design from 78-82 % to 76-80 %. In addition, the water-accessible AV content was proposed as a surrogate of the total AV content for mix design and evaluation. The improved mix design method also includes verification of drainability, durability, and stone-on-stone contact. Computation of the expected value of permeability ($E[k]$) and measurement of the water flow value were recommended, respectively, for verification of drainability in the laboratory (using specimens compacted in the Superpave Gyratory Compactor (SGC)) and in the field. The Cantabro loss test conducted in both dry- and wet-conditions was suggested for assessing mixture durability. Improved criteria were proposed for verification of stone-on-stone contact based on the evaluation of the AV content in the coarse aggregate fraction of the mixture. In addition, comparison of the internal structure of field-and laboratory-compacted mixtures supported recommendation of a field-compaction control. Recommendations to reduce the horizontal heterogeneity of AV encountered in PFC specimens included using road cores with a minimum 152.4 mm diameter and coring SGC specimens from 152.4 to 101.6 mm in diameter.

DEDICATION

I dedicate this dissertation to my beloved parents and sisters for the love and support that they provided me to pursue my dreams.

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NOMENCLATURE

AASHTO	American Association of State Highway and Transportation Officials
ANOVA	Analysis of Variance
AR	Asphalt Rubber
AV	Air Voids
CEDEX	Centro de Estudios y Experimentación de Obras Públicas
COV	Coefficient of Variation
DEM	Discrete Element Method
DEM-IA	Discrete Element Method and Image Analysis Techniques
G_{mb}	Bulk Specific Gravity of the Compacted Mixture
G_{mm}	Theoretical Maximum Specific Gravity of the Mixture
HMA	Hot Mix Asphalt
HWTT	Hamburg Wheel-Tracking Test
LMLC	Laboratory Mixed-Laboratory Compacted
NCAT	National Center for Asphalt Technology
NMAS	Nominal Maximum Aggregate Size
OAC	Optimum Asphalt Content
OGFC	Open-Graded Friction Course
OT	Overlay Test
PFC	Permeable Friction Course
PG	Performance Grade
PMLC	Field Mixed (Plant Mixed)-Laboratory Compacted
SGC	Superpave Gyratory Compactor
TSR	Retained Tensile Strength Ratio
TTI	Texas Transportation Institute
TxDOT	Texas Department of Transportation
VCA	Voids in Coarse Aggregate
VCA_{mix}/VCA_{DRC} ratio	*VCA* Ratio
WFV	Water Flow Value
X-ray CT	X-ray Computed Tomography

TABLE OF CONTENTS

Page

Page

Page

LIST OF FIGURES

FIGURE Page

FIGURE Page

FIGURE Page

FIGURE Page

LIST OF TABLES

TABLE Page

1. INTRODUCTION

1.1 OVERVIEW

New generation open-graded friction course (OGFC), or permeable friction course (PFC) mixtures as defined by the Texas Department of Transportation (TxDOT) are special asphalt mixtures characterized by a high total air voids (AV) content (i.e., 18 to 22 %) as compared to the most commonly used dense-graded hot mix asphalt (HMA). Advantages related to the use of PFC mixtures are improvements in safety, economy, and the environment, which make these mixtures one of the safest, cleanest, and quietest alternatives currently available for surface paving (Alvarez et al. 2006). Thus, PFC mixtures have been typically used as sacrificial wearing courses over Portland cement concrete pavements and dense-graded HMA in new construction, major rehabilitation projects, and maintenance overlays (Estakhri et al. 2008).

As compared to the mix design method for dense-graded HMA, the PFC mix design is less structured and a common method is not available at present. Many agencies in the United States use the method proposed by the National Center for Asphalt Technology (NCAT) (Kandhal 2002; Watson et al. 2004a; Watson et al. 2003), which includes an evaluation of both functionality and durability. In addition, ASTM D 7064-04 (ASTM International 2006) presents a design methodology for new generation OGFC mixtures based on volumetric properties to determine the optimum asphalt (or asphalt binder) content (OAC).

Volumetric mixture properties (primarily density) constitute the main parameters in the design practice of several agencies for selecting the OAC of PFC mixtures. For example, the current TxDOT method for PFC mix design specifies a density range of 82 to 78 %, computed on specimens compacted at 50 gyrations of the Superpave Gyratory Compactor (SGC), to determine the OAC (TxDOT 2005). In addition, the mix design method includes an evaluation of draindown (Tex-235-F) and moisture susceptibility using the “boiling” test (Tex-530-C) on specimens produced at the selected OAC (TxDOT 2005).

Materials currently specified by TxDOT for fabrication of PFC mixtures include polymer modified asphalts, fibers, additives to reduce mixture susceptibility to moisture damage, and high-quality aggregates. Performance Grade (PG) asphalt (PG 76-XX) and Asphalt Rubber

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This dissertation follows the style of *Journal of Materials in Civil Engineering, ASCE.*

(AR) with contents of 6 to 7 % and 8 to 10 %, respectively, are required (TxDOT 2005). These high asphalt binder contents provide thicker asphalt binder films (as compared to dense-graded HMA), which may improve durability in terms of resistance to aging and moisture damage, but increase the probability of draindown issues, especially in PG mixtures. Therefore, either cellulose or mineral fibers are added to satisfactorily prevent this problem in PG mixtures. In addition, lime is specified to minimize moisture susceptibility in PG mixtures. PFC mixtures fabricated with AR do not incorporate lime, fibers, or any other additive to improve performance. Furthermore, the specified gradation band differs for AR and PG mixtures to allocate different amounts of asphalt binder and still obtain similar AV contents (typically 20 %). Therefore, differences are expected not only in functionality, but also in durability for these two types of PFC mixtures.

The advantages previously indicated for PFC mixtures are closely related to the use of a high quality open-graded aggregate to obtain a HMA with: (*i*) a coarse granular skeleton that develops stone-on-stone contact and (*ii*) a high proportion of connected AV. The granular skeleton guarantees adequate durability in terms of resistance to raveling and permanent deformation, whereas the connected AV form paths for water and air flow through the mixture, which ensures proper functionality in terms of both high permeability and capacity to reduce tire-pavement noise (as compared to dense-graded HMA). Therefore, taking into account both durability and functionality requirements, the mix design and construction of a PFC mixture should lead to a compacted mixture with an equilibrium density. After properly seating the aggregates to obtain stone-on-stone contact, the equilibrium density should lead to a connected AV content higher than the minimum that guarantees the expected functionality and smaller than the maximum that can lead to durability problems.

Although substantial improvements in mixture performance have been achieved in PFC mixtures as compared to the performance of OGFC mixtures constructed up to the 1990's, the lack of a standard mix design method for PFC mixtures constitutes at present one of the main limitations to further use of these mixtures. These conditions motivate conducting additional research, as subsequently described, to improve the PFC mix design method and promote standardization of the design practice.

1.2 PROBLEM STATEMENT AND RESEARCH OBJECTIVES

Mix design and construction practices for PFC mixtures can be further improved to better guarantee their adequate functionality and durability. The overall objective of this research study is to enhance the current PFC mix design method (over the current TxDOT mix design method) and recommend construction practices, in terms of compaction control, to promote proper reproduction of the mix design determinations under field conditions. Achievement of this general objective includes the specific objectives subsequently indicated, which are related to particular aspects to enhance PFC mixture design and evaluation:

- Propose improvements for determining the inputs required to calculate the total AV content of PFC mixtures.
- Evaluate and recommend techniques to quantify connected AV content in PFC mixtures. This volumetric parameter is assessed as a surrogate of the total AV content for mix design and evaluation.
- Evaluate the current approaches used to assess drainability in PFC mix design and explore alternatives to improve this evaluation.
- Recommend a durability test that can be included in PFC mix design to enhance the determination of the OAC obtained based on volumetric properties.
- Assess the effect of compaction on PFC mixture properties and performance to promote improvements in the construction practice in terms of compaction control.
- Recommend improvements for the quantitative determination of stone-on-stone contact in compacted PFC mixtures.
- Evaluate the internal structure of both field- and laboratory-compacted PFC mixtures, and propose the required enhancements in the fabrication of laboratory specimens to better reproduce the internal structure of field-compacted mixtures.

1.3 DISSERTATION OUTLINE

This dissertation combines several papers, presented according to the style and format of the *Journal of Materials in Civil Engineering, ASCE*, as well as the guidelines provided in the Texas A&M University Thesis Manual. The dissertation is organized in nine sections as subsequently described. Each section included in the dissertation body corresponds to a paper that is related to one of the specific objectives previously indicated.

Section 1 presents an introduction that includes overview, problem statement and research objectives, and the dissertation outline. A relevant literature review is included in each section (paper) according to the corresponding topic treated in the paper.

Section 2 corresponds to a paper related to the determination of volumetric properties of PFC mixtures, which was published in the *Journal of Testing and Evaluation* (2009). The authors of this paper are Allex E. Alvarez, Amy Epps Martin, Cindy Estakhri, and Richard Izzo.

Section 3 presents a paper related to the determination of the connected AV content in PFC mixtures. This paper was published in the *Journal of Testing and Evaluation* (2009), and the authors are Allex E. Alvarez, Amy Epps Martin, and Cindy Estakhri.

Section 4 is a paper submitted for publication (December 2008) in the *Journal of Materials in Civil Engineering, ASCE* (authors: Allex E. Alvarez, Amy Epps Martin, and Cindy Estakhri) that explores the assessment of drainability in PFC mixtures.

Section 5 is related to durability of PFC mixtures and corresponds to a paper published in the *International Journal of Pavement Engineering* (2009). The authors of this paper are Allex E. Alvarez, Amy Epps Martin, Cindy Estakhri, and Richard Izzo.

Section 6 contains the paper published in the *Journal of Testing and Evaluation* (2009): "Effects of Densification on PFC Mixtures". The authors of this paper are Allex E. Alvarez, Amy Epps Martin, and Cindy Estakhri.

Section 7 presents a paper written by Allex E. Alvarez, Enad Mahmoud, Amy Epps Martin, Eyad Masad, and Cindy Estakhri on the determination of stone-on-stone contact of PFC mixtures. This paper was submitted for publication to the *Journal of Materials in Civil Engineering, ASCE*.

Section 8 corresponds to a paper centered on the evaluation of the internal structure of PFC mixtures. This paper was written by Allex E. Alvarez, Amy Epps Martin, and Cindy Estakhri and submitted for publication in the *Construction and Building Materials* journal.

Section 9 presents the conclusions and recommendations of the dissertation. In addition, topics for further research are suggested in this section.

2. DETERMINATION OF VOLUMETRIC PROPERTIES FOR PERMEABLE FRICTION COURSE MIXTURES*

2.1 OVERVIEW

Current HMA mix design methods used to determine the OAC for PFC mixtures are based on volumetric properties, primarily total AV content. This calculated volumetric parameter depends on the bulk specific gravity (G_{mb}) and the theoretical maximum specific gravity (G_{mm}) of the mixture, which are generally difficult to measure in a laboratory due to the high asphalt contents, high total AV contents, and the use of modified asphalts for PFC mixtures. This study evaluated two methodologies for determining G_{mb} (vacuum and dimensional analysis) and two methodologies for determining G_{mm} (measured and calculated) for use in calculations of total AV content. For the mixtures assessed in this study, originally designed with a total AV content of 20 %, the alternative methodologies studied led to total AV content values outside the design range (18 to 22 %), which implies the necessity of gradation modifications or changes in the fiber content to meet AV requirements and define an OAC. Dimensional analysis and a calculation procedure, based on values of G_{mm} measured in the laboratory at low asphalt contents, are recommended for determining G_{mb} and G_{mm} values, respectively. In addition, dimensional analysis is preliminarily recommended to compute the water-accessible AV content of PFC mixtures based on the assessment of two methods (vacuum and a methodology proposed for dimensional analysis) to compute this parameter. Water-accessible AV content is considered as an alternative parameter for mix design and evaluation.

2.2 INTRODUCTION

PFC are HMA mixtures placed at the surface of an asphalt pavement structure in a thin layer to produce several benefits for the traveling public in terms of safety, economy, and the environment (Alvarez et al. 2006). The use of PFC reduces the risk of hydroplaning and wet skidding; decreases splash and spray, fuel consumption, tire wear, and pavement noise; improves ride quality and visibility of pavement markings at night and in wet weather; and results in cleaner runoff when compared to dense-graded HMA (Brown 1973; Button et al. 2004; Kearfott

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* Reprinted with permission from "Determination of Volumetric Properties for Permeable Friction Course Mixtures" by Allex E. Alvarez, Amy Epps Martin, Cindy Estakhri, and Richard Izzo, 2009. *Journal of Testing and Evaluation,* 37 (1), 1-10, Copyright [2009] by ASTM International.

et al. 2005; Khalid and Pérez 1996; Ruiz et al. 1990). PFC mixtures are new generation OGFC designed with a minimum of 18 % AV content to create a highly permeable layer.

To obtain the benefits described previously, a mix design system that produces both a functional and durable PFC mixture is required. Although a common mix design procedure for these mixtures does not currently exist, many states in the United States use the NCAT method (Kandhal 2002; Watson et al. 2004a; Watson et al. 2003).

The primary parameter utilized in selecting the OAC for PFC mixtures is total AV content. Therefore, further examination of the process used to determine the inputs required to calculate this volumetric property is warranted for this type of mixture. Total AV content expressed as a percent of the total volume in a compacted HMA mixture is calculated as follows:

$$Total\ \ AV\ content = 100 \times \frac{G_{mm} - G_{mb}}{G_{mm}} \quad (\%) \qquad (2\text{-}1)$$

where G_{mm} is the theoretical maximum specific gravity of the mixture and G_{mb} is the bulk specific gravity of the compacted mixture. While the AV calculation is simple, measuring G_{mm} and G_{mb} is a difficult task for PFC mixtures due to high total AV contents, high asphalt contents, and the use of modified asphalts.

Previous research (Watson et al. 2004a; Watson et al. 2003) compared the vacuum method and dimensional analysis to determine G_{mb} on OGFC fabricated with different PG asphalts and recommended the vacuum method. When using the vacuum method and dimensional analysis to compute G_{mb}, a minimum total AV content for mix design of 16 and 18 %, respectively, was also proposed. Crouch et al. (2003) recommended the vacuum method for determining G_{mb} of OGFC. However, the conclusions stated in this former research suggest the necessity of additional investigation to further compare the vacuum method and dimensional analysis and establish the most convenient method for computing G_{mb} in PFC mixtures. Furthermore, fabrication of PFC mixtures using not only PG asphalts, but also employing AR (which exhibits different physical, chemical, and rheological properties compared to those of PG asphalts) motivated additional research to guarantee adequate characterization of the AR mixtures.

Difficulties experienced by the TxDOT personnel in handling PFC mixtures produced in the laboratory motivated additional research on the determination of G_{mm} for PFC mixtures. These difficulties (qualitatively evaluated by TxDOT) were related to: (*i*) loss of asphalt during the process of measurement due to the adhesiveness of these asphalt-rich mixtures, particularly high asphalt content (8 to 10 %) AR mixtures, and (*ii)* greater tendency of the mixture to form clumps compared to that of dense-graded HMA. Formation of mixture clumps may pose problems with ensuring complete extraction of air before measuring the total sample volume, using the buoyancy principle, according to the testing procedure applied (Tex 227-F) (TxDOT 2005). Consequently, this study evaluated two methodologies for determining G_{mm} values for use in the computation of total AV content (or corresponding densities) and related OAC selection. These methodologies correspond to: (*i*) direct measurement of G_{mm} at the asphalt content used for mix design (6 to 10 %) and (*ii*) calculation of G_{mm} based on measurements of G_{mm} at low asphalt content (3 to 5 %).

On the other hand, PFC mixtures are characterized by large water-accessible AV content (i.e., proportion of the total volume of a compacted mixture that is accessible to water) that provide high permeability and capacity to reduce tire-pavement noise. Research conducted by Watson et al. (2003) preliminarily studied the determination of the water-accessible AV content (also called effective AV content) in PG-OGFC mixtures using the vacuum method. To continue the investigation on this topic, this research included a comparison of water-accessible AV content values determined by both the vacuum method and a methodology proposed for dimensional analysis. The water-accessible AV content is considered an alternative volumetric parameter that can be integrated in the future for mix design and evaluation, because it may provide more insight into the mixture structure in terms of the AV content directly associated with functionality and durability properties.

The paper describes the experimental design used in this study for determining G_{mm}, G_{mb}, and water-accessible AV content, followed by a discussion of G_{mm} and G_{mb} test results presented in terms of total AV content. Next, discussions of additional variability of total AV content in compacted specimens and the effect of the determination methods for G_{mm} and G_{mb} on the selection of the OAC for PFC mixtures are presented. Finally, a comparison of total AV content and water-accessible AV content values is stated. Conclusions and recommendations complete the paper.

2.3 EXPERIMENT DESIGN

This section presents the main aspects related to mix design, material requirements, and selection and fabrication of specimens used in this study. In addition, a description of the methods employed to compute G_{mm}, G_{mb}, and water-accessible AV content is presented.

2.3.1 Mix Design and Material Requirements

Mix design was performed according to the current TxDOT PFC mix design method, which is defined in TxDOT Test Method Tex-204 Part V (TxDOT 2005). Material requirements for PFC mix design are defined in Item 342 of the TxDOT Standard Specifications book (TxDOT 2004), which allows the following two types of asphalts:

- a Type I or II AR asphalt with a minimum of 15 % by weight of asphalt of Grade C or Grade B crumb rubber, and
- a PG asphalt with a minimum high temperature grade of PG76-XX , a minimum of 1.0 % of lime by weight of dry aggregate, and a minimum of 0.2 % of cellulose or mineral fibers by weight of mixture.

According to the current mix design method, the OAC must be between 6 and 7 % for PG mixtures and between 8 and 10 % for AR mixtures (TxDOT 2004). An OAC is selected based on the minimum asphalt content requirements and the target laboratory density specified (between a suggested limit of 78 and a maximum of 82 % or equivalently between total AV contents of 18 and 22 %) evaluated using dimensional analysis. Next, specimens at the selected OAC are produced for an evaluation of draindown (Tex-235-F) and moisture susceptibility using the “boiling” test (Tex-530-C) (TxDOT 1999). Although dimensional analysis is specified, within the last three years PFC mix design has been conducted in Texas using dimensional analysis as well as the vacuum method. Incidentally, according to ASTM D 7064-04 (ASTM International 2006), OGFC mix design can be conducted by applying either dimensional analysis or the vacuum method to compute the total AV content.

2.3.2 Material Selection and Specimen Fabrication

Both asphalt types (AR and PG) and corresponding aggregate gradations were evaluated in laboratory mixed-laboratory compacted (LMLC) specimens as required in a mix design procedure and field mixed (plant mixed)-laboratory compacted (PMLC) specimens. Table 2-1 provides details for each mixture and Table 2-2 and Table 2-3 present aggregate gradations for these specific mixtures. All specimens for both mixture types, AR and PG, were mixed at 163°C and compacted at 149°C. The compaction was performed using the SGC with $N_{design} = 50$ gyrations to dimensions of 115 ± 5 mm in height and 150 mm in diameter.

Table 2-1. Description of Mixtures Used to Assess Volumetric Properties

Mixture	TxDOT District	Asphalt Type	Opt. Asphalt Content, %	Aggregate Type	Other Materials	Specimen Type
I-35-PG	San Antonio	PG 76-22S	6.1	Sandstone Limestone	Lime (1 %) Fibers (0.3 %)	LMLC and PMLC
US-83-PG	Abilene	PG 76-22S	6.4	Limestone		PMLC
IH-20-PG	Abilene	PG 76-22	6.5	Limestone		PMLC
IH-30-PG	Paris	PG 76-22	6.6	Sandstone		PMLC
US-59-PG	Lufkin	PG 76-22	5.9	Granite Limestone		PMLC
US-59Y-PG	Yoakum	PG 76-22S	5.8	Limestone		PMLC
US-281-AR	San Antonio	AC-10 w/16 % crumb rubber	8.1	Sandstone Limestone	None	LMLC and PMLC
US-288-AR	Houston	AC-10 w/17 % Type II rubber	8.0	Granite Limestone	None	PMLC
US-290-AR	Austin	AC-10 w/17 % crumb rubber	8.3	Sandstone	None	PMLC

Table 2-2. Aggregate Gradations for PG Mixtures Used to Assess Volumetric Properties

Sieve	Specification (Passing)		I-35-PG (LMLC)	I-35-PG (PMLC)	US-83-PG	IH-20-PG	IH-30-PG	US-59-PG	US-59Y-PG
3/4	100	100	100	100	100	100	100	100	100
1/2	80	100	89.8	90.3	90.5	85.3	81	80.2	84.5
3/8	35	60	59.5	59.5	50.9	59.4	43	57.7	52.8
#4	1	20	8	10.1	3.2	18.6	15.5	15.9	6.6
#8	1	10	4.8	5.2	1.5	2	6.7	6	4.2
#200	1	4	2.3	2.3	1.1	1.6	2.2	2.1	2.4

Table 2-3. Aggregate Gradations for AR Mixtures Used to Assess Volumetric Properties

Sieve	Specification (% Passing)		US-281-AR (LMLC)	US-281-AR (PMLC)	US-288-AR	US-290-AR
3/4	100	100	100	100	100	100
1/2	95	100	99	99	95.6	99.7
3/8	50	80	54.6	54.6	54.9	75.7
#4	0	8	5	5	4	7.9
#8	0	4	2	1.9	2.1	1.1
#200	0	4	1	1	0.8	0.6

2.4 DETERMINATION OF BULK SPECIFIC GRAVITY OF THE COMPACTED MIXTURE AND WATER-ACCESSIBLE AIR VOIDS CONTENT USING THE VACUUM METHOD AND DIMENSIONAL ANALYSIS

In the vacuum method, the buoyancy principle is used to determine the total volume of a compacted specimen wrapped in a plastic bag subjected and sealed under vacuum. This sample preparation was performed by using the Corelok® device for double large bag testing (InstroTek® 2003), since initial evaluations using a single bag resulted in frequent puncture problems allowing water to flow into the sealed specimen. Based on the vacuum method G_{mb} was calculated as:

$$G_{mb-vacuum} = \frac{W}{W_b + W - W_{bs,w} - \frac{W_b}{CF}} = \frac{W}{V_{tv}} \tag{2-2}$$

where W is the weight of the specimen in air (g), W_b is the weight of the bag in air (g), $W_{bs,w}$ is the weight of the sealed bag and the specimen in water (g), CF represents the double bag correction factor supplied by the manufacturer (InstroTek® 2003) to account for the bag volume, and V_{tv} represents the total volume of the compacted specimen. In addition to G_{mb}, water-accessible AV content can be calculated by measuring the vacuum-saturated weight of the specimen in water (W_{sv}). Measuring W_{sv} (in grams) requires: (*i*) cutting the sealed bag under water, (*ii*) removing the bag from the water tank, and (*iii*) allowing access to water until a stable weight is obtained (i.e., saturation is reached). In these conditions, the volume of solids and unconnected AV (included in the computation of the volume of AV accessible to water) is determined using the buoyancy principle without having to deal with the bag volume as originally indicated (InstroTek® 2003) in the vacuum method. The minimum saturation time used to determine W_{sv} was four minutes, but this time is variable for each mixture. Therefore:

$$Water\ accesible\ AV_{vacuum} = \frac{W_b + W - W_{bs,w} - \left(\frac{W_b}{CF}\right) - (W - W_{sv})}{W_b + W - W_{bs,w} - \left(\frac{W_b}{CF}\right)} \times 100\ (\%) \tag{2-3}$$

A second method for determining G_{mb} is known as dimensional analysis. Instead of referring to the buoyancy principle as in the vacuum method, the dimensional analysis method uses a direct geometrical calculation of total volume assuming that the specimen is a regular cylinder with smooth faces. Calculating the total volume of each specimen involved four diameter and three height measurements using a caliper with a precision of 0.00254 mm. Two diameter measurements were taken at the top and two at the bottom of the specimen, and the height measurements were taken uniformly distributed around the specimen circumference. Average diameter and height were used to define the total volume (V_{td}), expressed in cm^3, used in the dimensional G_{mb} calculated as follows:

$$G_{mb-\dim ensional} = \frac{\frac{W}{V_{td}}}{\rho_w} \tag{2-4}$$

where ρ_w is the density of water (g/cm^3). Specimens were kept for approximately 15 minutes in the mold after compaction to minimize changes of shape that were observed in specimens extracted at shorter times, and dimensions were taken as indicated after allowing the specimens to cool overnight.

Water-accessible AV content can also be calculated in the dimensional analysis method as follows:

$$Water\ accesible\ AV_{\dim ensional} = \frac{V_{td} - \frac{(W - W_s)}{\rho_w}}{V_{td}} \times 100\ (\%) \tag{2-5}$$

where W_s is the saturated sample weight in water (in grams). The dimensional analysis and the vacuum method differ in the determination of water-accessible AV content since the quantification of total volume is different and the saturated weight was redefined for the dimensional procedure as the saturated sample weight in water obtained after direct immersion of the specimen without any vacuum application.

2.5 DETERMINATION OF THEORETICAL MAXIMUM SPECIFIC GRAVITY OF THE MIXTURE

Tex 227-F Theoretical Maximum Specific Gravity of Bituminous Mixtures was the test procedure used to determine G_{mm} at a specific asphalt content (TxDOT 2005). This measured G_{mm} value is also known as Rice Specific Gravity. In addition, Tex 227-F includes a second procedure for the calculation of G_{mm} at other asphalt contents assuming a constant effective specific gravity (G_{se}) for the aggregate. For PFC mixtures, direct measurement of G_{mm} at the design asphalt content generates difficulties given the high asphalt content used, especially for extremely sticky AR mixtures with OAC typically above 8 %. These characteristics of AR mixtures and in general the high asphalt content in PFC mixtures lead to loss of asphalt and some fine granular material (i.e., mineral filler) throughout the methodology used to directly measure G_{mm}.

Thus, a second method that comprises measuring G_{mm} at different lower asphalt contents (i.e., 3 to 5 %) to quantify an average effective specific gravity of the aggregate (G_{se}), and then calculating the G_{mm} at the actual asphalt content used for mix design (6 to 10 %) was assessed. Calculation of G_{se} requires the measured asphalt specific gravity (G_b), asphalt content (P_b), and measured G_{mm}:

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} \tag{2-6}$$

The calculated G_{mm} values for the higher asphalt contents (equal to or greater than 6 %) used for mix design were then determined as follows:

$$Calculated\ G_{mm} = \frac{100}{\frac{100 - P_b}{G_{se}} + \frac{P_b}{G_b}} \tag{2-7}$$

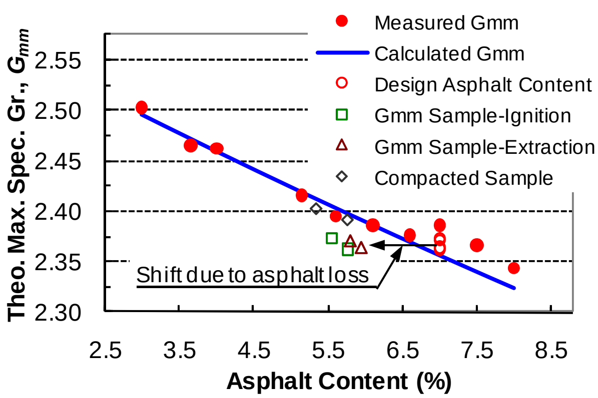
Loose mixture samples used for G_{mm} measurement were oven-cured for two hours at the compaction temperature (149ºC). Afterwards, the mixtures were spread on a clean, non-absorbent surface in a single aggregate layer to cool to room temperature. Next, the mixture was separated by hand as much as possible into individual particles to minimize inter-particle entrapment of air. The weights needed to measure G_{mm} were established using a metal vibratory pycnometer. All the samples used for measuring G_{mm} were obtained from small batches with weights between 6,000 g and 6,500 g. Larger batches with weights between 14,000 g and 17,000 g were used for producing compacted specimens.

2.6 RESULTS AND DISCUSSION

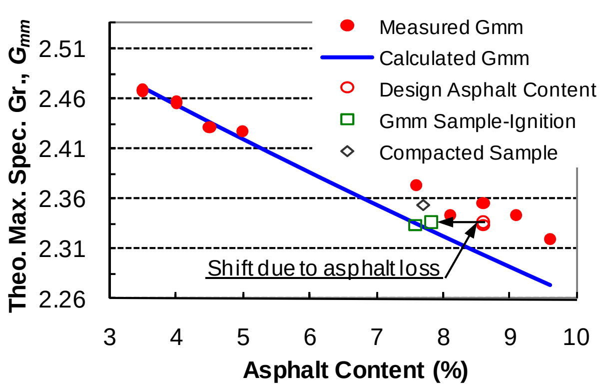
This section presents results of G_{mm}, G_{mb} (in terms of total AV content determinations), additional variability of total AV content in compacted specimens, and an illustration of the effect of the methods used to compute G_{mm} and G_{mb} on the selection of OAC. In addition, this section discusses the results obtained for water-accessible AV content.

2.6.1 Comparison and Variability of Theoretical Maximum Specific Gravity of the Mixture

Figure 2-1 illustrates the differences resulting from the two methods used to determine G_{mm}. The measured G_{mm} values correspond to the average of two or three tests whose difference between individual values meets the maximum difference (0.011) specified by the American Association of State Highway and Transportation Officials (AASHTO) in T 209-05 (AASHTO 2005) for two properly conducted tests. The discrepancy between values of measured G_{mm} and calculated G_{mm} near the OAC range is significant and shows a horizontal shift of asphalt content lost in the G_{mm} measurement process. At asphalt contents lower than 5 %, the mixture is drier and less cohesive and results in less asphalt loss during the G_{mm} measurement process. In the higher asphalt content mixes, which tend to be very sticky, loss of asphalt results when the asphalt sticks to the elements used to handle the mixture during testing.



(a)

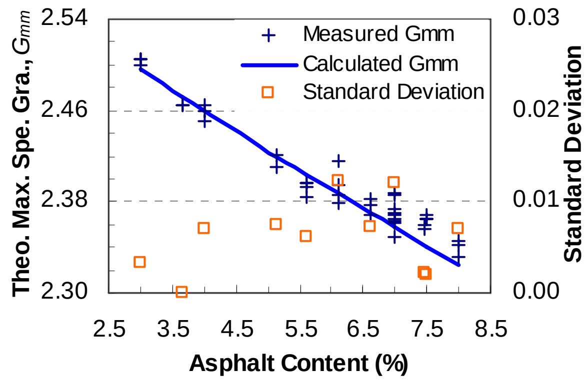


(b)

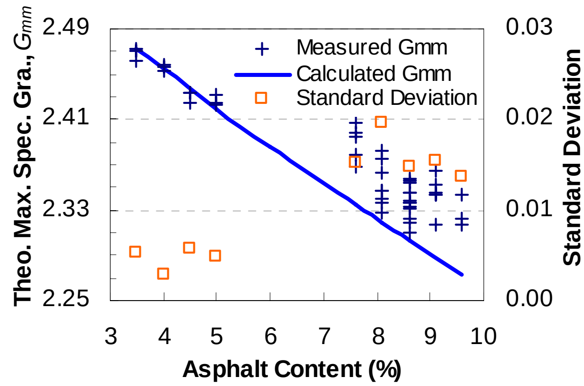
Figure 2-1. Comparison of Theoretical Maximum Specific Gravity (G_{mm}) for (a) I-35-PG and (b) US-281-AR Mixtures

The loss of asphalt was further explored by conducting ignition oven (Tex-236-F) (TxDOT 2005) and extraction (Burr et al. 1993) processes to provide alternate quantification of asphalt content before and after G_{mm} measurement on two types of samples: G_{mm} (loose mix) and compacted mixture. The G_{mm} values for the G_{mm}-Ignition sample and the G_{mm}-Extraction sample were shifted in Figure 2-1 from the target asphalt content to the actual measured asphalt content, which shows that the shifted measured G_{mm} values are relatively close to the calculated G_{mm} magnitudes. These results provide evidence that the horizontal shift (asphalt loss) accounts for the differences between measured G_{mm} and calculated G_{mm}. Data summarized in Figure 2-1 also show that the compacted mixture samples require a minimum shift to match the calculated G_{mm} values compared to that encountered for the smaller G_{mm} samples. This is explained by the differences in asphalt content loss between smaller G_{mm} and compacted mixture samples. These differences come from the effect of the batch size (with the compacted mixture batches at least twice as big in weight as the G_{mm} sample batches) that implies less asphalt loss in total proportion, and from the difference in the degree of mixture handling.

Figure 2-2 shows G_{mm} values for replicate specimens at different asphalt contents and corresponding standard deviations. Both mixtures exhibit smaller variability of measured G_{mm} values at low asphalt contents, which provides additional rationale for recommending calculation of G_{mm} based on an average G_{se} value evaluated at low asphalt contents. In fact, G_{se} values evaluated at low asphalt contents showed smaller variability than those assessed at the design asphalt content. The coefficient of variation (COV) for G_{se} values at low asphalt contents was 0.0028 and 0.0027 for the I-35-PG and US-281-AR mixtures, respectively, whereas the COV for G_{se} values at high asphalt contents was, respectively, 0.0076 and 0.0068 for the I-35-PG and US-281-AR mixtures. These COV were computed using average G_{se} values determined using data from a minimum of three replicate specimens at each of four low asphalt contents and a minimum of five high asphalt contents for each mixture type. In summary, calculation of G_{mm} is recommended over measured G_{mm} since the former procedure showed to have less variability and the error associated with the loss of asphalt is reduced providing results that are more accurate. In addition, producing and handling low asphalt content mixtures in the laboratory is straightforward.



(a)



(b)

Figure 2-2. Variability of Theoretical Maximum Specific Gravity (G_{mm}) for (a) I-35-PG and (b) US-281-AR Mixtures

2.6.2 Bulk Specific Gravity of the Compacted Mixture and Total Air Voids Content

Figure 2-3 defines four zones to distinguish the differences in total AV content values when dimensional analysis and the vacuum method are used to determine corresponding values of G_{mb} and the AV computation is based on measured G_{mm} and calculated G_{mm} values. Zones III and IV contained all data presented in Figure 2-3 gathered from LMLC specimens produced at different asphalt contents. These results show that in all cases the total AV content values determined from dimensional analysis are higher than those obtained from the vacuum method (a similar conclusion was obtained for PMLC specimens), which is expected due to the inclusion of all surface AV in the dimensional analysis. In most cases, the total AV content obtained from calculated G_{mm} values are less than those established based on measured G_{mm} values.

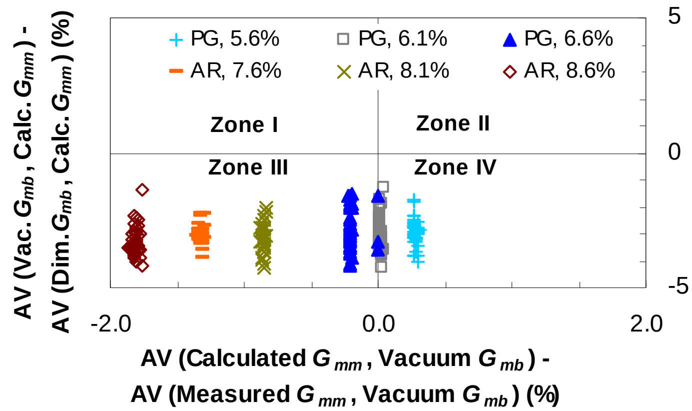


Figure 2-3. Comparison of Total Air Voids (AV) Content Based on Different Bulk Specific Gravity (G_{mb}) and Theoretical Maximum Specific Gravity (G_{mm}) Calculations for I-35-PG and US-281-AR Mixtures

The difference in total AV content values calculated using the vacuum method and dimensional analysis ranges from 1.3 to 4.3 percentage points (with a COV equal to -0.20 and -0.15 for the I-35-PG and US-281-AR mixtures, respectively) for LMLC specimens. Similar calculations for PMLC specimens showed that these differences were between 2.5 and 4.8 percentage points (COV of 0.14 and 0.15 for PG and AR mixtures, respectively), and differences between 3.1 and 10.8 percentage points (COV of 0.32 and 0.39 for PG and AR mixtures, respectively) were found for road cores extracted from the mixtures listed in Table 2-1.

This variability in the difference between total AV content values computed by dimensional analysis and the vacuum method, limitations observed to correlate these differences, and the potential effect of these differences in selecting the OAC (subsequently illustrated in this paper) suggested the necessity of recommending one specific method to design and conduct consistent mixture quality control. This approach is therefore preferred over suggesting minimum total AV content values for designing with either dimensional analysis or the vacuum method as previously recommended by Watson et al. (2004a).

Computation of G_{mb} using dimensional analysis presents several advantages (compared to the vacuum method). This methodology is simpler, faster, and less expensive. The required equipment is readily available, additional testing supplies are not needed, and environmental disposal of the vacuum bags is also not required. In addition, total AV content values obtained by dimensional analysis can be directly used as primary inputs to analyze images from X-ray

Computed Tomography scanning to study the internal structure of PFC mixtures (Alvarez et al. 2009a). Additional discussion on this particular application is beyond the scope of this paper.

A discussion on G_{mb} test accuracy requires defining the true value of total volume of a compacted specimen because determination of the specimen weight is straightforward. Although different methods have been proposed to compute G_{mb} (ultimately, to compute the total volume), there is not current consensus on the most accurate method to study PFC mixtures. Therefore, a brief discussion on test accuracy for the methodologies assessed in this study is subsequently stated in terms of their discrepancies and adequacy of using either dimensional analysis or the vacuum method to determine the total volume of compacted PFC mixtures. The differences in total volume values obtained using these methods are due to discrepancies in: (*i*) the quantification of surface AV (AV in contact with the specimen surface) and (*ii*) the capacity to capture major geometrical deviations (not related to the irregularities created by the surface AV) in the shape of the specimen with respect to a regular cylinder.

Dimensional analysis includes all surface AV since the compacted specimen is assumed as a regular cylinder with smooth faces. In the vacuum method the particular stiffness of the bag used can be the main variable defining the shape of the bag surrounding each surface AV and, therefore, the proportion of each surface AV that is included as part of the total volume. Taking into account that the surface AV should be included in the computation of total AV content as long as they form part of the actual internal structure of PFC mixtures, dimensional analysis may provide a more representative mixture characterization as compared to that obtained using the vacuum method. However, the vacuum method may be able to better capture major geometrical deviations in the shape of the specimen with respect to a regular cylinder. This can be especially important in evaluating road cores whose surface texture is not always completely regular. Proper practices for coring and fabricating gyratory compacted specimens (or SGC specimens) can minimize the existence of shape distortions, which would minimize corresponding differences in the computation of total volume obtained by dimensional analysis and the vacuum method.

Based on the previous discussion of the advantages and test accuracy, dimensional analysis is recommended over the vacuum method. In addition, based on the results of this study and for practical reasons for routine application, diameter measurements at the top, bottom and center of the specimens are recommended to further improve the accuracy of the total volume determination. Furthermore, direct measurement of dimensions was preferred over the height reported by the SGC and the nominal mold diameter, since expansion in the vertical direction (measured after cooling overnight) was noted, especially for AR mixtures. These differences in height led, for example, to total AV content discrepancies up to three percentage points in LMLC specimens of the US-281-AR mixture.

2.6.3 Additional Variability of Total Air Voids Content in Compacted Specimens

In addition to variability introduced in the determination of G_{mm} and G_{mb} and differences in total AV content values generated by different determination methods for G_{mm} and G_{mb}, the compaction process and the handling of hot compacted specimens influence the volumetric properties of laboratory compacted specimens of PFC mixtures, probably even more than in dense-graded HMA. Table 2-4 summarizes the average total AV content and respective standard deviations obtained per batch for two types of specimens compacted in the laboratory to evaluate functionality and durability. Using these batches, LMLC specimens with identical asphalt contents were produced targeting different total AV content values, which implies different weights of compacted mixture since the number of gyrations in the SGC was fixed at 50 according to the current design specification (TxDOT 2005).

The data included in Table 2-4 suggest first that the relationship between the target AV content (or in other words the weight of the mixture) and the total AV content obtained in compacted specimens does not always exhibit a 1:1 correspondence. Second, additional variability is induced in the selection of the OAC (when this selection is based exclusively on total AV content computations or corresponding densities) due to the variability of the total AV content measured on replicate specimens required for mix design. In fact, the total AV content values of shorter specimens (57 mm and 61 mm) exhibited higher average COV, evaluated for each asphalt content, as compared to the total AV content values obtained for larger specimens (115 mm) in height (conventionally used for mix design), except at the intermediate asphalt content evaluated (8.1 %). The higher variability in the shorter specimens led to greater difficulty fabricating replicates of these shorter specimens compared to the production of larger specimens. Allowing the specimens to cool down for approximately 15 minutes in the mold after compaction to minimize changes of shape that were observed in specimens extracted at shorter times helped to minimize the variability of total AV content values for replicate specimens produced as part of this study.

Table 2-4. Variability of Total Air Voids (AV) Content for US-281-AR Mixture

Specimen	Asphalt Content, %	Target AV SGC, %	Total No of Specimens	Average of Total AV[a], %	Stand. Dev. of Total AV	Coefficient of Variation
114 mm[b]	7.6	18.5	3	18.9	0.57	3.01
	7.6	18.5	4	18.4	0.29	1.60
	7.6	18.5	4	19.3	0.38	1.96
	7.6	19.5	3	21.3	0.57	2.67
	7.6	19.5	3	18.7	0.46	2.47
	8.1	20.0	3	19.4	0.26	1.36
	8.1	20.0	3	18.3	0.27	1.46
	8.1	22.0	2	20.0	0.92	4.61
	8.1	22.0	4	19.5	0.08	0.42
	8.1	22.0	4	19.3	0.51	2.62
	8.1	22.0	2	18.3	0.07	0.39
	8.1	22.5	3	19.3	1.05	5.43
	8.1	22.5	3	19.1	0.06	0.30
	8.6	25.0	3	19.6	0.50	2.58
	8.6	25.0	4	18.3	0.93	5.07
	8.6	25.5	4	19.3	0.95	4.92
	8.6	25.5	3	19.3	0.22	1.14
	8.6	26.0	3	17.3	0.50	2.90
	8.6	26.0	4	18.2	0.53	2.93
57 mm and 61 mm[b]	7.6	21.0	2	23.2	0.07	0.31
	7.6	21.0	2	21.7	1.48	6.86
	8.1	24.0	2	19.6	0.28	1.44
	8.1	24.0	2	21.4	0.07	0.33
	8.1	26.0	2	23.2	0.42	1.83
	8.1	26.0	2	21.2	0.49	2.34
	8.6	21.5	2	20.2	1.48	7.37
	8.6	21.5	2	20.0	0.49	2.48

[a] The total AV content was computed using calculated G_{mm} and G_{mb} measured by applying the vacuum method.
[b] Height tolerances were 115 ± 5 mm, 62 ± 2 mm, or 57 mm.

This evaluation provides evidence of an additional source of variability involved in the selection of OAC related to the particular characteristics of PFC mixtures. Although average values of total AV content computed from two replicate specimens compacted at each trial asphalt content are included for current PFC mix design (TxDOT 2005) to reduce the random error, additional research may be required to better take into account this source of variability into the mix design method.

2.6.4 Effects on Optimum Asphalt Content Selection

Based on the results in Figure 2-3, the use of measured G_{mm} values and the vacuum method to determine G_{mb} values may result in substantial changes in OAC or in a significant portion of specimens fabricated being rejected for subsequent mixture testing due to total AV content values outside the specification (18-22 %). This conclusion depends on the assumption that the calculated G_{mm} and dimensional analysis provide the best methods to determine total AV content in PFC mixtures as the previous discussion suggested. Figure 2-4 shows an indication of the possible effect of the method used to determine G_{mm} and G_{mb} on the OAC calculation for both the I-35-PG and US-281-AR mixtures when a design total AV content of 20 % is used.

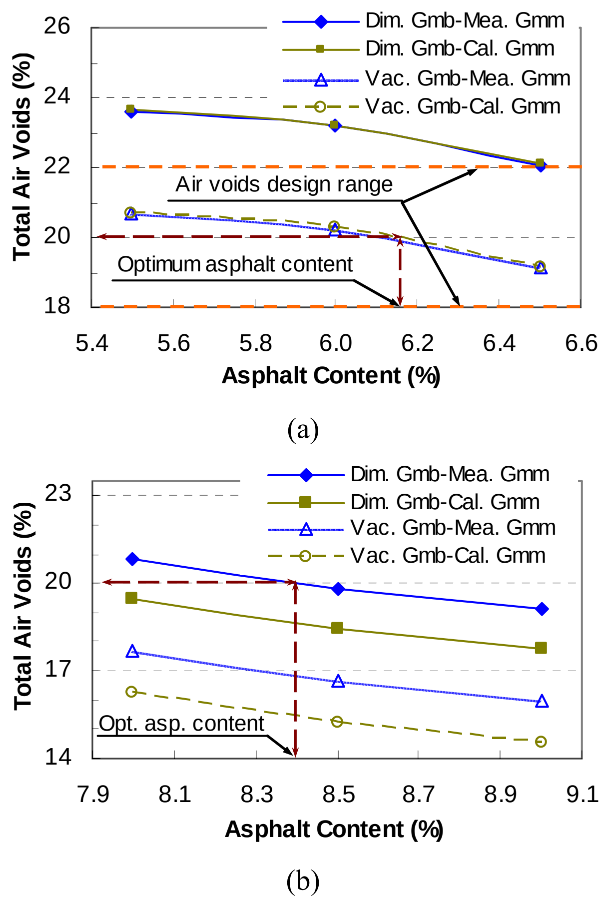


Figure 2-4. Effect of Volumetric Parameters on Optimum Asphalt Content (OAC) Selected at 20 % Total Air Voids (AV) Content for (a) I-35-PG and (b) US-281-AR Mixtures

The effect of the G_{mb} method in both mixtures is significant. In fact, when the G_{mb} method is changed (with respect to that used for the mix design), the OAC becomes undefined for both mixtures since the total AV content is higher than 22 % or less than 18 %, which implies the necessity of gradation modifications or changing fiber content to meet AV requirements. The procedure used to determine G_{mm} has more of an effect on the AR mixture as compared to the PG mixture. In fact, no modification is indicated on the OAC established in the original design for the I-35-PG mixture. Conversely, the use of calculated G_{mm} values for the US-281-AR mixture leads to values of total AV content that do not allow defining an OAC at a total AV content of 20 %. Since the minimum asphalt content specified for AR mixtures is 8 %, these results imply the necessity of modifying the aggregate gradation to meet the indicated AV requirement. This analysis does not account for the variability in total AV content values associated with determinations conducted on replicate specimens.

2.6.5 Water-Accessible Air Voids Content

Figure 2-5 suggest the existence of a linear relationship between water-accessible AV content and total AV content values determined on PMLC specimens using either the vacuum method or dimensional analysis to establish both G_{mb} and water-accessible AV content. This linear relationship is better defined for PG mixtures than for AR mixtures. Similar conclusions were obtained for the same relationship defined for LMLC specimens, and preliminary evidence in the same direction was found by evaluating corresponding road cores of these plant and laboratory mixtures. Approximately equal water-accessible AV content values were reported from dimensional analysis compared to those calculated using the vacuum method for PMLC specimens, but for road cores the water-accessible AV content computed using dimensional analysis were in some cases higher than those calculated applying the vacuum method. These differences are related at least to the combined effect of smaller saturated weight and higher total volume computed by dimensional analysis.

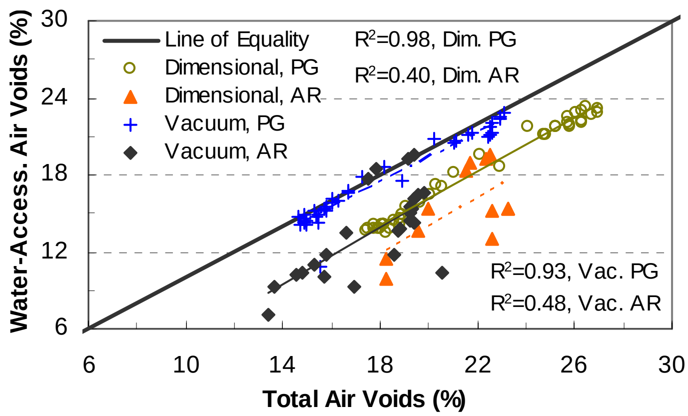
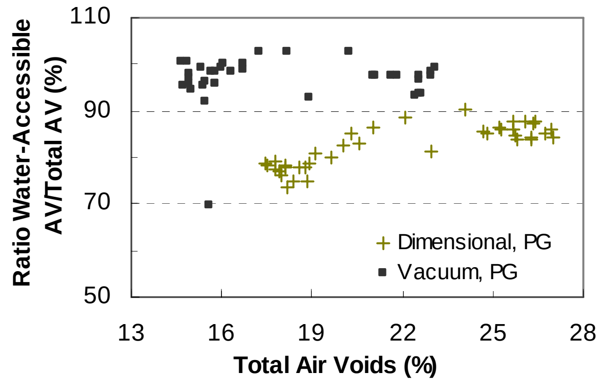
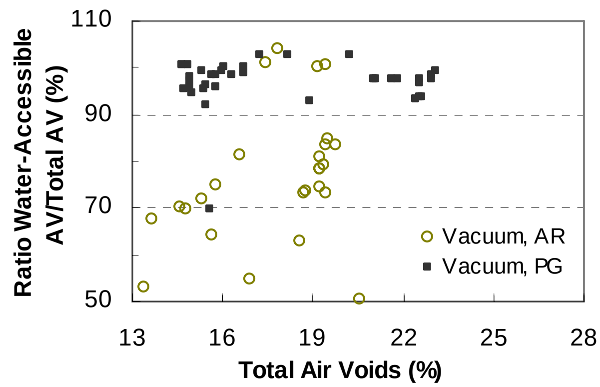


Figure 2-5. Comparison of Water-Accessible Air Voids (AV) Content and Total Air Voids Content for Plant Mixture (PMLC) Specimens

Figure 2-6 shows the ratio of water-accessible AV content to total AV content values for PMLC specimens. This data set suggests that most of the AV present in the mixture are water-accessible, and that in general, higher ratio of water-accessible AV content to total AV content values were obtained for: (*i*) PG mixtures as compared to AR mixtures and (*ii*) by the vacuum method as compared to dimensional analysis. Furthermore, some of the ratios computed based on the vacuum method were higher than 100 %. This can be partially explained by the fact that the total AV content of all the PMLC specimens required to be calculated using measured G_{mm} magnitudes. This aspect induced some variability in total AV content calculations. The large water-accessible AV content values obtained using the vacuum method may also be related to micro-damage induced in the specimen when it is subjected to a vacuum during the testing process. The occurrence of this type of damage was stated by Masad et al. (2007) when studying dense-graded HMA. This micro-damage will increase the AV connectivity and therefore the measured water-accessible AV content. This damage would also negatively affect any subsequent durability evaluation.



(a)



(b)

Figure 2-6. Comparison of Water-Accessible Air Voids (AV) Content to Total Air Voids Content Ratio Computed by Dimensional Analysis and the Vacuum Method (a) and for AR and PG Mixtures (b)

Computation of water-accessible AV content using dimensional analysis is preliminarily recommended for similar reasons to those indicated when comparing dimensional analysis and the vacuum method for G_{mb} determinations. In addition, the limited differences in water-accessible AV content values computed by dimensional analysis and the vacuum method suggest the possibility of applying the simpler dimensional analysis, although the ratios of water-accessible AV content to total AV content differ. Additional research may be required to establish if a vacuum is necessary to obtain a representative saturated weight in PFC mixtures and to establish the magnitude of the vacuum that may be needed to obtain saturation without inducing micro-damage in the specimen.

Previous research (Alvarez et al. 2008b) provided evidence of improved correlation between drainability and durability parameters measured in the laboratory for PFC mixtures and values of water-accessible AV content as compared to that obtained using values of total AV content. Detailed information on these correlations is beyond the scope of this paper. However, these preliminary findings suggest the possibility of exploring the use of water-accessible AV content as an alternative parameter to integrate in mixture design and evaluation in both the laboratory and the field.

2.7 SUMMARY AND RECOMMENDATIONS

Based on the results and discussion presented, the following conclusions are offered:

- Dimensional analysis, conducted as suggested in this paper, is recommended over the vacuum method to compute G_{mb} in PFC mixtures. The difficulties encountered to account for the differences in total AV content computed based on dimensional analysis and the vacuum method led to recommend only dimensional analysis to determine G_{mb} as a way to guarantee consistent evaluations of total AV content.
- The procedure explained in this paper to calculate the G_{mm} values based upon laboratory measurements for samples produced at low asphalt content (i.e., 3 to 5 %) was shown to be more reliable and accurate. Thus, this procedure is recommended for mix design and volumetric evaluation in both the laboratory and the field. The results obtained in this research suggest that the differences in values of total AV content computed using measured G_{mm} and calculated G_{mm} can be higher in AR mixtures compared to those in PG mixtures.
- Given the differences in total AV content computed using the recommended methodologies (dimensional analysis and calculated G_{mm}) and the methodologies currently used (vacuum method, dimensional analysis, and measured G_{mm}), corresponding density specifications for mix design should be modified from 78-82 % to 76-80 %. Adequate drainability and durability are expected for mixtures designed using this modified specification. However, future research is recommended to verify the adequacy of this specification.
- Dimensional analysis was preliminarily recommended for computing the water-accessible AV content of PFC mixtures. Higher ratios of water-accessible AV content to total AV content values obtained for PG mixtures compared to those established for AR mixtures, may suggest differences in the functionality and durability response of these mixtures.

- Since the current design practice for selecting the OAC in several agencies is still based only on volumetric mixture properties, reproduction of mix-design density in the field should be required as a minimum parameter of quality control related to mixture compaction. Current practice in most agencies does not include field density as a mixture placement requirement since compaction is easily facilitated and patching of cored sections with dense-graded HMA may cause localized clogging. However, additional research is required on this topic since inadequate compaction may limit both durability and functionality.

The following recommendations are provided based on the conclusions and analysis developed from data gathered during this study:

- Use dimensional analysis for determining G_{mb} of PFC mixtures. However, additional research is recommended to assess the variability of this test method.
- Measure G_{mm} at two low asphalt contents (i.e., 3.5 % and 4.5 % are suggested) to determine the average G_{se} of the aggregate, then calculate G_{mm} at the actual asphalt content at the design range for establishing total AV content.
- Include durability mixture testing in PFC mix design in addition to volumetric criteria, since the modifications necessary to meet volumetric criteria also affect durability. Additional research is required to recommend the durability test that should be used to evaluate durability in PFC mixtures.

3. CONNECTED AIR VOIDS CONTENT IN PERMEABLE FRICTION COURSE MIXTURES*

3.1 OVERVIEW

Current HMA mix design methods used to determine the OAC for PFC mixtures are based primarily on total AV content. Durability and functionality of PFC mixtures are also related to the total AV content. However, the connected AV content (defined as the proportion of AV that form connected pathways for air and water transport through PFC mixtures) may provide more insight into the mixture structure in terms of the AV content directly associated with functionality and durability properties and constitute an alternative parameter to conduct PFC mix design and evaluation. This study evaluated two laboratory methodologies (vacuum and dimensional analysis) for determining water-accessible AV content and two types of analysis to compute interconnected AV content based on X-ray Computed Tomography (X-ray CT) and image analysis techniques. Although both the interconnected AV content and water-accessible AV content constitute determinations of connected AV content, different nomenclature was used to differentiate the origin of the calculation. Dimensional analysis with application of vacuum and X-ray CT and image analysis with inclusion of surface AV are recommended for determining water-accessible AV content and interconnected AV content, respectively. Future work should focus on investigating the use of connected AV content as an alternative parameter to integrate in mix design and laboratory and computational evaluation of PFC mixtures.

3.2 INTRODUCTION

PFC, or new generation OGFC, are special asphalt concrete mixtures characterized by a high AV content (minimum 18 %) as compared to the most commonly used dense-graded HMA. Placed as a thin surface layer, the PFC mixture reduces the risk of hydroplaning and wet skidding, decreases splash and spray, and improves visibility of pavement markings in wet weather (Alvarez et al. 2006). These benefits are realized as water travels through connected AV within the mixture instead of over the surface. Consequently, driving safety is greatly improved, especially in wet weather. In addition, compared to dense-graded HMA, PFC offers better riding

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quality, cleaner runoff, and reduction of pavement noise (Button et al. 2004; Kearfott et al. 2005; Ruiz et al. 1990). These advantages make PFC the safest, cleanest, and quietest alternative currently available for surface paving.

The current mix design method used to obtain the OAC of PFC mixtures is based on volumetric properties, primarily density (or corresponding total AV content). This AV content is also directly related to both functionality (in terms of drainability and noise reduction properties) and durability (in terms of resistance to raveling and permanent deformation) of PFC mixtures. However, previous research (Alvarez et al. 2008b) provided evidence of better correlation between parameters of drainability and durability measured in the laboratory for PFC mixtures and values of connected AV content (i.e., water-accessible AV content) as compared to that obtained using values of total AV content.

The water-accessible AV content is defined as the proportion of the total volume of a compacted mixture that is accessible to water. This AV content is considered an alternative volumetric parameter (with respect to the total AV content) that can be used in the future for mix design and evaluation, because it may provide more insight into the mixture structure in terms of the AV directly associated with functionality and durability properties. As a volumetric parameter related to mixture functionality, the water-accessible AV content constitutes an indication of the proportion of AV that form connected pathways for air and water transport through PFC mixtures. From the durability point of view, the water-accessible AV content may be understood as the proportion of AV that constitutes connected pathways of mixture discontinuities that could initiate mixture disintegration if they act as potential interconnected fracture paths.

Special characteristics of PFC mixtures encourage additional investigation of alternative methodologies (with respect to those applied for characterizing dense-graded HMA) to determine the connected AV content. These characteristics include high values of total AV content, the amount and size of AV located at the surface, and the impossibility of obtaining representative results associated with saturated surface dry measurements. Previous research by Watson et al. (2003) studied the computation of water-accessible AV content in OGFC mixtures by applying the vacuum method (InstroTek® 2003). However, final recommendations were not indicated in terms of the laboratory methodology to apply for determining this volumetric property. Alvarez et al. (2009d) preliminarily recommended the method of dimensional analysis, over the vacuum method, to calculate the water-accessible AV content of PFC mixtures.

This study aims to continue the investigation on the computation of connected AV content in compacted PFC mixtures. For this purpose, the study assessed: (*i*) two laboratory techniques applied for computing water-accessible AV content to select the one most appropriate for mix design and evaluation and (*ii*) the similarity of water-accessible AV content values (computed using the selected laboratory test) and interconnected AV content values, calculated by applying X-ray CT and image analysis techniques.

Laboratory techniques applied to compute the water-accessible AV content were a proposed methodology for dimensional analysis and the vacuum method (InstroTek® 2003). The interconnected AV content (as calculated in this study) is the proportion of the total volume of a compacted mixture that forms void-connected paths from top to bottom of a compacted specimen. Application of X-ray CT and image analysis techniques allows characterizing the mixture in terms not only of the interconnected AV content, but also of the AV distribution. Although the interconnected AV content is related to the water-accessible AV content, different nomenclature was used throughout the paper to differentiate the origin of the calculation. Following a statement of the objective and methodology, the paper contains details on the experimental design, a description of the procedures applied to calculate the connected AV content, and results and discussion. A summary and recommendations complete the paper.

3.3 OBJECTIVE AND METHODOLOGY

The overall objective of this study focused on the assessment of techniques applied to quantify connected AV content in PFC mixtures, which include both laboratory tests and X-ray CT and image analysis techniques. The study included the following steps to analyze mixtures compacted in the field and in the laboratory:

- Laboratory determination of parameters required to calculate total AV content values, which were used: (*i*) as an input in the first stage of image analysis as subsequently discussed and (*ii*) to establish comparisons of water-accessible AV content and total AV content values.
- Determination of water-accessible AV content, computed in the laboratory by applying dimensional analysis and the vacuum method, and corresponding analysis to recommend one of these methods.
- X-ray CT scanning and application of image analysis techniques to compute total AV content and interconnected AV content and comparison of results with those obtained directly from laboratory measurements.

3.4 EXPERIMENTAL DESIGN

This section presents the experimental design defined for this study, which includes mix design, material requirements, material selection, specimen fabrication, and laboratory testing.

3.4.1 Mix Design and Material Requirements

Mix design was carried out according to the current TxDOT PFC mix design method (TxDOT 2005). Corresponding material specifications include master aggregate gradation bands for each of the following two types of asphalt binders allowed for PFC mixtures (TxDOT 2004):

- a Type I or II AR with a minimum of 15 % by weight of virgin asphalt of Grade C or Grade B crumb rubber. The grades C and B refer to the gradation of the crumb rubber as defined in Item 300.2.G (TxDOT 2004).
- a PG asphalt with a minimum high temperature grade of PG76-XX with a minimum of 1.0 % by weight of dry aggregate of lime and a minimum of 0.2 % by weight of mixture of cellulose or mineral fibers.

3.4.2 Material Selection and Specimen Fabrication

Road cores and PMLC specimens from nine PFC mixtures produced in the field (plant mixed) and used in actual field projects were employed in this study. Fabrication of PMLC specimens required reheating the mixtures to the compaction temperature (149°C) and applying 50 gyrations of the SGC as currently specified for mix design (TxDOT 2005). Table 3-1 provides details of the materials used to produce each of these mixtures, and Table 3-2 shows corresponding aggregate gradations.

Table 3-1. Description of Mixtures Used to Assess Connected Air Voids (AV) Content

Mixture	TxDOT District	Asphalt Type	Opt. Asphalt Content, %	Aggregate Type	Other Materials
I-35-PG	San Antonio	PG 76-22S	6.1	Sandstone Limestone	Lime (1 %), CF (0.3 %)
US-83-PG	Abilene	PG 76-22S	6.4	Limestone	Lime (1 %), CF (0.3 %)
IH-20-PG	Abilene	PG 76-22	6.5	Limestone	Lime (1 %), CF (0.3 %)
IH-30-PG	Paris	PG 76-22	6.6	Sandstone	Lime (1 %), CF (0.3 %)
US-59-PG	Lufkin	PG 76-22	5.9	Granite Limestone	Lime (1 %), CF (0.3 %)
US-59Y-PG	Yoakum	PG 76-22S	5.8	Limestone	Lime (1 %), CF (0.3 %)
US-281-AR	San Antonio	Type II AR, Grade B (AC-10 w/16 % CR)	8.1	Sandstone Limestone	None
US-288-AR	Houston	Type II AR, Grade B (AC-10 w/17 % CR)	8.0	Granite Limestone	None
US-290-AR	Austin	Type II AR, Grade B (AC-10 w/17 % CR)	8.3	Sandstone	None

Legend: CF = cellulose fibers; AR = Asphalt rubber; CR = crumb rubber.

Table 3-2. Aggregate Gradations for PG and AR Mixtures Used to Assess Connected Air Voids (AV) Content

Sieve	Specification (% Passing)		I-35-PG	I-30-PG	I-20-PG	US-83-PG	US-59-PG	US-59Y-PG	Specification (% Passing)		US-281-AR	US-288-AR	US-290-AR
¾	100	100	100	100	100	100	100	100	100	100	100	100	100
½	80	100	90.3	81	85.3	90.5	80.2	84.5	95	100	99	95.6	99.7
3/8	35	60	59.5	43	59.4	50.9	57.7	52.8	50	80	54.6	54.9	75.7
#4	1	20	10.1	15.5	18.6	3.2	15.9	6.6	0	8	5	4	7.9
#8	1	10	5.2	6.7	2	1.5	6	4.2	0	4	1.9	2.1	1.1
#200	1	4	2.3	2.2	1.6	1.1	2.1	2.4	0	4	1	0.8	0.6

3.4.3 Laboratory Testing

The laboratory assessment was conducted on replicate PMLC specimens and road cores subjected to the following sequence of testing: (*i*) X-ray CT scanning, (*ii*) G_{mb} and water-accessible AV content computation by dimensional analysis, and (*iii*) G_{mb} and water-accessible AV content computation by applying the vacuum method. The X-ray CT system at Texas A&M University was used for nondestructive three-dimensional imaging of the internal structure of compacted mixtures including two PMLC specimens and two road cores of each mixture. Information on the X-ray CT principles is documented elsewhere (Masad 2004).

3.5 LABORATORY COMPUTATION OF TOTAL AIR VOIDS CONTENT AND WATER-ACCESSIBLE AIR VOIDS CONTENT

Total AV content expressed as a percent of the total volume in a compacted HMA mixture is calculated as follows:

$$Total\ \ AV\ content\ (\%) = \frac{G_{mm} - G_{mb}}{G_{mm}} \times 100 \tag{3-1}$$

where G_{mm} is the theoretical maximum specific gravity of the mixture and G_{mb} is the bulk specific gravity of the compacted mixture. Computation of G_{mm} at a specific asphalt content was conducted according to Tex 227-F Theoretical Maximum Specific Gravity of Bituminous Mixtures (TxDOT 2005). Additional discussion on the determination of G_{mm} for PFC mixtures is documented elsewhere (Alvarez et al. 2009d).

Table 3-3 summarizes the equations applied for calculating G_{mb} and water-accessible AV content using both the vacuum method and dimensional analysis. The parameters included in the vacuum method computations are: (*i*) weight of compacted specimen in air, W (g), (*ii*) weight of bag in air, W_b (g), (*iii*) weight of sealed bag and specimen in water, $W_{bs,w}$ (g), (*iv*) correction factor supplied by the manufacturer (InstroTek® 2003) to account for the bag volume, *CF*, and (*v*) vacuum-saturated weight of the specimen in water, W_{sv} *(g)*. In these computations, the density of water (ρ_w) is 1 g/cm^3, and V_{tv} is the total volume of the specimen. Dimensional analysis includes the following additional parameters: (*i*) total volume of regular cylinder from average height and diameter, V_{td} (cm^3) and (*ii*) saturated weight of the specimen in water determined without application of vacuum, W_s (g).

Table 3-3. Equations Used to Compute Bulk Specific Gravity (G_{mb}) and Water-Accessible Air Voids (AV) Content

Method	Parameter	Equation	
Vacuum	Bulk Specific Gravity of Compacted Mixture	$G_{mb\ vac} = \dfrac{W}{W_b + W - W_{bs,w} - \dfrac{W_b}{CF}} = \dfrac{W}{V_{tv}}$	(3-2)
	Water-Accessible AV Content	$Acces\ AV_{vac} = \dfrac{W_b + W - W_{bs,w} - \left(\dfrac{W_b}{CF}\right) - (W - W_{sv})}{W_b + W - W_{bs,w} - \dfrac{W_b}{CF}} \times 100$	(3-3)
Dimensional Analysis	Bulk Specific Gravity of Compacted Mixture	$G_{mb\ \dim} = \dfrac{\dfrac{W}{V_{td}}}{\rho_w}$	(3-4)
	Water-Accessible AV Content	$Acces\, AV_{\dim\ no\ vacuum} = \dfrac{V_{td} - \dfrac{(W - W_s)}{\rho_w}}{V_{td}} \times 100$	(3-5)
	Water-Accessible AV Content-With Application of Vacuum	$Acces\, AV_{\dim\ vacuum} = \dfrac{V_{td} - \dfrac{(W - W_{sv})}{\rho_w}}{V_{td}} \times 100$	(3-6)

Computation of total volume (V_{tv}) to determine both G_{mb} and water-accessible AV content using the vacuum method is based on the buoyancy principle. For this purpose, a compacted specimen is wrapped in a plastic bag subjected and sealed under 29.7 in. Hg (1 atmosphere) of vacuum. This sample preparation was carried out by using the Corelok® device for double large bag testing (InstroTek® 2003). In addition, calculation of water-accessible AV content includes determining W_{sv} after completing the measurements needed to compute G_{mb} (InstroTek® 2003). In this study, measuring W_{sv} required: (*i*) cutting the sealed bag under water, (*ii*) removing the bag from the water tank, and (*iii*) allowing access to water until a stable weight is obtained. Under these conditions, the vacuum applied to seal the bag affects the process of sample saturation and the volume of solids and unconnected AV (included to compute the volume of AV accessible to water in the numerator of Equation 3-3) is determined using the buoyancy principle without the bag volume as originally indicated (InstroTek® 2003) in the vacuum method. The minimum saturation time used to determine W_{sv} was four minutes, but this time is variable for each mixture.

Calculation of total volume (V_{td}) to determine both G_{mb} and water-accessible AV content by dimensional analysis uses a direct geometrical computation assuming that the gyratory compacted specimen is a regular cylinder with smooth faces. Calculating the volume of each specimen in this study involved four diameter and three height measurements using a caliper with a precision of 0.00254 mm. Two diameter measurements were taken at the top and two at the bottom of each specimen, and the height measurements were uniformly distributed around the specimen circumference. Average diameter and height were used to define the total volume used in the dimensional G_{mb} calculation. Once completing the measurements required to compute G_{mb}, determination of W_s to calculate water-accessible AV content was carried out by direct immersion of the specimen to allow access to water until a stable weight (W_s) was obtained. This procedure defined the inputs needed to compute water-accessible AV content by dimensional analysis (Equation 3-5). However, for analysis purposes, the water-accessible AV content calculated by dimensional analysis with application of vacuum was computed by replacing W_s in Equation 3-5 by W_{sv} (measured using the vacuum method) as presented in Equation 3-6.

3.6 USE OF X-RAY COMPUTED TOMOGRAPHY AND IMAGE ANALYSIS TECHNIQUES TO DETERMINE THE TOTAL AIR VOIDS CONTENT AND INTERCONNECTED AIR VOIDS CONTENT

Computerized images acquired using X-ray CT were taken along the height of each specimen with a vertical gap of 1 mm. The pixel size was approximately 0.17 mm leading to a voxel size of 0.17 by 0.17 by 1 mm. This pixel size defines the scale used to compute the interconnected AV content. The analysis of these images included two stages. The first stage consisted of processing grayscale images to match: (*i*) the average value of total AV content computed for these images and (*ii*) the value of total AV content calculated in the laboratory for the corresponding compacted specimen. The second stage involved computing the interconnected AV content.

The first stage of image analysis was conducted by applying a macro developed using Image-Pro® Plus (Masad et al. 2007) that converts the original grayscale images to black and white compositions, where black is assigned to the voids and white represents the aggregates and the mastic. This conversion is executed based on a user-input threshold value between 0 and 56,000. Once the user defines the threshold value, the macro assigns a value of zero when the measured gray intensity is less than the indicated threshold (representing the voids), and a value of 256 if the gray intensity is higher than the threshold (representing the aggregates and the mastic). The final threshold value is established by matching the value of total AV content determined in the laboratory and the average value of total AV content computed for the set of images analyzed. Figure 3-1 shows one grayscale image and the outputs obtained after processing it. The first output (Figure 3-1[b]) corresponds to the black and white image obtained after applying the threshold value. The second and third outputs (Figure 3-1[c] and Figure 3-1[d]) correspond to images obtained after the analysis of interconnected AV, subsequently described, performed by excluding and including the AV that are in contact with the lateral surface (or surface AV), respectively.

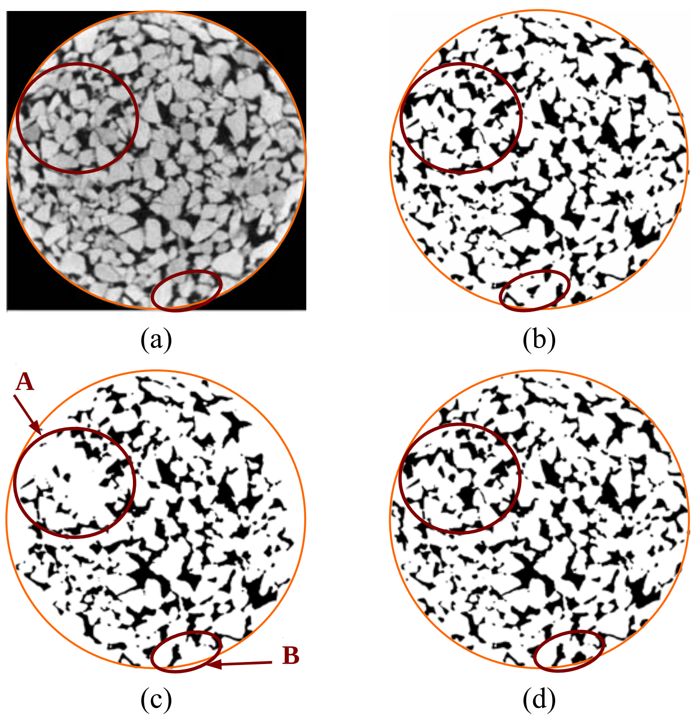


Figure 3-1. X-ray CT Image Analysis (a) Original Grayscale Image, (b) Black and White Image after Threshold, (c) Interconnected Air Voids (AV) Without Including Surface AV, and (d) Interconnected AV Including Surface AV

The total AV content of each black and white image (AV_i) and the total AV content of a specimen (AV_s) were computed as follows using a second macro previously developed by Masad et al. (2007) using Image-Pro® Plus:

$$AV_i = \frac{A_{vi}}{A_T} \tag{3-7}$$

$$AV_s = \frac{\sum_{i=1}^{n} \% AV_i}{n} \tag{3-8}$$

where A_{vi} is the area of AV in image i, A_T is the cross-sectional area of the image i, and n is the total number of images.

The second stage of image analysis determines the interconnected AV content based on the threshold black and white images (Figure 3-1[*b*]) obtained in the first stage of image analysis. These black and white images are converted to binary bit files by applying a third macro developed using Image-Pro® Plus (Masad et al. 2007). Then, using a FORTRAN-built algorithm (Masad et al. 2007) the binary files are analyzed to determine the connected paths from top to bottom of the compacted specimen. Bit files containing the resultant interconnected AV constitute the output of the algorithm. Masad et al. (2007) documented details of this algorithm. Then, the bit files are converted back to *.TIF* images (Figure 3-1[*c*]) using Image-Pro® Plus, and finally the AV content of this set of output images is quantified using Equations (3-7) and (3-8) to establish the interconnected AV content. This analysis of interconnected AV content did not allow for inclusion of surface AV (Figure 3-1[*c*]) as it was used in previous research (Masad et al. 2007) to study dense-graded HMA. Elements A and B in Figure 3-1(*c*) (replicated in Figure 3-1[*a*], [*b*], and [*d*] for comparison) identify both surface AV internally connected and surface AV not internally connected, respectively. In both cases, these AV were excluded in the previously developed analysis since they are in contact with the lateral surface.

A second type of analysis was conducted in this study including the surface AV of PFC mixtures. This analysis required pre-processing the threshold black and white images to clear the void zone around the specimen image (external black zone shown in Figure 3-1[*a*]) obtained in grayscale images and corresponding black and white images. Software ImageJ 1.38x was used to conduct this process. Figure 3-1(*b*) is an example of a threshold black and white image obtained after clearing the external void zone and Figure 3-1(*d*) shows the corresponding interconnected AV.

3.7 RESULTS AND DISCUSSION

This section presents results and discussion related to both laboratory determination of water-accessible AV content and computation of interconnected AV content based on X-ray CT and image analysis techniques.

3.7.1 Laboratory Determination of Water-Accessible Air Voids Content

The results of laboratory computations and corresponding discussion include: (*i*) comparison of total AV content and water-accessible AV content values and corresponding ratios, (*ii*) discussion of discrepancies of the laboratory methods evaluated, and (*iii*) quantification of differences in water-accessible AV content values resulting from these discrepancies. A recommendation of one method for future laboratory determinations of water-accessible AV content is also included.

Results shown in Figure 3-2 suggest the existence of a linear relationship between total AV content and water-accessible AV content values determined using either dimensional analysis or the vacuum method. Although this relationship is better defined for PMLC specimens, these data preliminary support the same type of relationship for road cores. In addition, data shown in Figure 3-3 suggest that most of the AV are accessible to water and that higher ratios of water-accessible AV content to total AV content were obtained for: (*i*) PG mixtures than for AR mixtures and (*ii*) using the vacuum method as compared to dimensional analysis.

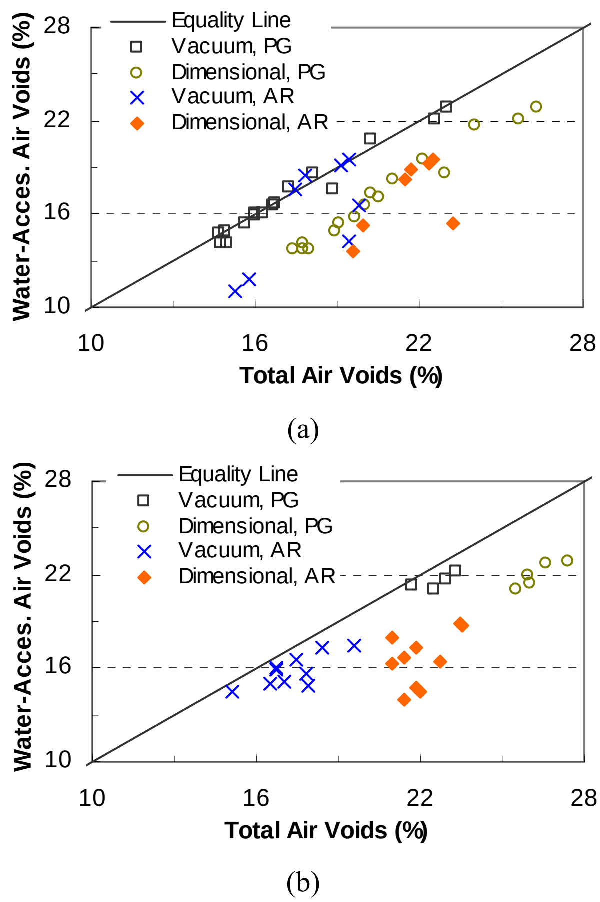


Figure 3-2. Comparison of Water-Accessible Air Voids (AV) Content and Total Air Voids Content for (a) Plant Mixed-Laboratory Compacted (PMLC) Specimens and (b) Road Cores

The comparison shown in Figure 3-4 suggests that both the vacuum method and dimensional analysis led to comparable values of water-accessible AV content. However, as shown in Figure 3-3, the ratio of water-accessible AV content to total AV content computed by these methods differed. These discrepancies are due to the combined effect of several differences between both methods, which are related to: (*i*) quantification of total volume of a compacted specimen (V_{tv} versus V_{td}) and (*ii*) determination of saturated weight of the specimen in water (W_s versus W_{sv}). In addition, the determination of total volume differs in the quantification of surface AV (AV in contact with the specimen surface) and the capacity to capture major geometrical deviations (not related to the irregularities created by the surface AV) in the shape of the specimen with respect to a regular cylinder. Comparison of dimensional analysis and the vacuum method in terms of each of these aspects is subsequently discussed.

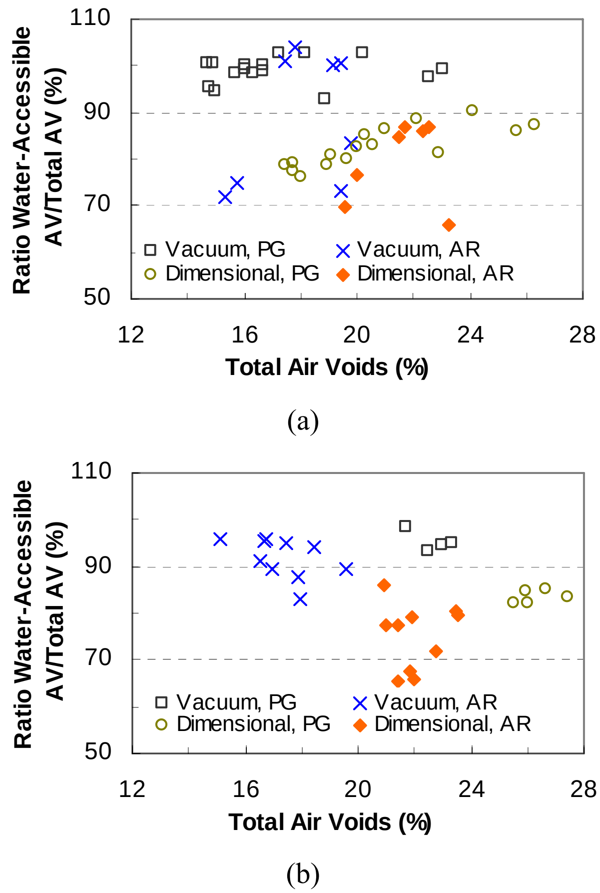


Figure 3-3. Ratio of Water-Accessible Air Voids (AV) Content to Total Air Voids Content for (a) Plant Mixed-Laboratory Compacted (PMLC) Specimens and (b) Road Cores

Dimensional analysis entirely includes the surface AV as part of the water-accessible AV content because computation of total volume assumes the compacted specimen as a regular cylinder with smooth faces. In the vacuum method the shape of the bag surrounding the specimen dictates the total volume, and the surface AV are partially included (compared to the dimensional computation) as part of the water-accessible AV content. Thus, it is hypothesized that a high-stiffness bag, as compared to the bag currently used, can lead to determinations of total volume from the vacuum method closer to those computed using dimensional analysis. In addition, there is no evidence showing that the particular stiffness of the bag currently used in the vacuum method leads to more accurate or representative determinations of total volume than the computation of volume used for dimensional analysis. Furthermore, the surface AV should be included in the determination of both total AV content and water-accessible AV content as long as they form part of the actual internal structure of PFC mixtures.

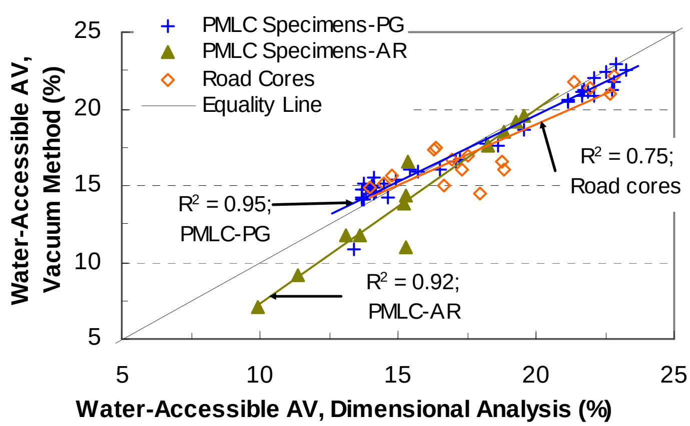


Figure 3-4. Comparison of Water-Accessible Air Voids (AV) Computed Using Dimensional Analysis and the Vacuum Method

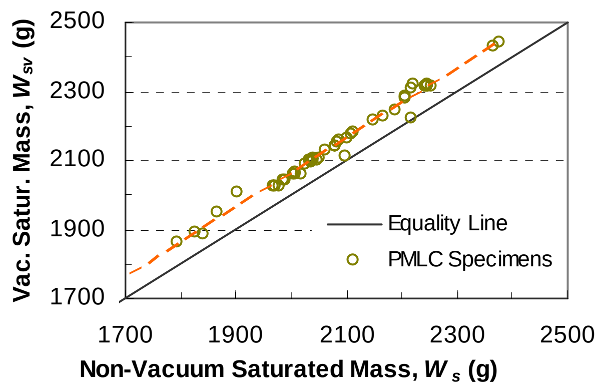
Previous studies (Tashman et al. 2002; Tashman et al. 2001) of the internal structure of HMA based on X-ray CT and image analysis provided evidence of non-uniform distributions of AV content along the vertical and horizontal directions of gyratory compacted specimens (PMLC and LMLC). However, similar analysis for corresponding road cores of dense-graded HMA indicated non-uniform distributions of AV content in the vertical direction and uniform distribution in the horizontal direction (Tashman et al. 2002; Tashman et al. 2001). Similar distributions may be expected in PFC mixtures based on preliminary results presented by Muraya (2007) and Alvarez et al. (2009b). The homogeneous horizontal distribution of AV reported for field-compacted mixtures suggest that the surface AV of a specimen (e.g., road core) obtained from any location in the field are AV that constitute part of the actual internal structure of the mixture. Therefore, inclusion of surface AV in the dimensional analysis offers a more representative mixture characterization as compared to that obtained using the vacuum method. However, additional research is required for improving the production of gyratory compacted specimens to resemble the AV distribution obtained in the field. These improvements would allow representative determinations of AV contents (total and water-accessible) using laboratory compacted specimens.

Compared to dimensional analysis, the vacuum method may better capture possible geometrical deviations in the shape (or shape distortions) of the compacted specimen with respect to a regular cylinder because the bag follows the actual shape of the specimen. This can be important in evaluating road cores whose shape is not always completely regular. However, proper practices for coring and fabricating gyratory compacted specimens can minimize the existence of shape distortions, which would minimize corresponding differences in the computation of total volume obtained by dimensional analysis and the vacuum method. This study did not include computations to separate the effect of shape distortions and surface AV. However, the effect of surface AV is deemed the main source of divergence in the values of total volume determined by dimensional analysis and the vacuum method.

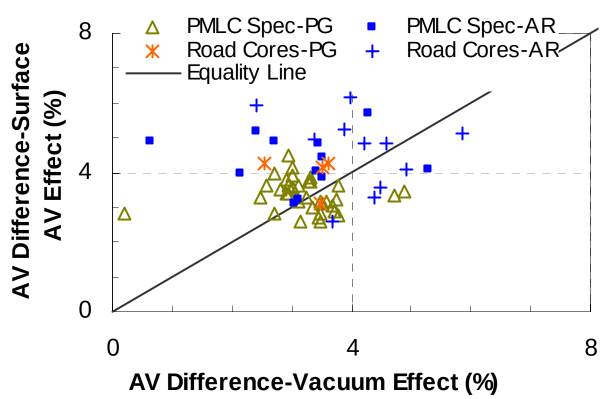
As previously indicated, determination of the saturated weight in water of a compacted specimen included: (*i*) direct immersion in water for dimensional analysis and (*ii*) immersion of the specimen subjected to the vacuum applied to seal the bag for the vacuum method. The high ratio of water-accessible AV content to total AV content values that characterizes PFC mixtures (Figure 3-3) should facilitate the saturation process and encouraged the determination of the saturated weight by direct immersion to simplify laboratory measurements. Data presented in Figure 3-5(*a*) indicate that direct immersion led to partial saturation of the specimens and suggests that dimensional analysis should be modified to include determination of a more representative saturated weight measured after applying a vacuum of some magnitude. This application of vacuum would facilitate complete access of water to the entire AV structure, without the presence of trapped air, producing a laboratory computation that may better reproduce the field mixture response. In the field, complete saturation can be reached after air has been entirely displaced from the mixture AV by gradual penetration of water through the AV that allows gradual and complete displacement of air.

Additional research should be conducted to determine the optimum magnitude of vacuum and the corresponding time of application required to ensure saturation of PFC specimens. This vacuum magnitude and time may be smaller than those required to saturate dense-graded HMA as specified by AASHTO in T 283-07 (AASHTO 2007) (Lottman test).

These adjustments are expected considering that the open structure of PFC mixtures may be easier to saturate but also more susceptible to micro-damage as compared to that of dense-graded HMA. Masad et al. (2007) suggested the occurrence of micro-damage during the vacuum-conditioning process of dense-graded HMA, which can increase the AV connectivity and consequently the water-accessible AV content.



(a)



(b)

Figure 3-5. Specimen Saturated Weight Determined With and Without Application of Vacuum (a) and Differences in Water-Accessible Air Voids (AV) Content Related to the Effect of Surface Air Voids and Vacuum Application (b)

Figure 3-5(*b*) shows the differences in values of water-accessible AV content induced by discrepancies in the quantification of: (*i*) total volume (surface AV effect) and (*ii*) saturated weight of the specimen in water with and without the application of vacuum (vacuum effect).

The effect of surface AV was computed by subtracting the water-accessible AV content obtained by the vacuum method (Equation 3-3) and that obtained by dimensional analysis with application of vacuum (Equation 3-6). The difference of AV related to the effect of vacuum application was calculated by subtracting the water-accessible AV content obtained by dimensional analysis (Equation 3-5) and that obtained by dimensional analysis with vacuum application (Equation 3-6). The differences in values of water-accessible AV content associated with the effect of surface AV and vacuum application have similar orders of magnitude (between 2 and 5 percentage points) for the AR and PG mixtures evaluated, which may represent mixtures produced covering the entire gradation specification (Table 3-2). However, differences due to the vacuum effect will differ if the magnitude of vacuum applied is modified. Taking into account that the values of water-accessible AV content for PFC mixtures can be in the range of 14 to 22 % (Figure 3-2), the differences reported in Figure 3-5(*b*) are high enough to modify a mix design or performance evaluation conducted in terms of this volumetric property.

In summary, quantification of water-accessible AV content using dimensional analysis as described in the paper presents several advantages compared to the vacuum method. These advantages include the following facts: (*i*) dimensional analysis is simpler, faster, and less expensive; (*ii*) the required equipment is readily available; (*iii*) there is no need for additional testing supplies; and (*iv*) environmental disposal of the vacuum bags is not required. In addition, the inclusion of surface AV in dimensional analysis offers a more representative mixture characterization. However, the vacuum method may better capture shape distortions of compacted specimens and road cores. A common deficiency of both methodologies is that unconnected surface AV are included as part of the water-accessible AV content. Although these surface AV are actually accessible to water, they do not form connected paths to allow water transport.

Based on the previous discussion, dimensional analysis with application of a vacuum of some magnitude (to be established in future research) is recommended over the vacuum method to compute the water-accessible AV content of PFC mixtures. In addition, for practical reasons in routine application, diameter measurements at the top, center, and bottom of both laboratory compacted specimens and road cores are recommended to further improve the accuracy of the total volume determination by dimensional analysis.

3.7.2 Computation of Interconnected Air Voids Content

This section presents the comparison of values of interconnected AV content and water-accessible AV content (determined using the previously recommended dimensional analysis). An initial comparison is stated in terms of: (*i*) quantification of total volume for compacted specimens (including capacity to capture shape distortions and the reference volume employed to compute the total volume) and (*ii*) computation of unconnected AV located on the lateral surface of a compacted specimen. Finally, the similarity of interconnected AV content and water-accessible AV content values is evaluated in terms of the coefficient of correlation.

Image analysis carried out to determine both total AV content and interconnected AV content included quantification of total volume (i.e., corresponding total area per image) based on an external circumference of constant diameter (Figure 3-1) used in the entire stack of images acquired for a compacted specimen. Although the use of a constant diameter in these analyses generates the same limitation discussed previously for dimensional analysis in terms of capturing distortions of shape, the computations of total volume included in the determination of water-accessible AV and interconnected AV are comparable.

In fact, criteria used to select the final threshold value applied to differentiate the solid and void phases in grayscale images were: (*i*) visual inspection of black and white images to verify correct reproduction of the AV boundaries observed in grayscale images and (*ii*) reproduction of the total AV content computed based on dimensional analysis. Two reasons sustained the use of this total AV content: (*i*) dimensional analysis was recommended in previous research (Alvarez et al. 2009d) (over the vacuum method) to compute the total AV content in PFC mixtures and (*ii*) the selection of this method allows having the same reference volume to compute the total volume for both image analysis and laboratory determinations.

Therefore, compacted specimens were consistently analyzed using a regular cylinder with smooth faces as the reference volume in the computations of: (*i*) total AV content in the laboratory, (*ii*) total AV content based on image analysis, (*iii*) water-accessible AV content in the laboratory (using the previously recommended dimensional analysis), and (*iv)* interconnected AV content computed by image analysis. Figure 3-6 shows the agreement between values of total AV content calculated based on dimensional analysis and those computed using image analysis techniques (average of total AV content values computed for the image stack representing a compacted specimen). Thus, the average value of the vertical distribution of total AV is equivalent to the total AV content determined for the volume of a compacted specimen in the laboratory. These results agree with the fact that an unbiased estimate of the volume portion of voids in a specimen is the expected value of the area portion of voids computed in test planes (X-ray CT slices in this case), which was previously outlined by Masad et al. (1999a).

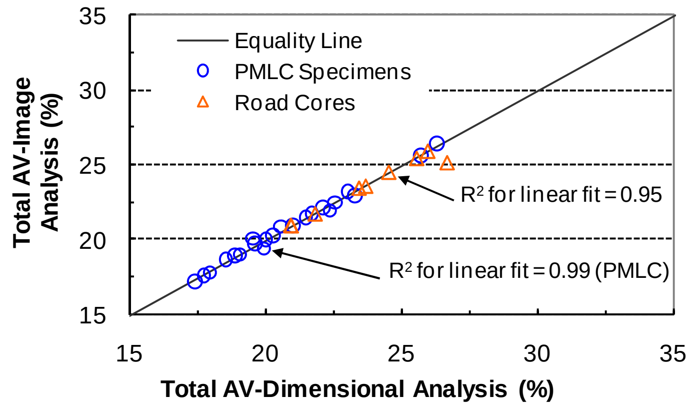


Figure 3-6. Comparison of Total Air Voids (AV) Content Computed Using Dimensional Analysis and Image Analysis

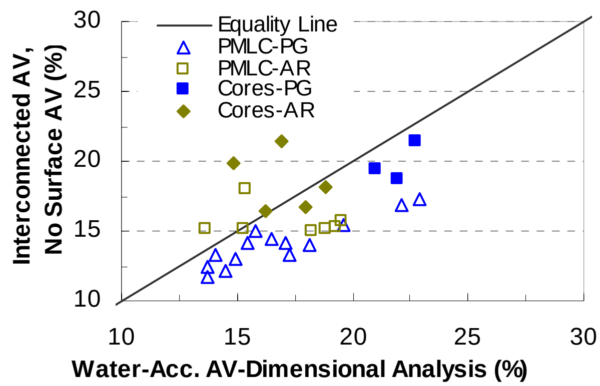
However, the computation of unconnected AV located on the lateral surface of a compacted specimen constitutes a source of differences between the values of water-accessible AV content and interconnected AV content. While these AV are not computed as interconnected AV (since they do not form connected paths from the top to the bottom of the specimen), they constitute part of the water-accessible AV content.

The analysis of similarity of connected AV content values determined in the laboratory and using computational techniques included the following variables: (*i*) water-accessible AV content calculated by dimensional analysis with and without application of vacuum and (*ii*) interconnected AV content computed excluding and including surface AV. The magnitude of the differences in values of water-accessible AV content related to the effect of both surface AV and vacuum application presented previously motivated this analysis of similarity. Table 3-4 presents correlation coefficients obtained in this analysis, and corresponding data are shown in Figure 3-7 and Figure 3-8.

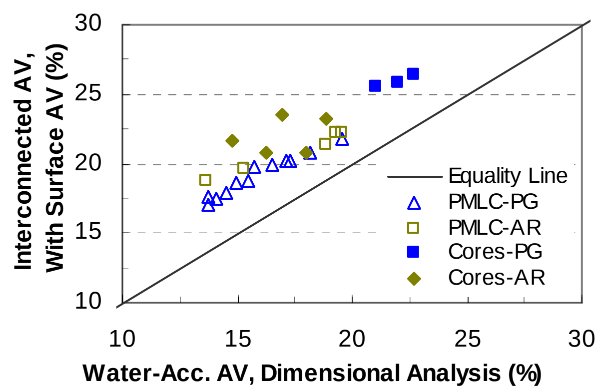
Table 3-4. Coefficients of Correlation for Values of Water-Accessible Air Voids (AV) Content and Interconnected Air Voids Content

Specimen	Mixture	$WAAV_{DA}$ – $IAV_{No\ SAV}$	$WAAV_{DA}$ – IAV_{SAV}	$WAAV_{DA\text{-}VAC}$ – $IAV_{No\ SAV}$	$WAAV_{DA\text{-}VAC}$ – IAV_{SAV}
PMLC Specimens	PG	0.90	0.98	0.92	0.98
	AR	-0.22	0.99	0.12	0.96
	PG and AR	0.63	0.96	0.58	0.84
Road Cores	PG	0.66	0.95	-0.59	-0.12
	AR	-0.29	0.34	0.24	0.82
	PG and AR	0.27	0.88	0.41	0.96

Legend: $WAAV_{DA}$ = Water-accessible AV content computed by dimensional analysis; $WAAV_{DA\text{-}VAC}$ = Water-accessible AV content computed by dimensional analysis with application of vacuum; $IAV_{No\ SAV}$ = Interconnected AV content computed excluding surface AV; IAV_{SAV} = Interconnected AV content computed including surface AV.

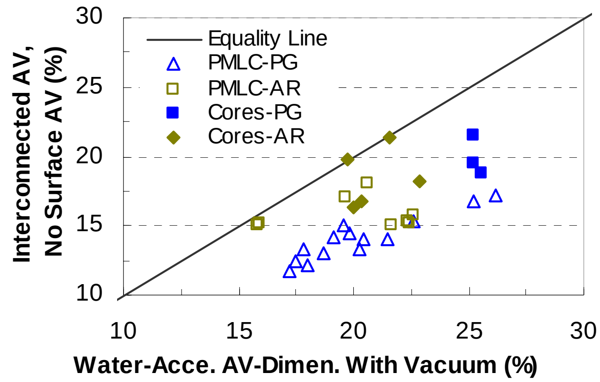


(a)

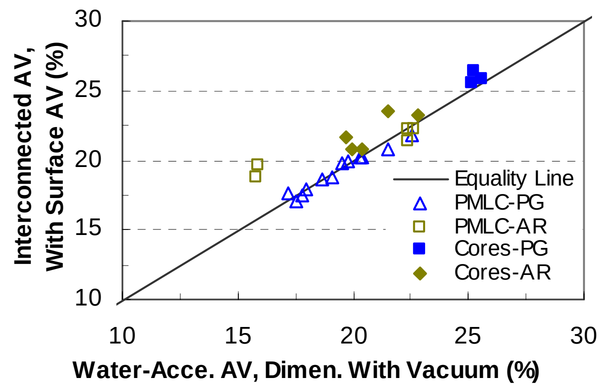


(b)

Figure 3-7. Comparison of Water-Accessible Air Voids (AV) Content Computed Using Dimensional Analysis Without Vacuum and Interconnected Air Voids Content Computed (a) Excluding Surface Air Voids and (b) Including Surface Air Voids



(a)



(b)

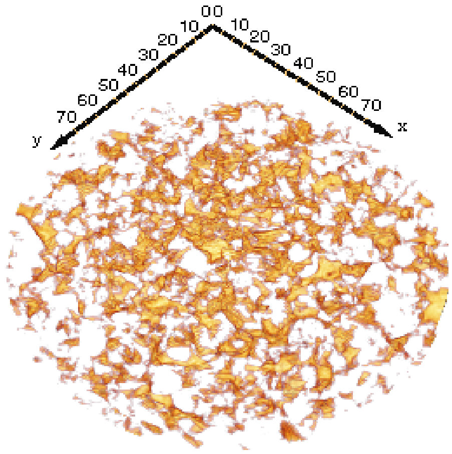
Figure 3-8. Comparison of Water-Accessible Air Voids (AV) Content Computed Using Dimensional Analysis With Vacuum and Interconnected Air Voids Content Computed (a) Excluding Surface Air Voids and (b) Including Surface Air Voids

These results indicate that: (*i*) the strongest linear association was obtained between values of interconnected AV content computed including surface AV and values of water-accessible AV content computed using dimensional analysis with application of vacuum and (*ii*) these techniques offered the most comparable results in terms of average values of connected AV content. The results also provide additional rationale to propose the inclusion of vacuum saturation as part of the dimensional analysis procedure. Although this inclusion led to smaller coefficients of correlation, closer values of interconnected AV content and water-accessible AV content were obtained as shown in Figure 3-7(*b*) and Figure 3-8(*b*). As expected, since dimensional analysis includes all surface AV, the inclusion of surface AV in the computation of interconnected AV content led to higher coefficients of correlation than those obtained based on interconnected AV content computed excluding surface AV. In addition, the differences in the linear association obtained for AR and PG mixtures (expressed in terms of the coefficient of correlation) suggest that these mixtures should be studied independently and additional improvements may be required to better characterize the AR mixtures.

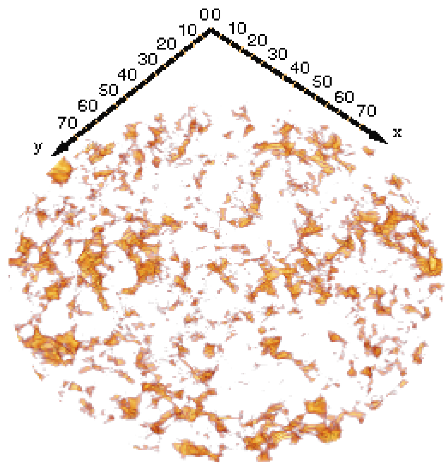
The results of the statistical analysis and the reasons subsequently indicated suggest that the surface AV should be included to determine the interconnected AV content of PFC mixtures:

- The surface AV form part of the internal structure (expressed in terms of the three-dimensional AV distribution) of the mixture.
- The evaluation of laboratory data previously presented suggested that the surface AV constitute an important proportion of the water-accessible AV content.
- The potential effect of surface AV on durability and functionality is included in corresponding laboratory evaluations of performance.

Although this study focused on determining average values of interconnected AV content, the application of X-ray CT and image analysis previously described constitute a nondestructive technique that also allows characterizing the internal structure of the mixture in terms of the AV distribution. As outlined by Masad et al. (1999b), the internal structure of HMA is related to the distribution of AV and the distribution, orientation, and contact of aggregates. This capability of characterizing the mixture internal structure constitutes a primary advantage of the computational technique (as compared to the laboratory determinations assessed) which can provide inputs for additional analysis in terms of mixture durability, functionality, and compaction. Three-dimensional renders of interconnected AV shown in Figure 3-9 provide evidence of the high AV connectivity in PFC mixtures and the heterogeneous distribution of AV in a typical SGC-compacted specimen. Since these AV distributions (not captured by the laboratory tests analyzed) have an effect on subsequent evaluations of both functionality and durability, further analysis of the internal structure of SGC-compacted specimens and field-compacted mixtures is required to improve the mix design and evaluation of PFC mixtures.



(a)



(b)

Figure 3-9. Three-Dimensional Render of Interconnected Air Voids (AV) in the (a) Top (0 to 15 mm) and (b) Middle (47 to 61 mm) Sections of a 108 mm in Height Specimen

3.8 SUMMARY AND RECOMMENDATIONS

This paper presents an evaluation of techniques applied to quantify the connected AV content in PFC mixtures including both laboratory tests and X-ray CT and image analysis. The following conclusions are provided based on the results gathered as part of this study:

- Dimensional analysis, conducted in the laboratory with application of vacuum to compute the saturated weight of the specimen in water, is recommended over the vacuum method to determine the water-accessible AV content of compacted PFC mixtures. Additional research is required to define a testing procedure for measuring this saturated weight.

- The interconnected AV content (computed using X-ray CT and image analysis techniques), showed strong linear association with the water-accessible AV content determined using dimensional analysis with application of vacuum. This result suggests that the techniques described can provide comparable results in terms of average AV content values.

In addition to average values of interconnected AV content, X-ray CT and image analysis can provide nondestructive characterization of the mixture internal structure (e.g., location, size, and distribution of AV), which constitute a primary advantage of this computational technique as compared to the macroscopic laboratory determinations. This characterization of the mixture internal structure can be applied to study both functionality and durability of PFC mixtures. For example, future research may focus on incorporating this characterization of AV in analytical predictions of permeability as well as in the study of noise reduction properties of PFC mixtures. Furthermore, the internal structure of laboratory- and field-compacted PFC mixtures can be compared to determine the suitability of current compaction techniques.

The following recommendations are drawn based on the analysis and conclusions previously indicated:

- Use dimensional analysis with application of vacuum to compute the water-accessible AV content of compacted PFC mixtures.
- Investigate the use of connected AV content as an alternative parameter to integrate in mix design and laboratory and computational evaluation of PFC mixtures.

4. DRAINABILITY OF PERMEABLE FRICTION COURSE MIXTURES*

4.1 OVERVIEW

Drainability is one of the main characteristics of PFC mixtures and is the primary reason for using these mixtures as the surface course in asphalt pavements in the United States. Current approaches suggested for PFC mix design to evaluate drainability (using gyratory-compacted specimens) include: (*i*) achieving a target total AV content as an indirect indication of permeability and (*ii*) direct measurement of permeability in the laboratory. The assessment conducted in this study suggested that these approaches are not effective in ensuring adequate drainability in field-compacted mixtures. Thus, different alternatives were evaluated to improve this assessment. Corresponding analysis suggested that: (*i*) the water-accessible AV content can be used as a surrogate of the total AV content to indirectly assess permeability and (*ii*) the water flow value (WFV), outflow time, can be applied to evaluate the field drainability of PFC mixtures. The expected value of permeability, determined using a modified version of the Kozeny-Carman equation, was recommended to analytically predict permeability for mix design and evaluation purposes.

4.2 INTRODUCTION

PFC are HMA mixtures placed at the surface of an asphalt pavement in a thin layer to produce benefits in terms of safety, economy, and the environment (Alvarez et al. 2006). The use of these mixtures reduces the risk of hydroplaning and wet skidding; decreases splash and spray, fuel consumption, tire wear, and pavement noise; and improves ride quality and visibility of pavement markings at night and in wet weather (Alvarez et al. 2006). To obtain the benefits of PFC mixtures used as the surface course in an asphalt pavement structure, a mix design system that produces mixtures that are both functional and durable is required. Functionality of PFC mixtures includes properties related to drainability, noise reduction, and surface friction. Further examination of drainability is warranted, since drainability is one of the main characteristics of PFC mixtures (and closely related to several of their advantages) and is the primary reason for using these mixtures as the surface course in asphalt pavements in the United States.

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* Submitted for publication in the *Journal of Materials in Civil Engineering, ASCE* (2008), by Allex E. Alvarez, Amy Epps Martin, and Cindy Estakhri.

At present, measurement of the coefficient of permeability (or permeability) is not directly included as part of PFC mix design (TxDOT 2005), and most agencies do not specify evaluation of drainability during mix design (Alvarez et al. 2006). Current approaches to assess drainability in PFC mix design include: (*i*) achieving a target total AV content value (e.g., 18 to 22 %) as an indirect indication of adequate drainability and (*ii*) laboratory measurement of permeability on laboratory-compacted specimens, primarily produced using the SGC. NCAT (Kandhal 2002) as well as ASTM D 7064-04 (ASTM International 2006) suggested this laboratory measurement of permeability as an optional evaluation and recommended a corresponding minimum permeability value of 100 m/day. However, verification of the relationship between drainability values obtained for laboratory- and field-compacted mixtures is still required to ensure that current mix design and construction practices are producing drainable mixtures in the field. In addition, further investigation of the analytical computation of permeability is required to facilitate prediction and engineering of this important property of PFC mixtures.

A few agencies specify a minimum field drainability value (Alvarez et al. 2006; TxDOT 2005), usually measured in terms of an outflow time. Thus, several pieces of equipment (erroneously designated in the literature as permeameters) have been developed in Europe and in the United States to measure the outflow time of a specific water volume, which has been adopted as an indication of the mean rate of water discharge. Although these measurements are often referred to as field permeability in the literature, the outflow time cannot be used to calculate the coefficient of permeability since the area and direction of flow during the test are not controlled. However, the outflow time is a useful parameter to compare the performance in terms of drainability for different mixtures or that of a specific mixture under different compaction conditions or stages or in different project locations.

This paper evaluates the suitability of the current approaches used to assess drainability of PFC mixtures and explores alternatives to improve this evaluation. The paper focuses on the assessment of the initial mixture drainability (as constructed) including permeability measurements conducted in the laboratory as well as determinations of WFV, or outflow times, used to assess field drainability right after construction. Thus, the paper includes the quantification of initial drainability without assessing the drainability loss due to progressive AV clogging during the mixture service life.

First the experiment design including mix design, materials, specimen fabrication, and test methods is described, followed by the results and discussion. A summary and recommendations complete the paper.

4.3 OBJECTIVE AND METHODOLOGY

The main objective of this study focuses on evaluating the current approaches used to assess drainability in PFC mix design and exploring alternatives to improve this assessment based on laboratory and field measurements as well as analytical computations. To accomplish this objective, the study was divided into the following steps:

- Evaluation of the relationship between permeability values and total AV content values determined for specimens compacted in the laboratory and in the field.
- Comparison of laboratory- and field-compacted specimens in terms of permeability, total AV content, thickness, and internal structure (based on X-ray CT and image analysis).
- Evaluation of alternatives to enhance the assessment of drainability including: (*i*) the relationship between permeability values and both water-accessible AV content (proportion of the total volume of a compacted mixture that is accessible to water) and field drainability and (*ii*) analytical computation of permeability.

4.4 EXPERIMENTAL DESIGN

This section presents the experimental design defined for this study, which includes mix design, material requirements, material selection, specimen fabrication, and laboratory and field testing.

4.4.1 Mix Design and Material Requirements

Mix design was conducted according to the current TxDOT PFC mix design method (TxDOT 2005). Corresponding material specifications include master aggregate gradation bands for each of the following two types of asphalt binders allowed for PFC mixtures (TxDOT 2004):

- a Type I or II AR with a minimum of 15 % by weight of asphalt of Grade C or Grade B crumb rubber.
- a PG asphalt with a minimum high temperature grade of PG76-XX with a minimum of 1.0 % by weight of dry aggregate of lime and a minimum of 0.2 % by weight of mixture of cellulose or mineral fibers.

Based on the type of asphalt binder selected, master aggregate gradation bands are also provided in Item 342 (TxDOT 2004).

4.4.2 Material Selection and Specimen Fabrication

Laboratory evaluations included in this study were conducted using road cores as well as PMLC specimens obtained from nine PFC mixtures produced in the field and used in actual field projects. Thus, corresponding evaluations of field drainability were also possible on these field projects. The nine mixtures included permitted evaluating both asphalt binder types (AR and PG) and corresponding aggregate gradations as part of this study. Details for each mixture and corresponding field projects are provided in Table 4-1. Aggregate gradations for these specific mixtures are presented in Table 4-2.

Table 4-1. Descriptions of Mixtures Used to Assess Drainability

Mixture	TxDOT District	Asphalt Type	Opt. Asphalt Content, %	Aggregate Type	Other Materials (Lime / CF)
I-35-PG or 1-PG	San Antonio	PG 76-22	6.1	Sandstone, Limestone	1 % / 0.3 %
IH-30-PG or 2-PG	Paris	PG 76-22	6.6	Sandstone	1 % / 0.3 %
IH-20-PG or 3-PG	Abilene	PG 76-22	6.5	Limestone	1 % / 0.3 %
US-83-PG or 4-PG	Abilene	PG 76-22	6.4	Limestone	1 % / 0.3 %
US-59-PG or 5-PG	Lufkin	PG 76-22	5.9	Granite, Limestone	1 % / 0.3 %
US-59Y-PG or 6-PG	Yoakum	PG 76-22	5.8	Limestone	1 % / 0.3 %
US-281-AR or 1-AR	San Antonio	Type II AR, Grade B (AC-10 w/16 % CR)	8.1	Sandstone, Limestone	0 % / 0 %
US-288-AR or 2-AR	Houston	Type II AR, Grade B (AC-10 w/17 % CR)	8.0	Granite, Limestone	0 % / 0 %
US-290-AR or 3-AR	Austin	Type II AR, Grade B (AC-10 w/17 % CR)	8.3	Sandstone	0 % / 0 %

Legend: OAC = optimum asphalt content; CF = cellulose fibers; AR = asphalt rubber; CR = crumb rubber.

Table 4-2. Aggregate Gradations for PG and AR Mixtures Used to Assess Drainability

Sieve	Specification (% Passing)		1-PG	2-PG	3-PG	4-PG	5-PG	6-PG	Specification (% Passing)		1-AR	2-AR	3-AR
¾	100	100	100	100	100	100	100	100	100	100	100	100	100
½	80	100	90.3	81	85.3	90.5	80.2	84.5	95	100	99	95.6	99.7
3/8	35	60	59.5	43	59.4	50.9	57.7	52.8	50	80	54.6	54.9	75.7
#4	1	20	10.1	15.5	18.6	3.2	15.9	6.6	0	8	5	4	7.9
#8	1	10	5.2	6.7	2	1.5	6	4.2	0	4	1.9	2.1	1.1
#200	1	4	2.3	2.2	1.6	1.1	2.1	2.4	0	4	1	0.8	0.6

Fabrication of the PMLC specimens (150 mm in diameter and 115 ± 5 mm in height) required reheating the mixtures to the compaction temperature and applying 50 gyrations of the SGC as currently specified for mix design (TxDOT 2005). The compaction temperature used was 149°C for both PG (76-22) and AR asphalts as recommended in the PFC mix design procedure (TxDOT 2005) and by the AR supplier, respectively. All specimens used in this study were cooled in the compaction mold before extrusion to preserve the internal structure of the compacted mixtures.

The majority of road cores 150 mm in diameter were 31 to 52 mm in height, but for the 3-PG and 4-PG mixtures, shorter road cores (150 mm in diameter and 19 to 25 mm in height) were used. To minimize any closure of AV during the sawing procedure, road cores were subjected to low temperature (4.4°C) for approximately 24 hours and then saw cut to separate the PFC layer from the original HMA core.

4.4.3 Laboratory and Field Testing

Falling head permeability tests were conducted in accordance with ASTM PS 129-01 (ASTM International 2001) to evaluate the drainability of road cores as well as PMLC specimens in the laboratory. The permeability test was performed on vacuum saturated samples using a falling head permeameter with a flexible wall to compute permeability values based on the application of Darcy's law.

Field assessments of drainability were conducted according to the Tex-246-F (TxDOT 2005) test procedure. This field-drainability test allows determining the WFV, which corresponds to the time, expressed in seconds, required to discharge a given volume of water channeled into the pavement surface with the use of a variable charge outflow meter 152 mm in diameter. The maximum WFV currently recommended for PFC mixtures (measured after compaction) is 20 seconds (TxDOT 2005).

The total AV content was computed in the laboratory based on dimensional analysis (Alvarez et al. 2009d) to determine G_{mb}. Dimensional analysis for G_{mb} calculation includes both determination of the dry specimen weight and direct geometrical computation of the total volume of the specimen using average height and diameter measurement. In addition, the water-accessible AV content was determined using the vacuum method as described by Alvarez et al (2009d). This computation makes use of the buoyancy principle to calculate the total volume of a compacted specimen wrapped in a plastic bag subjected and sealed under vacuum (InstroTek® 2003). The computation of water-accessible AV content also requires measurement of the dry weight and the saturated weight of the specimen in water, which is measured after cutting (under water) and extracting the plastic bag from the water.

The internal structure of compacted mixtures, analyzed in terms of the AV characteristics described subsequently, was studied using the X-ray CT system at Texas A&M University for nondestructive 2D imaging. Information on the principles of the X-ray CT system is documented elsewhere (Masad 2004). Computerized images acquired using X-ray CT were taken along the height of each specimen with a vertical gap of 1 mm. The pixel size was approximately 0.17 mm leading to a voxel size of 0.17 by 0.17 by 1 mm. The analysis of X-ray CT images required matching: (*i*) the value of total AV content calculated in the laboratory (based on dimensional analysis) for the compacted specimen and (*ii*) the average value of total AV content computed for the corresponding images. The total AV content of each image (AV_i) and the total AV content for the set of images representing a specimen (AV_s) were computed as follows using a macro developed by Masad et al. (2007) using Image-Pro® Plus:

$$AV_i = \frac{A_{vi}}{A_T} \tag{4-1}$$

$$AV_s = \frac{\sum_{i=1}^{n} AV_i}{N} \tag{4-2}$$

where A_{vi} is the area of AV in image i, A_T is the cross-sectional area of image i, and N is the total number of images. In addition, the average AV radius ($\bar{r}_i$) in image i is calculated as:

$$\bar{r}_i = \sqrt{\frac{A_{vi}}{\pi M_i}} \tag{4-3}$$

where M_i corresponds to the number of AV in each image. These analyses allowed determining the vertical distribution of total AV content and AV radius in compacted specimens.

4.5 ANALYTICAL COMPUTATION OF PERMEABILITY

Previous research (Al-Omari et al. 2002) applied the Kozeny-Carman equation to compute the permeability of HMA using AV characteristics (AV content, tortuosity of flow paths, and a surface area parameter). Additional research (Masad et al. 2004) also computed permeability for HMA based on the same equation, although the total AV content and the aggregate specific surface area were included as basic parameters. Furthermore, using the Kozeny-Carman equation, Masad et al. (2006) proposed Equation (4-4) to compute HMA permeability. Unlike the previous equations proposed, Equation (4-4) accounts for the effect of asphalt content in HMA by making use of an equivalent aggregate-particle diameter, which includes the average particle diameter coated with an average asphalt film thickness (Masad et al. 2006):

$$k_c = \frac{\overline{C}n^3}{(1-n)^2}\left[\overline{D}_s\left(1+\frac{G_{sb}(P_b - P_{ba}(1-P_b))}{G_b(1-P_b)}\right)^{\frac{1}{3}}\right]^2 \frac{\gamma}{\mu} \tag{4-4}$$

where k_c is the calculated coefficient of permeability (or calculated permeability) in m/s, $\overline{C}$ is an empirical coefficient to include both the effect of the AV-shape factor and saturation, n is the total AV content, $\overline{D}_s$ corresponds to the average aggregate-particle size, G_{sb} is the bulk specific gravity of the aggregate, P_b is the percent of asphalt content by total weight of the mix, P_{ba} is the percent of absorbed asphalt by weight of aggregate, G_b is the asphalt specific gravity, γ is the unit weight of the fluid (9.79 kN/m^3 for water at 20°C), and μ is the fluid viscosity (10^{-3} kg/m·s for water).

Based on a parametric analysis of Equation (4-4), Masad et al. (2006) concluded that the total AV content and the average aggregate-particle size were the variables with the largest effect on permeability. Consequently, to further improve the estimation of permeability in PFC mixtures, in this study the variability of both the aggregate-particle size and the total AV content (along the vertical axis of compacted specimens) was included in the estimation of permeability. For this purpose, the expected value of permeability ($E[k]$) was computed based on Equation (4-4), which was adopted as a function of both the aggregate-particle size and the total AV content. All other variables included in Equation (4-4) were adopted as constants and

$\overline{C}$ remained as an empirical coefficient to be determined by calibrating the expected value equation (Equation (4-5)) against permeability measurements. The expected value of permeability determined using a two-dimensional Taylor series approximation then becomes:

$$E[k] = A\overline{C} \times \left[\begin{array}{l} \left(\dfrac{\overline{n}^3}{(1-\overline{n})^2} \right)(\overline{D}_s^2 + \mathrm{var}(D_s)) + \left(\dfrac{3\overline{n}}{(1-\overline{n})^2} + \dfrac{6\overline{n}^2}{(1-\overline{n})^3} + \dfrac{3\overline{n}^3}{(1-\overline{n})^4} \right)\overline{D}_s^2 \times \mathrm{var}(n) + \\ \left(\dfrac{2\overline{n}^3}{(1-\overline{n})^3} + \dfrac{3\overline{n}^2}{(1-\overline{n})^2} \right) 2\overline{D}_s \times \mathrm{cov}(D_s, n) \end{array} \right] \quad (4\text{-}5)$$

where $\overline{n}$ is the average total AV content, var(n) is the variance of the distribution of total AV values (along the vertical axis of compacted specimens), var(D_s) corresponds to the variance of the distribution of aggregate-particle size, cov(D_s, n) is the covariance of the aggregate-particle size and the total AV content, and the constant A is defined as:

$$A = \left(1 + \frac{G_{sb}(P_b - P_{ba}(1-P_b))}{G_b(1-P_b)} \right)^{\frac{2}{3}} \frac{\gamma}{\mu} \quad (4\text{-}6)$$

Aggregate and asphalt parameters grouped in Equation (4-6) were obtained by conducting conventional HMA testing for mix design and evaluation. In addition, the vertical distribution of total AV content values obtained using X-ray CT and image analysis allowed computing the average and the variance of the total AV content. Furthermore, the same statistics were computed for the aggregate-particle size distribution by considering the aggregate gradation as a discrete random variable. Therefore:

$$\overline{D}_s = \sum_i D_{si} \times \%R_i \quad (4\text{-}7)$$

$$\mathrm{var}(D_s) = \sum_i D_{si}^2 \times \%R_i - \overline{D}_s^{\,2} \quad (4\text{-}8)$$

where D_{si} is the average particle size retained on sieve i, and $\%R_i$ is the proportion (not cumulative) of aggregate retained on sieve i.

In addition, the variance of the permeability values, var[k], was computed to provide a complete picture of the variability associated with the estimation of permeability. Using a two-dimensional Taylor series approximation, this variance is calculated as:

$$\text{var}[k] = \left(A\overline{C}\right)^2 \times \left[\begin{array}{l} \left(\dfrac{2\overline{n}^3}{(1-\overline{n})^2} \overline{D}_s \right)^2 \text{var}(D_s) + \left[\left(\dfrac{2\overline{n}^3}{(1-\overline{n})^3} + \dfrac{3\overline{n}^2}{(1-\overline{n})^2} \right) \overline{D}_s^2 \right]^2 \text{var}(n) + \\ \left(\dfrac{4\overline{n}^3}{(1-\overline{n})^2} \right) \left(\dfrac{2\overline{n}^3}{(1-\overline{n})^3} + \dfrac{3\overline{n}^2}{(1-\overline{n})^2} \right) \overline{D}_s^3 \times \text{cov}(D_s, n) \end{array} \right] \quad (4\text{-}9)$$

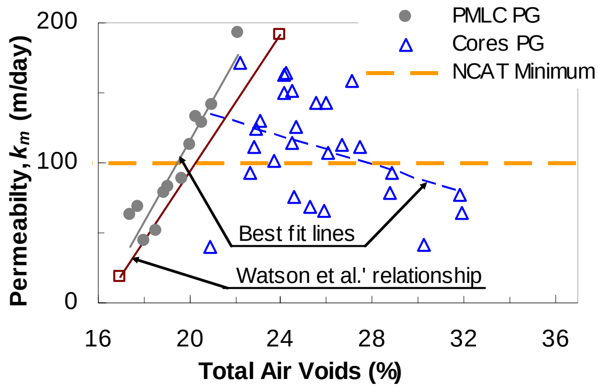
4.6 RESULTS AND DISCUSSION

This section presents results and discussion related to the evaluation of current approaches used to asses PFC drainability, the relationship of water-accessible AV content and laboratory-measured permeability, the relationship of laboratory and field drainability, and analytical computation of permeability.

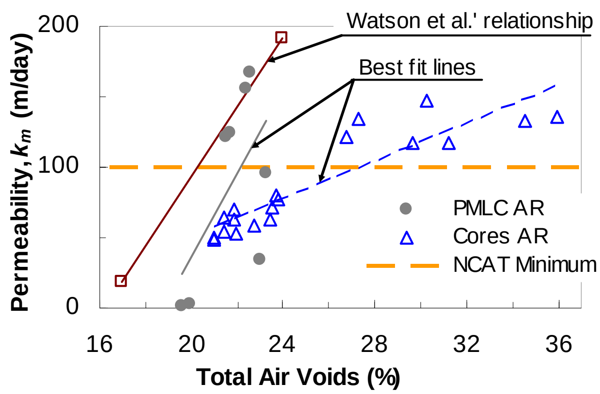
4.6.1 Evaluation of Current Approaches Used to Assess PFC Drainability

This section discusses the suitability of the current approaches used to guarantee adequate drainability (based on total AV content and direct measurement of permeability) of PFC mixtures as constructed in the field.

Figure 4-1(*a*) shows adequate agreement between the linear relationships of laboratory-measured permeability, k_m, and total AV content values determined in this study (for PMLC specimens of PG mixtures) and that reported in previous research by Watson et al. (2004a) (for LMLC specimens of OGFC). These OGFC mixtures were produced using three PG asphalts, one of which was rubber modified. Although the slopes reported for the same relationships of AR mixtures are coincident, these relationships are horizontally shifted, which suggest higher requirements for the AR mixtures in terms of total AV content to ensure similar permeability values. For example, the minimum permeability value suggested by NCAT (Figure 4-1[*b*]) to ensure adequate drainability of OGFC mixtures would be met at 20.3 and 22.2 % total AV content according to the relationships reported by Watson et al. (2004a) and in this study, respectively.



(a)



(b)

Figure 4-1. Comparison of Total Air Voids (AV) Content and Laboratory-Measured Permeability for (a) PG Mixtures and (b) AR Mixtures

Data shown in Figure 4-1 also suggests that the linear relationship between total AV content values and permeability values of PMLC specimens cannot be employed for road cores extracted from mixtures produced by applying the current construction specifications for PFC mixtures. Although a linear relationship between total AV content and permeability values is shown for road cores of the AR mixtures, the slopes of the linear relationships obtained for these road cores and corresponding PMLC specimens are not coincident.

Figure 4-2(*a*) shows the average, maximum, and minimum laboratory-measured permeability values for both laboratory- and field-compacted mixtures (PMLC and road cores, respectively). The magnitude and variability in permeability values for PMLC specimens and road cores provide additional evidence of the limitations encountered in predicting mixture drainability in the field based on permeability measurements conducted on laboratory (SGC)-

compacted specimens as currently suggested for mix design. In general, the road cores exhibited higher permeability values as compared to PMLC specimens.

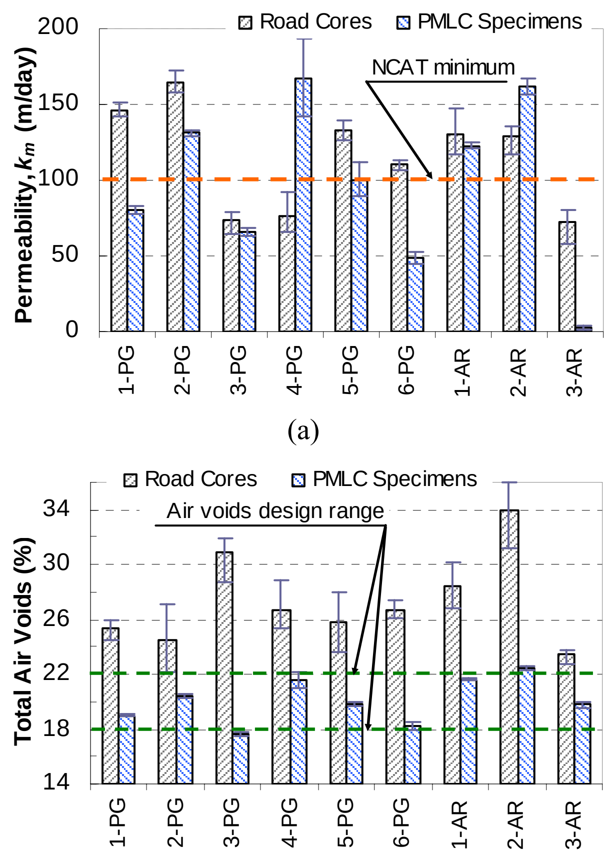


Figure 4-2. Comparison of Road Cores and Plant Mixed-Laboratory Compacted (PMLC) Specimens in Terms of (a) Laboratory-Measured Permeability and (b) Total Air Voids (AV) Content

Note: The total AV content of the 5-PG (US-59-PG) mixture was determined based on the vacuum method (Alvarez et al. 2009d).

Data previously presented suggest that specifying either a minimum total AV content value or permeability value measured on laboratory-compacted specimens (fabricated according to the current gyratory compaction methodology) does not constitute an effective way to evaluate whether adequate drainability is achieved in the field. More specifically, these results provide evidence of: (*i*) the lack of a defined relationship for permeability values as a function of the total AV content for field-compacted mixtures (road cores) and (*ii*) the difficulties encountered in correlating permeability values measured for laboratory- and field-compacted mixtures (PMLC and road cores, respectively). As discussed subsequently, these difficulties may be explained by the differences in terms of: (*i*) total AV content, (*ii*) specimen thickness, and (*iii*) internal structure for PMLC specimens and road cores fabricated from the same materials and proportions.

Higher total AV content values for road cores as compared to the corresponding PMLC specimens were computed (Figure 4-2[*b*]). Whereas the total AV content values of PMLC specimens were in the AV design range (i.e., 18 to 22 %), AV content for field-compacted mixtures exceeded the design range. These results are explained by the lack of compaction control during construction, since compaction of PFC mixtures to a minimum density has not been considered a necessity. In addition, in general, the road cores exhibit higher permeability values as compared to PMLC specimens, which can be expected based on the higher total AV contents of road cores. However, data for the 4-PG and 2-AR mixtures are exceptions to this tendency and, as previously discussed based on Figure 4-1, there is not a unique relationship between the values of total AV content and permeability measured for laboratory- and field-compacted mixtures (PMLC and road cores, respectively).

Permeability measurements were conducted on PMLC specimens 115 ± 5 mm in height (and 150 mm in diameter) and road cores 19 to 52 mm in height (and also 150 mm in diameter). Corresponding differences in the specimen thickness and in the compaction method used in the laboratory and in the field lead to diverse internal structures as subsequently discussed, which helps to explain the lack of correlation between permeability values determined for laboratory- and field-compacted mixtures.

The evaluation of the internal structure of PFC mixtures conducted in this study included determining the distributions of total AV and corresponding average AV radius for both road cores and PMLC specimens. For all the PMLC specimens, these distributions consistently resembled a "C" shape approximately symmetric with respect to the mid-height section of the specimens. Typical results of these AV distributions are shown in Figure 4-3, where the PMLC specimens and road cores are identified as P and C, respectively. This inhomogeneous AV distribution can be induced by the restriction imposed by the top and bottom surfaces of the SGC during compaction (Alvarez et al. 2009b) and by a non uniform temperature profile through the depth of the compacted mixture. Previous research reported AV distributions of similar shape and smaller differences between the maximum and minimum total AV content value for gyratory-compacted specimens of dense-graded HMA (Masad et al. 1999b; Tashman et al. 2001).

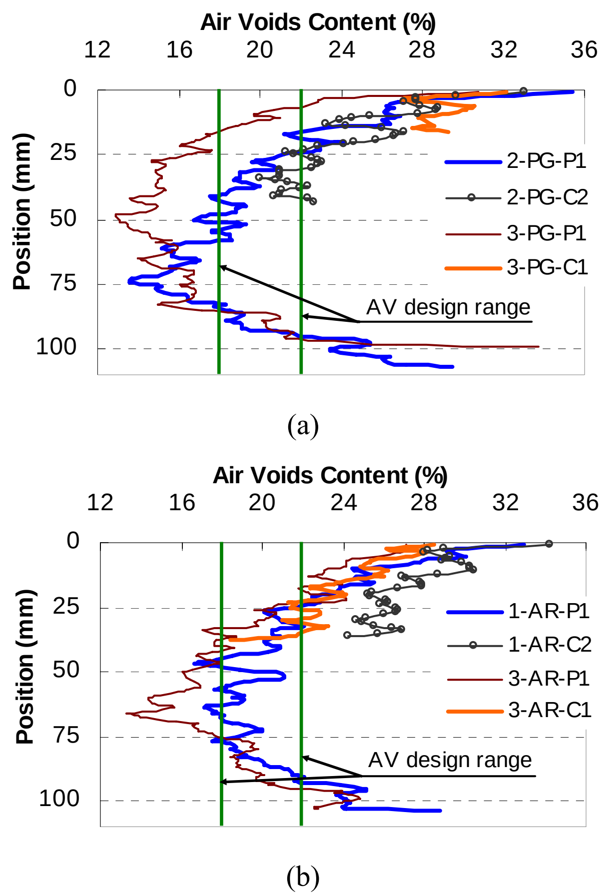


Figure 4-3. Vertical Distribution of Air Voids (AV) for (a) PG Mixtures and (b) AR Mixtures

Road cores did not always exhibit the same distribution of total AV and AV radius determined for PMLC specimens. An incremental decrease in AV content (with the highest value at the surface) characterized the typical distribution of AV determined for road cores, although a few road cores showed a “C” shape AV distribution. Similar patterns were also shown in terms of the distribution of AV radius for road cores. In addition, since the AV content of road cores was in general higher than the AV content of PMLC specimens, the AV distributions differed not only in shape, but in the values of AV content with depth. Detailed information on the internal structure of PFC mixtures is documented elsewhere (Alvarez et al. 2009c).

Although the permeability values measured on road cores and PMLC specimens agree for the 3-PG mixture and also the 1-AR mixture (Figure 4-2[*a*]), the distribution of AV (Figure 4-3) and AV radius for each of these mixtures are not coincident either in magnitude or in shape. On the contrary, the distribution of AV and AV radius for PMLC specimens and road cores for the 2-PG mixture and also the 3-AR mixture are similar (Figure 4-3), but the measured permeability values differed by more than 21 and 97 %, respectively. These comparisons suggest that the disparities in internal structure and thickness of PMLC specimens and road cores induce differences in the flow characteristics of these PFC mixtures and therefore in the permeability values obtained. Al-Omari and Masad (2004) also concluded that differences in compaction methods of HMA induce diverse AV distributions, which, at the same AV content, generate different permeability values. In addition, differences in the permeability values of road cores and SGC-compacted specimens can be associated with dissimilarities in the gradients of AV. Previous research (Masad et al. 2004) reported that gradients of AV promote horizontal flow (over vertical flow) and, consequently, modify the expected permeability of HMA.

The evaluation of mixture internal structure previously presented suggests the necessity of additional research to improve: (*i*) the control of AV in field-compacted mixtures to obtain total AV content values closer to the design values and (*ii*) the protocols to fabricate laboratory specimens that better reproduce the AV characteristics of field-compacted mixtures. These modifications should result in laboratory- and field-compacted mixtures with closer internal structures that can lead to evaluations that better represent functionality and durability.

Given the difficulties identified to evaluate drainability in PFC mix design according to the current approaches, three alternatives are subsequently presented to evaluate the drainability of these mixtures. These alternatives include evaluation of: (*i*) the relationship of water-accessible AV content and laboratory-measured permeability, (*ii*) the relationship of laboratory and field drainability, and (*iii*) analytical prediction of permeability.

4.6.2 Relationship of Water-Accessible Air Voids (AV) Content and Laboratory Drainability

Coefficients of correlation shown in Table 4-3 suggest improved linear relationships between values of laboratory-measured permeability and water-accessible AV content as compared to those obtained based on total AV content values. In addition, trends obtained for the relationship of laboratory-measured permeability and water-accessible AV content values are similar to those shown in Figure 4-1 for total AV content. Consequently, the data set presented in Table 4-3 provides preliminary evidence that water-accessible AV content may be adopted as a surrogate of the total AV content to indirectly assess the permeability of PFC mixtures. The water-accessible AV content may better capture the proportion of AV directly related to drainability, since it constitutes an indication of the proportion of AV that form connected pathways for air and water transport through PFC mixtures.

Table 4-3. Coefficients of Correlation for Air Voids (AV) Content and Laboratory-Measured Permeability

Data Set	Total AV Content	Water-Accessible AV Content
AR- and PG-PMLC Specimens	0.77	0.97
PG-PMLC Specimens	0.95	0.98
AR-PMLC Specimens	0.65	0.99

Since the computation of water-accessible AV content was proposed at an intermediate stage of this study, corresponding determinations are not available for all specimens included in the permeability evaluation. However, additional research should be conducted to determine if values of water-accessible AV content computed for road cores provide stronger correlation with permeability values than those calculated using total AV content values. Further research is also required to determine if values of water-accessible AV content computed by dimensional analysis as recommended in previous research (Alvarez et al. 2009a) can provide stronger correlation with permeability values than those computed using the vacuum method applied in this study.

4.6.3 Relationship of Laboratory and Field Drainability

The effect of repeated field-drainability tests on the WFV was assessed by conducting seven consecutive tests in a specific location of the 3-AR mixture. The coefficient of variation for the values established at this location corresponds to 2.3 % and provides evidence of the limited effect of repeated measurements (i.e., possible mixture saturation effect). Therefore, the WFV data subsequently reported in this section correspond to the average of two individual measurements in each particular location.

Figure 4-4 shows the relationships of laboratory-measured permeability values for road cores and average WFV determined in the field for both AR and PG mixtures. These relationships suggest the practical possibility of controlling a minimum requirement of permeability for PFC mixtures (e.g., 100 m/day as recommended by NCAT) based on the assessment of WFV measured during construction. Data shown in Figure 4-4 indicate that a maximum WFV of 21.5 and 13.3 seconds are required for PG and AR mixtures, respectively, to guarantee a minimum permeability value of 100 m/day.

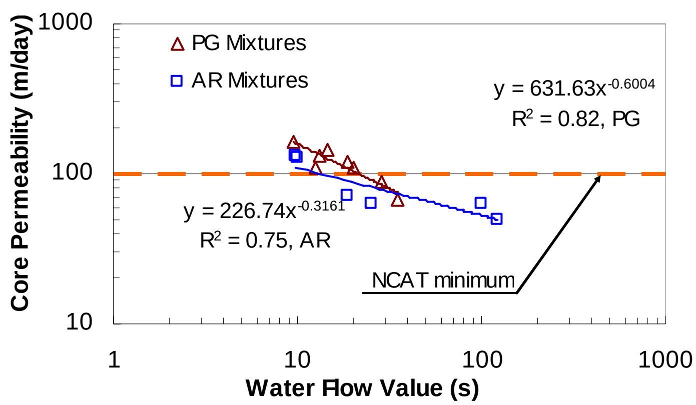


Figure 4-4. Relationship of Laboratory-Measured Permeability and Water Flow Value (WFV)

Additional data are required to: (*i*) further evaluate the variability of the WFV, (*ii*) better support the maximum WFV threshold, (*iii*) recommend a minimum WFV to prevent the construction of low density mixtures that lead to mixture-durability problems (Alvarez et al. 2009b), and (*iv*) evaluate if a unified WFV can be recommended for both AR and PG mixtures. The minimum and maximum WFV will constitute a range to ensure the proper balance of drainability and durability in PFC mixtures. In addition, dissimilarities in gradation, asphalt content, asphalt properties, compaction level, and use of other materials (e.g., lime and fibers in PG mixtures) may contribute to the differences in drainability identified for PG and AR mixtures

(Figure 4-1 and Figure 4-4). These dissimilarities suggest the necessity of defining independent WFV for each of these mixture types.

The WFV constitutes a practical parameter to verify the drainability of PFC mixtures in the field, although it does not allow computing a fundamental property (e.g., permeability) to facilitate comparisons with other field or laboratory measurements. This fact constitutes the main limitation of the WFV.

4.6.4 Analytical Computation of Permeability

Statistical regression analysis using the least square method was applied to compute the values of the $\overline{C}$ coefficient included in Equation (4-5). This computation was conducted by grouping the information available for 16 PMLC specimens and 16 road cores in two independent data sets. The values of the $\overline{C}$ coefficient obtained for PMLC specimens and road cores were 8.878E^{-5} and 3.524E^{-5}, respectively. Similarly, application of Equation (4-4) led to values of the $\overline{C}$ coefficient of 3.745E^{-4} and 1.236E^{-4} for PMLC specimens and road cores, respectively.

The data set shown in Figure 4-5 suggests that the expected value of permeability, $E[k]$, is a better estimator of laboratory-measured permeability, k_m, as compared to the calculated permeability, k_c, determined using Equation (4-4). In fact, for PMLC specimens, the coefficient of correlation for values of laboratory-measured permeability and expected value of permeability was 0.93, whereas the same coefficient for laboratory-measured and calculated permeability values was 0.69. However, the same comparison for road cores led to a coefficient of correlation of -0.04 and -0.34, respectively, which indicated difficulties in reproducing the laboratory-measured permeability values using either the calculated permeability or the expected value of permeability. These contrasting results for PMLC specimens and road cores may be related to the differences in the internal structure of road cores and PMLC specimens, which would include not only the distribution of AV content, but the arrangement of the granular skeleton and the characteristics of corresponding flow paths.

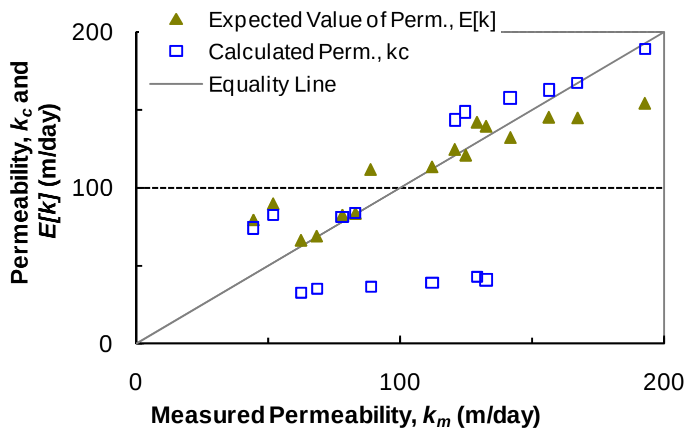
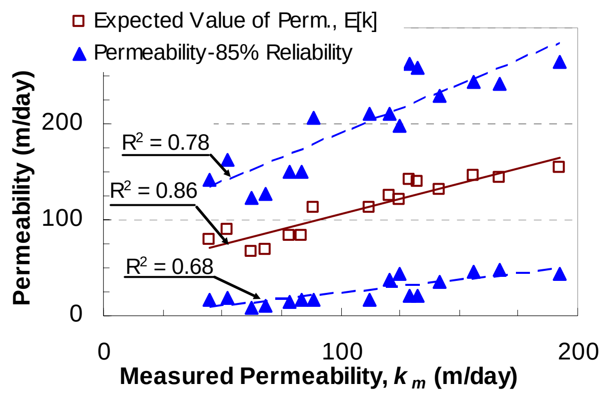


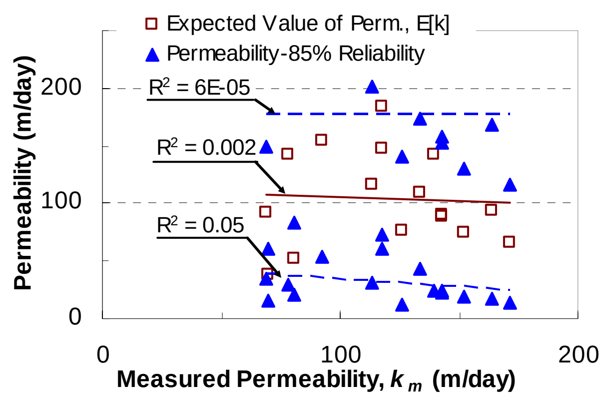
Figure 4-5. Comparison of Laboratory-Measured and Predicted Permeability for Plant Mixed-Laboratory Compacted (PMLC) Specimens

As more data become available, computation of the expected value of permeability may be improved by: (*i*) determining a particular value of the $\overline{C}$ coefficient for each mixture type (AR and PG) and for subsets of mixtures grouped by smaller ranges of total AV content and (*ii*) using the parameters associated with interconnected AV content computed using X-ray CT and image analysis. This AV content is comparable to the water-accessible AV content (Alvarez et al. 2009a) and defined as the proportion of the total volume of a compacted mixture that forms void-connected paths from top to bottom of a compacted specimen.

Figure 4-6 shows the results of expected value of permeability and corresponding variability for a reliability level of 85 % ($k_{85\%}=E[k] \pm 1.037(\sigma_k)$). The standard deviation (σ_k) used in this computation was determined using the variance of permeability determined according to Equation (4-9). These results illustrate the range of permeability values that can be expected in laboratory- and field-compacted mixtures (PMLC and road cores, respectively) due to the variability of both the aggregate-particle size and the total AV content along the vertical axis of compacted specimens (Figure 4-3). The poor correlation obtained between values of laboratory-measured permeability and the expected value of permeability for road cores is reflected again in the poor correlation obtained for the reliability data series shown in Figure 4-6(*b*), which impedes definition of clear trends of the variability that can be expected in this type of specimen.



(a)



(b)

Figure 4-6. Expected Value of Permeability and Variability at 85 % Reliability for (a) Plant Mixed-Laboratory Compacted (PMLC) Specimens and (b) and Road Cores

Given the previously discussed advantages of using the expected value of permeability as an estimator of permeability, the practical application of this approach (Equations (4-5) to (4-9)) is subsequently discussed. Determination of the parameters clustered in Equation (4-6) can be performed by conducting conventional testing for HMA mix design, and the computation of the statistics associated with the mixture gradation is straightforward. The total AV content determined in the laboratory corresponds to the average total AV content ($\overline{n}$) of the vertical AV distribution as reported in previous research (Alvarez et al. 2009a; Masad et al. 1999a) and confirmed in this study. In addition, the COV of the total AV content distribution determined in this study was computed and associated with corresponding average total AV content values (Equations (4-10) and (4-11)). The coefficient of correlation obtained for PMLC specimens and road cores were -0.61 and -0.47, respectively.

$$COV_{PMLC} = -1.103 \times \overline{n} + 0.386 \quad (4\text{-}10)$$

$$COV_{Cores} = -0.393 \times \overline{n} + 0.177 \quad (4\text{-}11)$$

Although the linear correlation of the COV and average total AV content values is not strong, the relationships previously presented may be used to compute the variance of the distribution of total AV content values, since a parametric analysis showed limited sensitivity of the expected value of permeability to the variance of the total AV content.

4.7 SUMMARY AND CONCLUSIONS

This paper evaluates the suitability of the current approaches employed to assess the drainability of PFC mixtures during the mix design process and proposes alternatives to enhance this evaluation. Conclusions subsequently provided are based on the analysis of laboratory and field-testing results as well as the analytical computations conducted as part of this study:

- The current approaches used to evaluate drainability in PFC mixtures are based on either achieving a minimum total AV content or measuring permeability on laboratory-compacted specimens. The results gathered in this study suggest that these approaches do not constitute effective ways to evaluate whether adequate drainability is achieved in the field. The alternatives evaluated in this study to improve this evaluation included establishing: (*i*) the relationship of water-accessible AV content and laboratory-measured permeability, (*ii*) the relationship of laboratory and field drainability, and (*iii*) analytical prediction of permeability.
- The relationship between laboratory-measured permeability and water-accessible AV content values determined for PMLC specimens preliminarily indicate that this AV content may be used as a surrogate of the total AV content to indirectly assess permeability in PFC mixtures. However, improvements in the comparison of mixture internal structure of field- and laboratory-compacted mixtures are required before pursuing the determination of a useful relationship between permeability and water-accessible AV content. In addition, further research is required to determine if a relationship between laboratory-measured permeability and water-accessible AV content values measured for field-compacted mixtures (road cores) can be established.
- The relationship determined for water flow value (WFV) measured in the field and laboratory-measured permeability values (computed for road cores) suggest that the WFV constitutes a practical alternative to assess the field drainability of PFC mixtures. An important limitation of

this parameter is that it does not allow for computation of a permeability coefficient that can be compared to other permeability measurements determined in the field (using different devices) or in the laboratory.

- The expected value of permeability (computed according to Equation (4-5)) proved to be a better estimator of the laboratory-measured permeability values as compared to the deterministic evaluation of Equation (4-4). The application of the expected-value equation for mix design is possible as suggested in this paper. Although strong correlation was found between the expected value of permeability and values of laboratory-measured permeability determined for gyratory-compacted specimens, poor results were encountered when estimating the permeability measured for corresponding road cores. This fact constitutes a limitation in assessing the permeability of field-compacted mixtures based on estimations conducted using laboratory-compacted mixtures. Additional research was suggested to further improve the computations of the estimated value of permeability and is also required to obtain laboratory- and field-compacted mixtures with more similar internal structures that lead to evaluations that can better represent functionality and durability in the laboratory.

The following recommendations are drawn based on the analysis and conclusions previously indicated:

- Use the expected value (Equation (4-5)) as an estimator of permeability values for PFC mix design and evaluation. However, additional research should be conducted to assess the permeability of field-compacted mixtures based on estimations conducted using laboratory-compacted mixtures. Alternatively, the WFV can be used to assess the drainability of PFC mixtures in the field.
- The permeability evaluation included in this study focused on determining the initial drainability of PFC mixtures. However, future research should be performed to evaluate the AV clogging rate, service life, and corresponding actions to extend the service life of PFC mixtures.

5. EVALUATION OF DURABILITY TESTS FOR PERMEABLE FRICTION COURSE MIXTURES*

5.1 OVERVIEW

Durability of PFC is an important aspect to address when designing this type of hot mix asphalt. At present, several agencies perform the mix design of PFC primarily by determining volumetric mixture properties. This approach ensures adequate mixture functionality, but it does not guarantee mixture durability. This paper evaluates the Cantabro Loss test (or Cantabro test), the Hamburg Wheel-Tracking test (HWTT), and the Overlay test (OT) to determine the one most appropriate for mix design and laboratory performance evaluations. The Cantabro Loss test, performed in both dry and wet conditions, is recommended for PFC mix design to corroborate the suitability of the OAC defined based on volumetric determinations. The HWTT and the OT are not recommended, since the variability of the test results indicated that these tests may not be suitable for PFC mixtures.

5.2 INTRODUCTION

PFC are HMA mixtures placed at the surface of an asphalt pavement structure in a thin layer to produce several benefits for the traveling public in terms of safety, economy, and the environment (Alvarez et al. 2006). The use of PFC reduces the risk of hydroplaning and wet skidding; decreases splash and spray, fuel consumption, tire wear, and pavement noise; improves ride quality and visibility of pavement markings at night and in wet weather; and results in cleaner runoff when compared to dense-graded HMA (Button et al. 2004; Kearfott et al. 2005; Ruiz et al. 1990). PFC mixtures are new generation OGFC designed with a minimum of 18 % AV content to create a permeable structure.

To obtain the benefits described previously, a mix design system that produces both a functional and durable PFC mixture is required. Although a common mix design procedure for these mixtures does not currently exist, many states in the United States use the NCAT method (Kandhal 2002; Watson et al. 2004a; Watson et al. 2003), which includes an evaluation of both

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functionality and durability. However, volumetric mixture properties still constitute the main parameters in the design practice of several agencies for selecting the OAC. This design practice is oriented to guarantee mixture functionality, but it does not directly account for durability, which is still a main concern for PFC and OGFC performance.

At present an analytical model is not available to evaluate PFC performance in terms of durability, and important work also remains in terms of assessing the aging potential of PFC mixtures and the resulting effect on durability. Phenomenological approaches have been used to evaluate durability in OGFC and European porous asphalt mixtures similar to PFC. These approaches include the retained tensile strength ratio (TSR), the HWTT, and the Cantabro test. The TSR is used in Switzerland to design porous asphalt and was also proposed by NCAT to design new generation OGFC (Kandhal 2002; Watson et al. 2004a). Denmark reported the use of HWTT to evaluate permanent deformation of porous asphalt; and Australia, South Africa, and some European countries use the Cantabro test to design porous asphalt mixtures (Alvarez et al. 2006).

The current TxDOT PFC mix design procedure includes an evaluation of draindown (in TxDOT Texas test method Tex-235-F) and moisture susceptibility using the “boiling” test (Tex-530-C) on specimens produced at the OAC selected based on volumetric properties. PFC mixtures are fabricated using not only PG asphalts, but also AR, which exhibits different physical, chemical, and rheological properties compared with PG asphalts. The necessity of improving the limited evaluation of durability conducted at present on these particular mixtures, motivated additional research on the applicability of existing durability tests (used in dense-graded HMA and porous asphalt) to evaluate PFC mixtures. The main objective of this study is to recommend a durability test that can be included in PFC mix design to improve the determination of the OAC obtained based on volumetric properties.

This paper presents the results of this research including an evaluation of the Cantabro test, the HWTT, and the OT to determine the one most appropriate test for PFC mix design and laboratory performance evaluations. In addition, the paper contains an evaluation of the suitability of the test selected to differentiate the effect of material quality, AV content, and changes in the asphalt properties induced by subjecting compacted specimens to diverse conditioning processes. Furthermore, a preliminary durability comparison of PFC mixtures fabricated using both mixture systems (PG 76-22 and AR) is included. The paper contains the experimental design, the results and discussion, and a summary and recommendations.

5.3 EXPERIMENTAL DESIGN

The experimental design included two stages. The first stage allowed a comparison of the Cantabro test, the HWTT, and the OT to determine the one most suitable test for PFC laboratory durability evaluations. The experimental design of this stage included testing conducted on specimens of four different mixtures to identify the variability of test results and the possibility of differentiating the results with respect to total AV content and asphalt content in terms of selecting an OAC. The second testing stage focused on further evaluating the selected test to possibly differentiate the results with respect to material quality, AV content, and changes in the asphalt properties obtained after subjecting compacted specimens to diverse conditioning processes. The corresponding experimental design included testing LMLC specimens as required in a mix design procedure and PMLC specimens from nine different mixtures, however most of the evaluation was conducted using LMLC specimens from the I-35-PG and US-281-AR mixtures. This section of the paper includes descriptions of mix design and material requirements, material selection, mixture evaluation tests, specimen fabrication, and laboratory conditioning.

5.3.1 Mix Design and Material Requirements

Mix design was performed according to the current PFC mix design method defined in TxDOT Test Method Tex-204-F, Part V (TxDOT 2005). The mix design included an evaluation of draindown and moisture susceptibility, as previously indicated, conducted on specimens fabricated at the selected OAC, which is determined based only on volumetric properties. Item 342 of the 2004 TxDOT Standard Specifications book defines the material requirements for this design including master aggregate gradation bands based on the type of asphalt selected (TxDOT 2004). This specification allows the following two types of asphalts:

- Type I or II AR with a minimum of 15 % by weight of asphalt of Grade C or Grade B crumb rubber.
- PG asphalt with a minimum high temperature grade of PG76-XX, a minimum of 1.0 % by weight of dry aggregate of lime, and a minimum of 0.2 % by weight of mixture of cellulose or mineral fibers.

5.3.2 Material Selection

Both mixture systems that include different asphalts (AR and PG) and other materials and corresponding aggregate gradations were evaluated. These mixtures were also used in actual field projects. Table 5-1 provides details of the materials used for each mixture, and Table 5-2 and Table 5-3 present the aggregate gradations for these specific mixtures.

Table 5-1. Descriptions of Mixtures Used to Assess Durability

Mixture	TxDOT District	Asphalt Type	Opt. Asphalt Content, %	Aggregate Type	Other Materials	Specimen Type
I-35-PG	San Antonio	PG 76-22S	6.1	Sandstone[a] Limestone[b]	Lime (1 %) Fibers (0.3 %)	LMLC and PMLC
US-83-PG	Abilene	PG 76-22S	6.4	Limestone		PMLC
IH-20-PG	Abilene	PG 76-22	6.5	Limestone		PMLC
IH-30-PG	Paris	PG 76-22	6.6	Sandstone		PMLC
US-59-PG	Lufkin	PG 76-22	5.9	Granite Limestone		PMLC
US-59Y-PG	Yoakum	PG 76-22S	5.8	Limestone		PMLC
US-281-AR	San Antonio	AC-10 w/16 % crumb rubber	8.1	Sandstone[a] Limestone[b]	None	LMLC and PMLC
US-288-AR	Houston	AC-10 w/17 % Type II rubber	8.0	Granite Limestone	None	PMLC
US-290-AR	Austin	AC-10 w/17 % crumb rubber	8.3	Sandstone[a]	None	PMLC

[a] The same sandstone was used in all three mixtures. [b] The limestone used in the US-281-AR and I-35-PG mixtures is similar.

Table 5-2. Aggregate Gradations for PG Mixtures Used to Assess Durability

Sieve	Specification (% Passing)		I-35-PG (LMLC)	I-35-PG (PMLC)	US-83-PG	IH-20-PG	IH-30-PG	US-59-PG	US-59Y-PG
¾	100	100	100	100	100	100	100	100	100
½	80	100	89.8	90.3	90.5	85.3	81	80.2	84.5
3/8	35	60	59.5	59.5	50.9	59.4	43	57.7	52.8
#4	1	20	8	10.1	3.2	18.6	15.5	15.9	6.6
#8	1	10	4.8	5.2	1.5	2	6.7	6	4.2
#200	1	4	2.3	2.3	1.1	1.6	2.2	2.1	2.4

Table 5-3. Aggregate Gradations for AR Mixtures Used to Assess Durability

Sieve	Specification (% Passing)		US-281-AR (LMLC)	US-281-AR (PMLC)	US-288-AR	US-290-AR
¾	100	100	100	100	100	100
½	95	100	99	99	95.6	99.7
3/8	50	80	54.6	54.6	54.9	75.7
#4	0	8	5	5	4	7.9
#8	0	4	2	1.9	2.1	1.1
#200	0	4	1	1	0.8	0.6

5.3.3 Mixture Evaluation Tests

The tests evaluated corresponded to the Cantabro test, the HWTT, and the OT. The Cantabro test provides an indirect evaluation of mixture cohesion, resistance to disintegration, and aggregate interlock (Centro de Estudios y Experimentación de Obras Públicas (CEDEX) 1986). Although the test was originally proposed on dry specimens, since 2001 the Spanish have required performing the Cantabro test using specimens in both dry and wet conditions. The moisture conditioned test was introduced as a way to evaluate aggregate-asphalt combinations with poor adhesion, and the effect of low quality fillers, which were identified as responsible for accelerated mixture deterioration (i.e., raveling) (Ruiz et al. 1990). The Cantabro test was performed as described in Tex-245-F (TxDOT 2005) by placing a SGC compacted specimen 115 ± 5 mm in height and 150 mm in diameter into the Los Angeles abrasion machine without any abrasive load. The initial weight of the specimen (W_o) was compared to its final weight (W_f) obtained after applying 300 revolutions in the Los Angeles abrasion machine, to calculate the Cantabro loss as follows:

$$\text{Cantabro loss (\%)} = \frac{W_o - \left(W_f - \left(W_d - W_o\right)\right)}{W_o} \times 100 \tag{5-1}$$

where W_d is the weight of the specimen after drying to eliminate the water trapped during measurements of water-accessible AV content (defined as the proportion of the total volume of a compacted mixture that is accessible to water). For dry specimens, Equation (5-1) simplifies to:

$$\text{Cantabro loss (\%)} = \frac{W_o - W_f}{W_o} \times 100 \tag{5-2}$$

The Cantabro loss specification used in Spain for high traffic highways corresponds to a maximum of 20 and 35 % loss in dry and wet conditions, respectively (Alvarez et al. 2006); and research conducted by NCAT also recommended limiting the Cantabro loss evaluated in dry condition to 20 % (Watson et al. 2004a). Since PFCs are relatively new mixtures in Texas, long-term performance data in terms of mixture resistance to disintegration under field service conditions are not yet available for correlation with Cantabro loss values to suggest maximum Cantabro losses for PFC mixtures. However, based on previous research (Ruiz et al. 1990) that concluded that the Cantabro test was suitable to evaluate the resistance to disintegration (i.e., raveling) of similar porous asphalt mixtures with appropriate correlation to field performance, the Cantabro test was used to evaluate the durability of different PFC mixtures in the laboratory. Nielsen (2006) reported more recently the lack of correlation for porous asphalt mixtures, especially those constructed using modified asphalts.

Texas has used the HWTT since 2000 in different types of HMA mixtures as a tool for evaluating rutting and moisture damage susceptibility. The HWTT was conducted as defined for dense-graded HMA mixtures in Tex-242-F (TxDOT 2005) applying a repeated load of 705 N on two trimmed SGC molded specimens using a 47 mm wide steel wheel that rolls back and forth on the surface of the specimens while they are immersed in a water bath at 50°C. Specimens used in the HWTT were 62 ± 2 mm in height and 150 mm in diameter. Rut depths were measured during the test at 11 different positions along the wheel path, and the average rut depth from the three central measurements was reported. The minimum number of passes, at 12.5 mm rut depth tested at 50°C, specified for dense-graded HMA fabricated using PG 76-XX asphalt corresponds to 20,000 (TxDOT 2004).

The OT was conducted as defined for dense-graded HMA mixtures in Tex-248-F (TxDOT 2005) using the Texas Transportation Institute (TTI) Overlay Tester and SGC compacted specimen 57 mm in height and 150 mm in diameter. Furthermore, these specimens required saw cutting to the final dimensions and shape as indicated in Tex 248-F (TxDOT 2005). Thus, corresponding control of total AV content was based on cut specimens. For the OT, the specimen is glued on two metallic plates and the full depth of glue located in between the two metallic plates is manually notched to ensure measuring the actual specimen response starting at the first loading cycle. The width of the joint primarily depends on human/operator accuracy.

The Overlay Tester operates in a controlled-displacement mode (constant maximum displacement of 0.62 mm) to induce horizontal movement in the mobile plate to simulate the opening and closing of joints or cracks in old pavements beneath an overlay. The test is conducted at 25ºC, with a load rate of 10 sec per cycle and a repeated load applied in a cyclic triangular waveform. The cracking life (expressed as number of cycles) was calculated by applying a modified version of the load reduction method suggested by Zhou et al. (2006). In this study, the average of the 93 and 80 % load reduction levels for the first and the second load cycles, respectively, was used to establish the cracking life for PFC mixtures. The second cycle was included to take into account possible distortions in the first load cycle due to differences in the setting of the plates and induction of residual stresses. The pass/fail criterion proposed in previous research for dense-graded HMA corresponds to 300 cycles (Zhou et al. 2006). While the Cantabro test and the OT may be used to define a minimum asphalt content that limits mixture fracture and disintegration, the HWTT could be utilized to establish a maximum asphalt content that minimizes permanent deformation issues.

5.3.4 Specimen Fabrication

Replicate specimens were produced to maintain the total AV content in the range 20 ± 1 %. However, this range was modified to 18-20 % for the Cantabro test specimens compacted at the highest asphalt content of the I-35-PG and US-281-AR mixtures (LMLC specimens) and for the PMLC specimens due to practical difficulties encountered in producing replicate specimens within the initial AV range. Some HWTT and OT, and a more extensive set of Cantabro tests were also performed using specimens with lower and higher total AV content values compared to the range of 20 ± 1 % to evaluate the effect of this parameter on durability. For the Cantabro specimens, not only total AV content, but also water-accessible AV content was computed. The total AV content was calculated by applying both the vacuum method and dimensional analysis to determine G_{mb}, and water-accessible AV content was determined using the vacuum method. Details of these tests are documented elsewhere (Alvarez et al. 2009d).

5.3.5 Laboratory Conditioning

Since the HWTT test is performed with wet specimens, no special conditioning was applied after trimming the specimens to their final shape as indicated in Tex-242-F (TxDOT 2005). After cutting and determining G_{mb} for the OT specimens, these specimens were dried at room temperature for a minimum time of 24 hours under forced ventilation before testing.

The Cantabro test was performed on compacted specimens subjected in total to five different conditioning processes (dry, wet, low temperature, and 3- and 6-months aging). The dry and wet conditioning processes were selected to evaluate the mixture response in its original state (dry-no aging) and after inducing moisture damage using controlled laboratory conditions, respectively. The dry conditioning consisted of drying the specimens (after saturation to measure water-accessible AV content) for a minimum time of 24 hours using forced ventilation at room temperature (25°C). The wet conditioning required keeping the specimens for 24 ± 0.5 hours in a water bath with a constant temperature of 60°C, and then drying the specimens for 24 ± 0.5 hours using forced ventilation at room temperature (CEDEX 1992).

The low-temperature conditioning process allowed assessing the material response when the asphalt became stiffer and more susceptible to brittle fracture. In the field, these conditions favor raveling. The low temperature conditioning was similar to the dry conditioning, but instead of testing after drying, the specimens were first placed in a cool room at 3°C for a minimum time of 24 hours. Since the Los Angeles abrasion machine does not have temperature control, some variability was induced due to differences in ambient temperature. Differences of approximately 4.4 to 8.3°C between initial and final temperatures were measured during testing. Finally, to investigate the potential effect of asphalt aging on the loss of cohesion of PFC mixtures, compacted specimens were subjected to accelerated aging for 3 and 6 months in a temperature-controlled room at 60°C with heated air circulation.

5.4 RESULTS AND DISCUSSION

Table 5-4 presents the comparison of the durability tests in terms of the following criteria: (*i*) specimen preparation for testing, (*ii*) specimen fabrication to meet specific total AV content ranges, (*iii*) equipment availability in Texas, (*iv*) testing time, and (*v*) variability in the test results. The ease of specimen fabrication is expressed in terms of the COV of the total AV content of replicate specimens from the US-281-AR mixture, and the variability of test results was determined based on the results of LMLC specimens from the I-35-PG and US-281-AR mixtures at three different asphalt contents.

Table 5-4. Comparison of Durability Tests

Test, Testing Condition	Specimen Preparation for Testing	Variability of Total AV Content, COV	Availability of Equipment in Texas	Testing Time (hours)	Test Results Variability, COV
HWTT, wet	Saw trimming	0.030	Medium	5	0.02 to 0.57
OT, dry	Saw cutting, drying, final AV checking, and gluing	0.030	Low	2	0.22 to 1.17
Cantabro test, dry	Not required	0.016	High	0.3	0.07 to 0.36

Legend: HWTT = Hamburg Wheel-Tracking test, and OT = Overlay test; the COV for Cantabro tests conducted in wet, low temperature, and aged conditions were in the range of 0.06 to 0.47 for both I-35-PG and US-281-AR mixtures.

Based on these criteria, the Cantabro test is recommended over the HWTT and the OT for evaluating PFC mix durability. The following sections summarize the evaluation of results for these tests exploring in detail the variability of the test results presented in Table 5-4, and the possibility of differentiating the test results with respect to AV content and asphalt content in terms of selecting an OAC. This analysis provided additional rationale to recommend the Cantabro test. Consequently, additional testing using the Cantabro test was conducted to establish its potential to differentiate the effect of: (*i*) the change in the asphalt properties induced by applying different conditioning processes (dry, wet, low temperature, and aging), (*ii*) material quality, and (*iii*) AV content. Results from this additional testing program are also included subsequently.

5.4.1 Evaluation of Hamburg Wheel-Tracking Test (HWTT) Results

Figure 5-1(*a*) shows the rut depth and respective COV determined for the I-35-PG and US-59Y-PG mixtures after applying 20,000 load cycles in the HWTT, and Figure 5-1(*b*) shows the number of cycles required to reach a rut depth of 12.5 mm and respective COV for the US-281-AR and US-290-AR mixtures. These different types of testing are defined in Tex-242-F for rut resistant mixtures (Figure 5-1[*a*]) and for mixtures more susceptible to rutting (Figure 5-1[*b*]). The average values obtained for the I-35-PG mixture define the expected tendency corresponding to higher rut depths as the asphalt content increases, whereas the US-281-AR data do not indicate the same trend. However, in these two cases the variability plays an important role in the results and makes it difficult to assess the effect of asphalt content on the rut resistance of these mixture systems. These results agree with previous studies that indicate that the variability in the HWTT results should be included in evaluating dense-graded HMA (TxDOT 2006). Data collected in this study suggest that a COV of approximately 0.15 is a representative value, although extreme values of 0.57 and 0.02 suggest that this index can vary substantially.

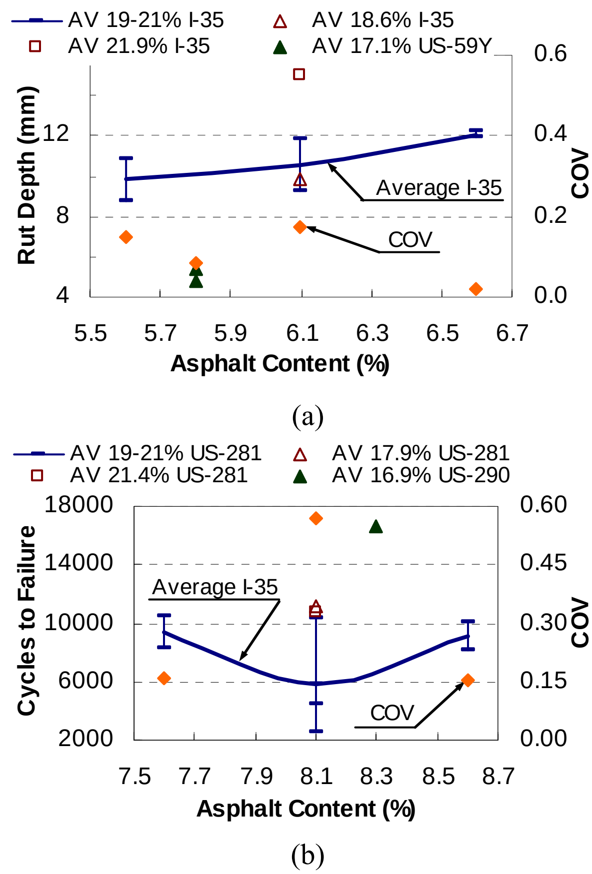


Figure 5-1. Hamburg Wheel-Tracking Test (HWTT) Results for (a) I-35-PG and US-59Y-PG and (b) US-281-AR and US-290-AR Mixtures

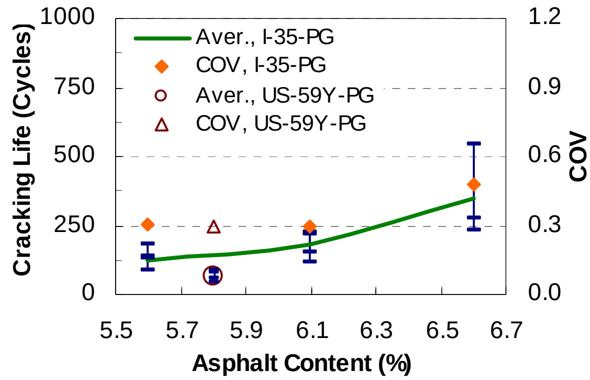
The effect of AV content on HWTT results is not clear, most likely due to the variability in the test results. For example, the US-281-AR mixture specimens with total AV content values of 17.9, 19.8, and 21.4 % showed similar number of cycles to failure. However, the smaller total AV content of specimens from the US-59Y-PG and US-290-AR mixtures (compared respectively to their PG and AR counterparts) may explain the improved performance of the

US-59Y-PG and US-290-AR mixtures in the HWTT. Additional data are required to establish rutting resistance as a function of AV content in PFC mixtures.

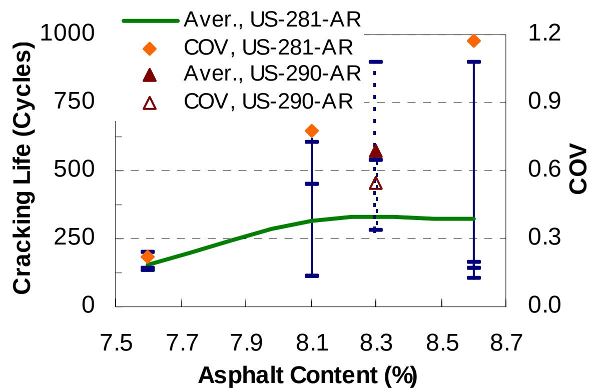
5.4.2 Evaluation of Overlay Test (OT) Results

The cracking life values (expressed as number of cycles to failure) and respective COV obtained from the OT are shown in Figure 5-2. While the I-35-PG mixture data represent the expected tendency (longer cracking life should be obtained as the asphalt content increases), the US-281-AR mixture may reflect the improvements that a higher asphalt content should offer. Substantially higher COV were obtained with the OT data, especially for the AR mixture system, as compared to the HWTT and the Cantabro loss data. Data gathered as part of this study suggest that a COV of approximately 0.30 is a representative value, although extreme magnitudes of 0.78 and 1.17 for the AR mixtures suggest that this index can vary substantially for the OT. This variability is expected to contribute substantially to any conclusions drawn from the data.

The effect of total AV content on cracking life is shown in Figure 5-3. This data set provides evidence of a poor relationship between these variables for the PFC mixtures studied. The high variability of the cracking life values determined on both LMLC and PMLC specimens is an additional element that impedes establishing the response of the mixture in terms of AV content and cracking life. The amount, distribution, and, probably most important, the ratio of void sizes to sample dimensions (150 mm long by 75 mm wide by 38 mm high) probably have an important effect on the variability of the cracking life values because the voids may be large enough to influence the development of cracking during the test. Additional research is required to evaluate whether modifications in the specimen size, failure criterion, and the testing setup (e.g., loading time, width of the joint, and maximum displacement) can reduce the variability in the OT results.

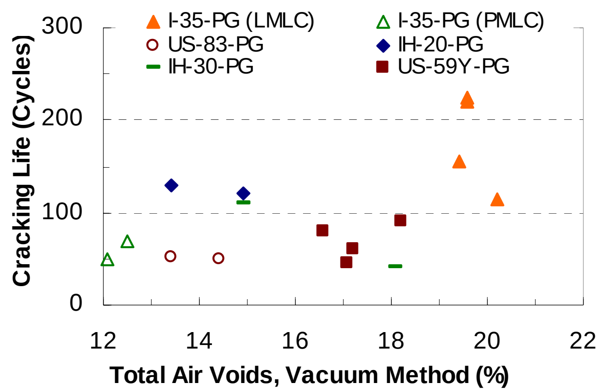


(a)

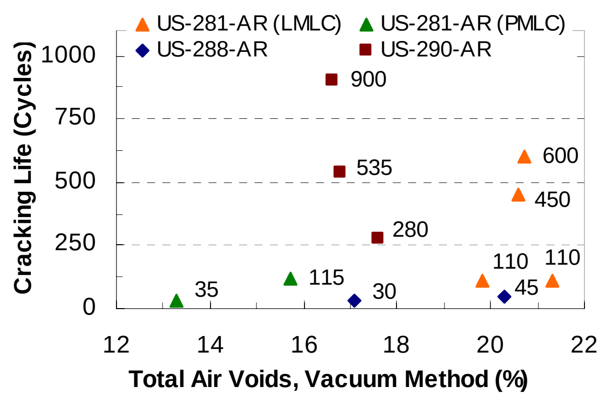


(b)

Figure 5-2. Overlay Test (OT) Results for (a) I-35-PG and US-59Y-PG, and (b) US-281-AR and US-290-AR Mixtures



(a)

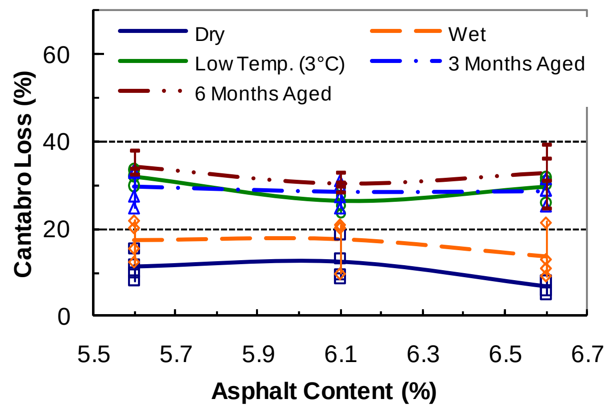


(b)

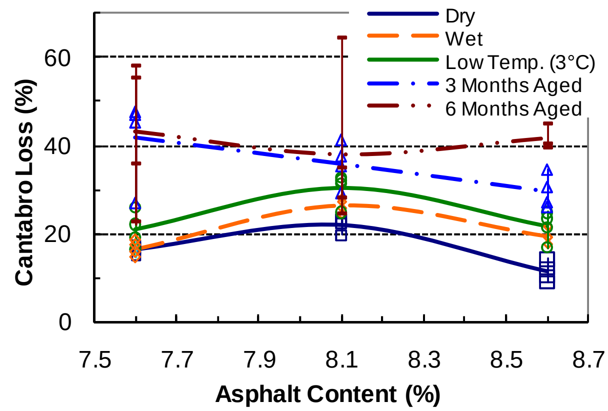
Figure 5-3. Effect of Air Voids (AV) Content on Overlay Test (OT) Results for (a) PG and (b) AR Mixtures (Plant Mixed-Laboratory Compacted (PMLC) Specimens)

5.4.3 Evaluation of Cantabro Loss Test Results

Data presented in Figure 5-4 show the Cantabro test results at different conditions and asphalt contents. The Cantabro loss comparison presented in Figure 5-5 includes results from specimens compacted using 50 gyrations (50G) and 15 gyrations (15G) applied by the SGC, which permitted obtaining similar AV contents for all four mixtures and allowed direct comparison of these mixtures. Data corresponding to wet and aged specimens (3 and 6 months) for the US-290-AR mixture fabricated by applying 15 gyrations are not presented in Figure 5-5 because these specimens disintegrated during the conditioning processes at high temperature (60°C).



(a)



(b)

Figure 5-4. Average Cantabro Loss for Different Conditioning Processes in (a) I-35-PG and (b) US-281-AR Mixtures (Laboratory Mixed-Laboratory Compacted (LMLC) Specimens)

Cantabro loss data presented in Figure 5-4 and Figure 5-5 suggest that for the mixture systems studied, the Cantabro test was sensitive to changes in chemical and viscoelastic properties of the asphalt. Although quantification of fundamental properties related to those changes is not provided, the Cantabro test offered an indirect indication of the potential effect of those changes on the PFC mixture resistance to disintegration, which has been associated with mixture durability and resistance to abrasion (Ruiz et al. 1990). In addition, for the mixtures included in this study the Cantabro test indicated that the properties of the aggregate may have a greater influence on the mixture performance evaluated in the laboratory than the asphalt does. This result agrees with the findings reported by Molenaar et al. (2006) on the relative importance of the mixture composition parameters assessed using Artificial Neural Networks analysis applied to porous asphalt. Furthermore, as discussed subsequently, the Cantabro loss values showed a direct relationship with water-accessible AV content, and thus provided an indication of the importance of the volumetric properties on the durability of PFC mixtures. The following subsections provide further discussion of these general conclusions.

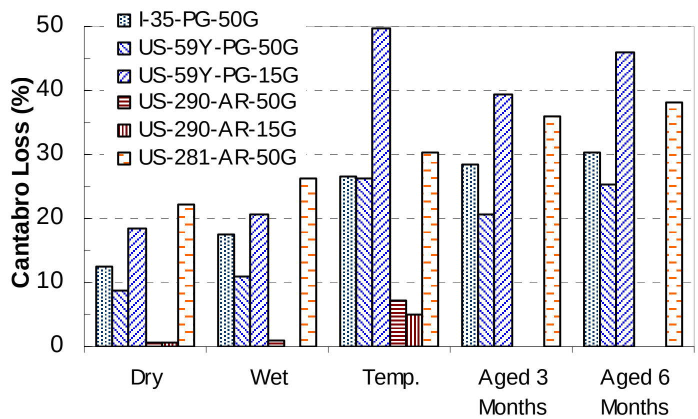


Figure 5-5. Cantabro Loss at Optimum Asphalt Content (OAC) for Different Conditioning Processes

Despite these positive results, the trends and the variability in Cantabro loss values obtained for the mixtures systems included in this study suggest that the Cantabro test may not provide enough sensitivity to be selected as a definitive tool for determining the OAC of PFC mixtures based on durability. However, the Cantabro test is a simple and quick test that may be useful as an initial screening tool for selecting material combinations to include in more advanced testing toward selection of the OAC.

Effect of Different Conditioning Processes on Cantabro Loss and Selection of Optimum Asphalt Content (OAC)

The COV of the Cantabro loss values obtained for LMLC specimens in the dry condition of the I-35-PG and US-281-AR mixtures were in the range of 0.07 to 0.36. These magnitudes are comparable to those obtained in the HWTT and smaller than those calculated for the OT results. In addition, the COV of the Cantabro loss values determined on LMLC specimens in wet, low temperature, and aged conditions were in the range of 0.06 to 0.47 for both I-35-PG and US-281-AR mixtures.

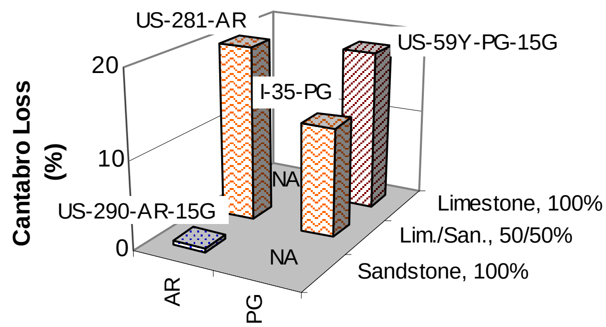
In contrast, results from t-tests at a 95 % significance level conducted using the Cantabro loss data at the OAC showed for the US-281-AR mixture that the average loss in the dry condition is statistically different from that in the other conditions (wet, low temperature, and 3 and 6 months aged). The same conclusion is valid for the I-35-PG mixture, except that the average losses in the dry and wet conditions are statistically equivalent at a 95 % significance level. This analysis shows that statistically different Cantabro loss values were obtained for specimens tested after applying different conditioning processes used to induce modifications in the asphalt chemical properties through moisture conditioning and aging and visco-elastic properties through low temperature conditioning. This result suggests that the Cantabro test was sensitive to the changes induced to alter mixture resistance to disintegration. However, when each mixture system was analyzed independently based on both the average and the variability of the Cantabro loss values, the effect of asphalt content on the mixture resistance to disintegration cannot be accurately differentiated. This fact suggests that the Cantabro test may not provide enough sensitivity for selection as a definitive tool for determining the OAC of PFC mixtures.

The comparison of the Cantabro loss obtained in the dry condition and those established after 3 and 6 months of aging shows an important effect of asphalt aging on mixture resistance to disintegration. However, the difference in Cantabro loss for specimens tested after 3 and 6 months of aging is consistently smaller than that obtained by comparing the results of aged and dry specimens. This finding may indicate a decreasing rate of aging with time and/or the existence of an initial jump in aging that occurred after a short time as suggested by Glover et al. (2005) in previous research on asphalt durability.

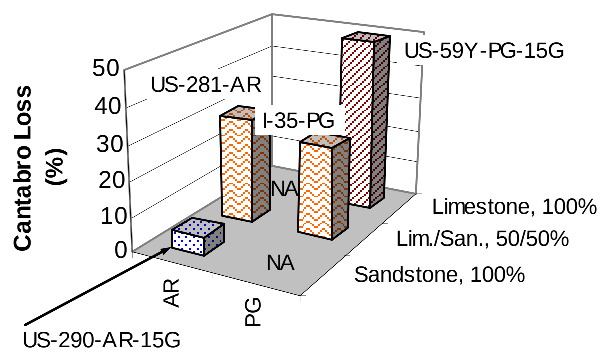
Effect of Material Quality on Cantabro Loss

Comparison of the results presented in Figure 5-6 illustrates the effect of different material combinations on the mixture resistance to disintegration evaluated using Cantabro loss. The US-290-AR and US-281-AR mixtures were produced with the same type of asphalt and their OAC differs by 0.2 percentage points, but the aggregate composition was substantially different. The differences in the Cantabro loss values in dry and low temperature conditions for these two mixtures may be mainly related to the effect of the type of aggregate on mixture resistance to disintegration as discussed subsequently. The same comparison can be established for the

I-35-PG and US-59Y-PG mixtures, which were fabricated with similar asphalts and small differences in OAC (0.3 percentage points), but again the aggregate composition was different.



(a)



(b)

Figure 5-6. Cantabro Loss Comparison at Optimum Asphalt Content (OAC) for (a) Dry and (b) Low Temperature Conditioned Specimens
Note: NA = information is not available.

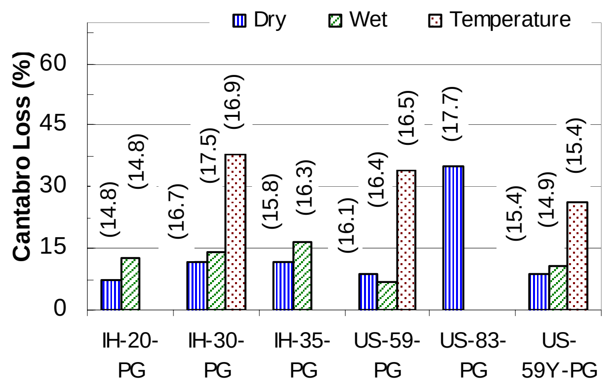
As discussed in the next section, differences in total AV content may partially explain the differences in Cantabro loss for the compared mixtures. However, the influence of this AV content is believed to be minimal, since the total AV contents of the specimens were similar. In addition, although the compaction energies were different in order to reach similar AV contents in specimens of diverse mixtures, the fact that most of the compaction is completed with 15 gyrations of the SGC permits the comparison of the Cantabro loss as discussed. Thus, the differences in Cantabro loss can be related at least to two other mechanisms: (*i*) aggregate breakage during compaction and (*ii*) asphalt-aggregate interaction.

First, higher Cantabro loss values are expected as the mixture becomes more prone to disintegration due to the presence of unbound aggregate particles produced by crushing. Direct observation of both laboratory-compacted specimens and road cores cut in the laboratory showed evidence of aggregate crushing induced by compaction. This phenomenon primarily affected the soft limestone used in the mixtures studied. Watson et al. (2003) also reported aggregate breakage of OGFC induced by compaction, which ranged from approximately 10 % on the No. 4 sieve (4.75 mm) to zero on the No. 200 sieve (0.075 mm) for the mixtures studied. Specimens compacted by applying 30 and 60 gyrations of the SGC exhibited similar breakdown (Watson et al. 2003). Second, the reduced Cantabro loss in the US-290-AR and I-35-PG mixtures compared to that computed for the US-281-AR and US-59Y-PG mixtures, respectively, can most likely be associated with a better interaction (higher work of adhesion) between aggregate and asphalt in the US-290-AR and I-35-PG mixtures, which contain aggregates of comparatively higher quality. Additional research performed to evaluate the surface free energy of the aggregates and asphalts used in these four mixtures and respective calculations of work of adhesion in both wet and dry conditions did not show a defined relationship between work of adhesion and Cantabro loss (Alvarez et al. 2008b). This shows that another parameter related to the mechanical response of the mixture is required to fully explain the mixture response.

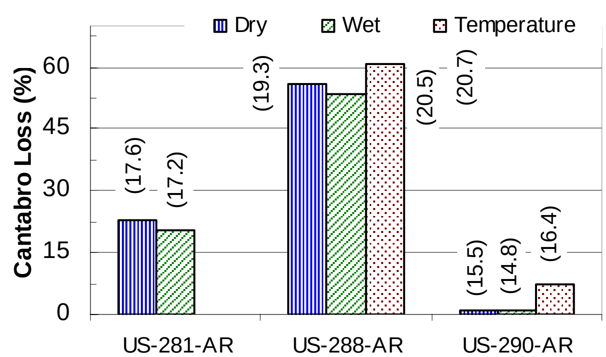
In addition, since the aggregate composition and the water-accessible AV contents are approximately equal for the US-281-AR and the I-35-PG mixtures, the magnitude of the differences in Cantabro loss between these specific mixtures (Figure 5-6) shows that the type of asphalt also plays a role in the mixture resistance to disintegration and therefore possibly to raveling. Comparison of the differences in Cantabro loss for the mixtures in Figure 5-6 leads to the conclusion that the influence of aggregate type is greater than that of the asphalt. Dissimilarities in gradation between AR and PG mixture systems may also be related to the differences in Cantabro loss of these two types of mixtures, although this aspect may be indirectly reflected in the Cantabro loss through AV content and the effect of a different OAC on these mixtures.

Figure 5-7 shows the average Cantabro loss values measured for PMLC specimens and respective average total AV content values computed using the vacuum method. These Cantabro loss values were obtained from two specimens in each case except for those corresponding to the

IH-20-PG wet conditioned mixture and the IH-30-PG low temperature conditioned mixture, which are results based on one available specimen. Due to differences in AV contents, the Cantabro loss values shown in Figure 5-7 were not directly compared to those presented in Figure 5-6. However, the comparison of data presented in Figure 5-7 illustrates similar tendencies to those shown in Figure 5-6, except for the values determined for the I-35-PG and US-59Y-PG mixtures. The inversion of Cantabro loss values of these mixtures can be related to the variability of this parameter.



(a)



(b)

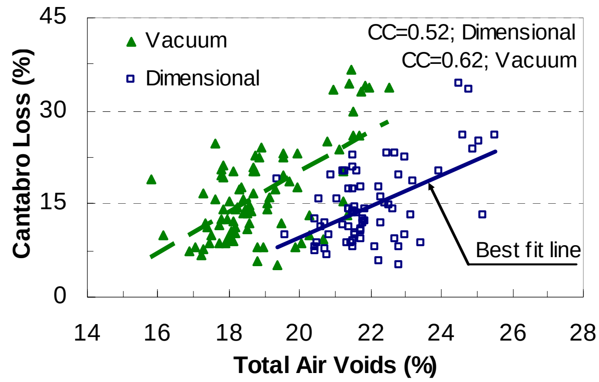
Figure 5-7. Cantabro Loss of Plant Mixed-Laboratory Compacted (PMLC) Specimens for (a) PG and (b) AR Mixtures

The comparison of the Cantabro loss obtained for the US-83-PG, IH-20-PG, and US-59Y-PG mixtures, fabricated using limestone from three different sources and similar PG asphalts, illustrates the important effect of each particular combination of materials on the mixture resistance to disintegration. In this case, differences in both asphalt and aggregate material properties may explain the substantial differences in Cantabro loss of these mixtures that have similar compositions. On the other hand, the effect of two aggregate combinations can be observed by comparing the Cantabro loss values of the I-35-PG and US-59-PG mixtures constructed with sandstone and limestone and granite and limestone, respectively. Similarly, Cantabro loss values ordered by increasing magnitude for the AR mixtures (Figure 5-7[*b*]) were reported for the US-290-AR, US-281-AR, and US-288-AR mixtures, which contain sandstone, sandstone and limestone, and granite and limestone, respectively, and were fabricated with similar AR.

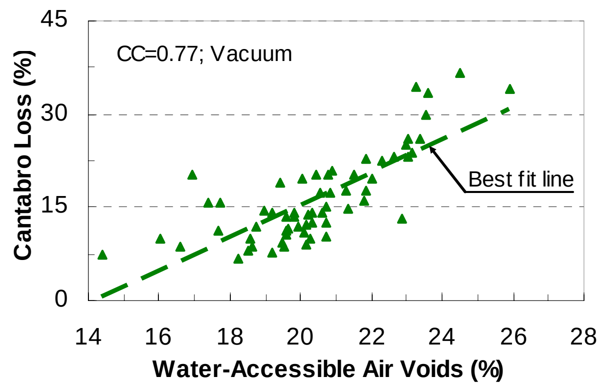
Effect of Air Voids (AV) Content on Cantabro Loss

In addition to the effect of the combination of materials, the Cantabro loss in both mixture systems (PG and AR) showed a direct relationship with AV content, which is in agreement with previous research on the effect of density and corresponding AV content on field performance of porous asphalt and OGFC. For example, in Spain, inadequate compaction has been identified as one of the causes of rapid failure in terms of raveling of porous asphalt mixtures (Ruiz et al. 1990), and Huber concluded that OGFC is more susceptible to raveling than dense-graded HMA when low densities are obtained (Huber 2000).

The Cantabro loss values showed a better relationship, as indicated by a higher coefficient of correlation, with water-accessible AV content values than with total AV content values (Figure 5-8). Water-accessible AV as connected pathways of mixture discontinuities can initiate mixture disintegration if they act as potential interconnected fracture paths. Data shown in Figure 5-8 provide rationale for recommending evaluation of PFC durability in terms of water-accessible AV content instead of total AV content. In addition, based on the relationship between the Cantabro loss and the mixture resistance to disintegration indicated by Ruiz et al. (1990), these results suggest the necessity of including the control of density in the field as an additional aspect to obtain adequate PFC mixture durability.



(a)



(b)

Figure 5-8. Cantabro Loss (Dry Condition) Compared with Total Air Voids (AV) Content (a) and Water-Accessible Air Voids Content (b) for I-35-PG and US-281-AR Mixtures
Note: CC = coefficient of correlation.

5.4.4 Comparison of Asphalt Rubber (AR) and Performance Grade (PG) Mixture Systems

AR and PG mixture systems are compared in this section based on the previous laboratory durability evaluation. The comparison of these mixture systems was based on data gathered from I-35-PG and US-281-AR laboratory mixtures because they were similar in aggregate composition and total AV content values. At the OAC established from volumetric mixture properties (6.1 and 8.1 % for the I-35-PG and US-281-AR mixtures, respectively) and for all Cantabro test conditions except low temperature, the I-35-PG mixture exhibited smaller Cantabro losses as compared to the US-281-AR mixture (Figure 5-4[*a*] and Figure 5-4[*b*]). This result could be an indication of better resistance to disintegration of the PG mixture system, assuming the same aggregate is used. However, the ratios of Cantabro loss established for the

I-35-PG mixture (Figure 5-9) indicate that the proportional effect of the conditioning processes, which may represent the modification that the asphalt properties can experience in the field, is higher for the PG mixture system compared to the AR mixture system. The ratios of low temperature to dry Cantabro loss shown in Figure 5-9 suggest that the effect of low temperature on the Cantabro loss could be higher in PG mixtures than in AR mixtures. This result may have an important effect on the mixture response to disintegration in the field when temperature decreases and the asphalt becomes stiffer.

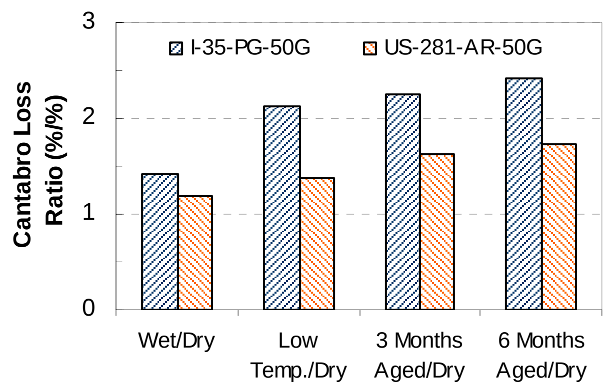


Figure 5-9. Cantabro Loss Ratio at Optimum Asphalt Content (OAC) for Different Conditioning Processes

Test results from the HWTT showed the I-35-PG mixture to be more resistant to permanent deformation as compared to the AR mixture. This comparison is reasonable in terms of similar materials and comparable AV contents, but the result is limited by the fact that the aggregate gradations are different as required by specifications. Test results from the OT may suggest the US-281-AR mixture to be more resistant to cracking, where the maximum number of cycles to failure was greater. However, the variability of the test results restricts this analysis.

In summary, test results from the Cantabro test, the HWTT, and the OT suggest that the PG mixture is more resistant to rutting, cracking, and raveling as compared to the AR mixture evaluated in this study. However, the high variability and the lack of defined trends in the test results for the AR mixture might be an indication of the limitations of these tests to capture the response of this particular material. The lack of defined trends in the mixture response as the AR asphalt content increases may be associated with limited development of the potential modification that the crumb rubber might induce in the asphalt due to the large particle size of the specified crumb rubber. As suggested in previous research, smaller crumb rubber particles (0.18 mm) may more easily promote the formation of a tridimensional network of rubber within the AR asphalt that can substantially change its rheological properties (Estakhri et al. 1993).

5.5 SUMMARY AND RECOMMENDATIONS

The Cantabro test, the Hamburg Wheel-Tracking test (HWTT), and the Overlay test (OT) were assessed as potential tools for mix design and laboratory performance evaluations of PFC mixtures using two mixture systems with different asphalts (PG and AR), aggregate gradations, and other materials. The following conclusions are stated based on the results and discussion presented:

- The Cantabro test is recommended to evaluate the durability of PFC mixtures during the mix design stage and production. The HWTT and the OT are not recommended at this time to evaluate mixture performance of PFC mixtures. The variability of the test results from this study indicate that these tests may not be suitable for PFC mixtures. However, future assessment is required to establish the actual service life of PFC mixtures in the field, failure mechanisms, and their relationship with the laboratory evaluations presented, since most of the PFC mixtures constructed at present in Texas have been in service for a maximum of approximately five years.
- The trends and the variability in Cantabro loss values obtained for the mixtures included in this study suggest that the Cantabro test may not provide enough sensitivity to become a definitive tool for selecting the OAC of PFC mixtures. However, the Cantabro test is a simple and quick test that may be useful as an initial screening tool for selecting material combinations to include in more advanced testing towards selection of the OAC. In the absence of any analytical model or any other test to evaluate PFC durability, the Cantabro test can be used to corroborate the suitability of the OAC defined based on volumetric determinations.
- The Cantabro loss values of the mixtures evaluated in this study suggest that mixture resistance to disintegration is affected more by aggregate properties than by those of the asphalt.
- The Cantabro loss values showed a direct relationship with water-accessible AV content values, providing an indication of the importance of the volumetric properties on the durability of PFC mixtures. Additional research relating laboratory and field performance is recommended

to establish a maximum AV content (minimum density) to prevent mixture disintegration problems based on a maximum allowable Cantabro loss.

- Additional research to develop an improved mix design system to evaluate the durability of PFC mixtures supported by material properties and analytical models is recommended. Potential advantages of this type of approach include less variability compared to that reported for the tests evaluated in this research, better understanding of material response (especially for the AR mixtures), and an improved relationship with field performance.

The conclusions and analysis developed from data gathered in this study lead to the following recommendations:

- Utilize the Cantabro test in both dry and wet conditions to evaluate mixture durability in the laboratory and to select the final OAC. Since temperature variation is an important source of variability in the Cantabro loss, conducting the test in a controlled temperature environment at 25°C is recommended.
- Direct future research efforts toward the development of a more fundamental analytical model that provides a better understanding of PFC mixture performance and a more reliable mix design method.
- Specify density requirements for field compaction.

6. EFFECTS OF DENSIFICATION ON PERMEABLE FRICTION COURSE MIXTURES*

6.1 OVERVIEW

Compaction of PFC mixtures is generally considered a process without major issues, and field density requirements (or corresponding total AV content) are not currently specified for this type of HMA. However, proper densification is one of the most important aspects to control during construction to prevent raveling, the distress most frequently reported as the cause of failure in these mixtures. This paper presents an evaluation of the effect of densification on PFC mixtures. This evaluation included both the study of the internal structure of compacted mixtures and a comparison of performance based on macroscopic response. Results from this study showed that differences encountered in the internal structure of road cores and specimens compacted using the SGC limit the use of these laboratory-compacted specimens in durability and functionality evaluations of PFC mixtures. In addition, changes in densification, after reaching stone-on-stone contact, modified the mixture properties and performance. The magnitude of these modifications provided evidence of the ease of verifying not only stone-on-stone contact during mix design, but also of the importance of controlling the density during construction to ensure an equilibrium density that guarantees the balance between mixture durability and mixture functionality.

6.2 INTRODUCTION

PFC mixtures, or new generation OGFC, are special asphalt mixtures characterized by a high AV content (minimum 18 %) as compared to the most commonly used dense-graded HMA. Placed as a thin surface layer, the PFC mixture reduces the risk of hydroplaning and wet skidding, decreases splash and spray, and improves visibility of pavement markings in wet weather (Alvarez et al. 2006). These benefits are realized as water travels through connected AV within the mixture instead of over the surface. Consequently, driving safety is greatly improved, especially in wet weather. In addition, compared to dense-graded HMA, PFC offers better riding quality, cleaner runoff, and reduction of pavement noise (Button et al. 2004; Kearfott et al. 2005;

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* Reprinted with permission from "Effects of Densification on Permeable Friction Course Mixtures" by Allex E. Alvarez, Amy Epps Martin, and Cindy Estakhri, 2009. *Journal of Testing and Evaluation,* 37 (1), 11-20, Copyright [2009] by ASTM International.

Ruiz et al. 1990). These advantages make PFC the safest, cleanest, and quietest alternative currently available for surface paving.

The current mix design procedure used to determine the OAC of PFC mixtures is based on volumetric properties, primarily density. The specified density range for mix design corresponds to 82 to 78 % (or corresponding total AV content between 18 and 22 %), and the target density selected in this range to determine the OAC is evaluated on specimens compacted at 50 gyrations of the SGC (TxDOT 2005). Since volumetric mixture properties are primarily used to design PFC mixtures, field density, or corresponding total AV content, should be required as a parameter of quality control related to mixture compaction.

The control of density is also important from the point of view of mixture durability. Raveling is the distress most frequently reported as the cause of failure in new generation OGFC mixtures (Huber 2000). This distress can be associated not only with aging asphalt (oxidation and hardening), asphalt softening generated by oil and fuel drippings from traffic accidents, or insufficient asphalt content, but also with inadequate compaction (California Department of Transportation (Caltrans) 2006; Chopra and Andre 2000; Kuennen 2007). In fact, although compaction is generally considered a process without major issues in this type of mixture, improper compaction has been identified in Spain as one of the causes of rapid failure (by raveling) of similar porous asphalt mixtures (Alvarez et al. 2006). Huber (2000) also concluded that OGFC is more susceptible to raveling than dense-graded HMA when low densities are obtained. In addition, based on finite element modeling of the stress state in porous asphalt mixtures, Mo et al. (2007) indicated the positive effect of increasing the densification in this type of mixture. Moreover, based on Artificial Neural Network techniques Molenaar et al. (2006) suggested limiting the AV content to 24 % to avoid premature raveling (within five years) of single layer porous asphalt. Preliminary laboratory evaluations showed the decrease in mixture resistance to disintegration, determined using the Cantabro loss test, as the AV content of porous asphalt mixtures increases (Khalid and Pérez 1996; Pérez and Gordillo 1990). Recent research provided additional evidence of this relationship for OGFC (Hassan and Al-Jabri 2005) and PFC mixtures (Alvarez et al. 2009e).

Despite the importance with respect to mixture durability, field density requirements are not currently specified. In general, compaction of the mixture to a minimum density has not been considered a necessity. Only in Spain, the acceptance criterion for field compaction of porous asphalt mixtures corresponds to a maximum difference of 2 % in total AV content in comparison with the reference AV content, which is computed on Marshall compacted specimens fabricated by applying 50 blows twice (Dirección General de Carreteras-Ministerio de Fomento 2004). Recognizing the importance of compaction on mixture durability, Nicholls and Carswell (2001) suggested the comparison of Cantabro loss values determined during mix design and those computed for road cores. Although they recognized that differences in compaction patterns should lead to differences in Cantabro loss, substantial increases in this parameter compared to the mix design values should indicate inadequate compaction.

On the other hand, a minimum total AV content is required to ensure proper mixture functionality (in terms of drainability and noise reduction properties). This minimum AV content has been indirectly evaluated in the field by some agencies. For example, a specified field hydraulic conductivity is required in England to account for drainability of porous asphalt mixtures (Alvarez et al. 2006). Similarly, a field assessment of drainability is conducted for PFC mixtures in Texas after completing mixture compaction (TxDOT 2005). However, the current practice in most agencies for mixture approval is based on the evaluation of asphalt content and gradation and visual inspection of the mixture after compaction to evaluate (qualitatively but not quantitatively) the density, material variability, and segregation. Essentially all agencies specify a minimum smoothness (Huber 2000).

Taking into account durability and functionality requirements, the design and construction of a PFC mixture should lead to a compacted mixture with an equilibrium density. After properly seating the aggregates to ensure stone-on-stone contact, the equilibrium density should lead to a total AV content higher than the minimum that guarantees the expected functionality and smaller than the maximum that can lead to durability problems (in terms of raveling and permanent deformation). These durability problems may be realized when incomplete seating of aggregates leads to poor aggregate interlock to resist the shear stresses induced by vehicle loads and the mixture response relies in higher proportion on the cohesion provided by the asphalt. Since there is limited information available at present to establish whether the current PFC mix design and construction practices are leading to mixtures that satisfy this balance of functionality and durability, corresponding research was conducted. Results of this research are presented in this paper.

Following a statement of the objective and methodology, the paper contains experimental design, results and discussion, and a summary and recommendations.

6.3 OBJECTIVE AND METHODOLOGY

The overall objective of this study focused on evaluating the effect of densification on PFC mixture properties and performance. This evaluation included both the study of the internal structure of compacted mixtures and a comparison of performance based on macroscopic response. For this purpose, the study was divided into the following steps:

- Determination and comparison of the total AV content obtained under both field and mix design compaction conditions and reproduction in the laboratory of these total AV contents.
- Evaluation of the internal structure of mixtures compacted in both the field and the laboratory (at two different levels of densification) using X-ray CT and image analysis.
- Comparison of mixture properties and laboratory performance including the following aspects: stone-on-stone contact, density, durability, and functionality (in terms of laboratory and field drainability).

6.4 EXPERIMENTAL DESIGN

This section presents the experimental design defined for this study, which includes mix design, material requirements, material selection, specimen fabrication, and laboratory and field testing.

6.4.1 Mix Design and Material Requirements

Mix design was performed according to the current TxDOT PFC mix design method (TxDOT 2005). Corresponding material specifications include master aggregate gradation bands for each of the following two types of asphalt binders allowed for PFC mixtures (TxDOT 2004):

- a Type I or II AR with a minimum of 15 % by weight of asphalt of Grade C or Grade B crumb rubber.
- a PG asphalt with a minimum high temperature grade of PG76-XX with a minimum of 1.0 % by weight of dry aggregate of lime and a minimum of 0.2 % by weight of mixture of cellulose or mineral fibers.

6.4.2 Material Selection and Specimen Fabrication

A total of seven PFC mixtures produced in the field (plant mixed) and used in actual field projects were employed in this study to compare the total AV content obtained under field and laboratory compaction conditions. The total AV content achieved in the laboratory and in the field were computed, respectively, on PMLC specimens (150 mm in diameter and 115 ± 5 mm in height) and road cores (150 mm in diameter and 31 to 52 mm in height). However, cores of 21 to 25 mm in height were used to assess the US-83-PG mixture. Fabrication of the PMLC specimens required reheating the mixtures to the compaction temperature and applying 50 gyrations of the SGC (for this specific comparison) as currently specified for mix design (TxDOT 2005). The compaction temperature used was 149°C for both PG (76-22) and AR asphalts as recommended in the PFC mix design procedure (TxDOT 2005) and by the AR supplier, respectively. All specimens used in this study were cooled in the compaction mold before extrusion to preserve the internal structure of the compacted mixtures. Table 6-1 provides details of the materials used to produce each of these mixtures, and Table 6-2 presents corresponding aggregate gradations.

Table 6-1. Description of Mixtures Used to Assess the Effects of Densification

Mixture	TxDOT District	Asphalt Type	Opt. Asphalt Content, %	Aggregate Type	Other Materials
I-35-PG	San Antonio	PG 76-22S	6.1	Sandstone Limestone	Lime (1 %) Fibers (0.3 %)
US-59Y-PG	Yoakum	PG 76-22S	5.8[a]	Limestone	
IH-30-PG	Paris	PG 76-22	6.6	Sandstone	
US-83-PG	Abilene	PG 76-22S	6.4	Limestone	
US-281-AR	San Antonio	AC-10 w/16 % Crumb Rubber	8.1	Sandstone Limestone	None
US-290-AR	Austin	AC-10 w/17 % Crumb Rubber	8.3	Sandstone	None
US-288-AR	Houston	AC-10 w/17 % Type II Rubber	8.0	Granite Limestone	None

[a]Proportion used to produce the plant mix. The optimum asphalt content from mix design was 6.2 %.

Table 6-2. Aggregate Gradations for PG and AR Mixtures Used to Assess the Effects of Densification

Sieve	Specification (% Passing)		I-35-PG	US-59Y-PG	IH-30-PG	US-83-PG	Specification (% Passing)		US-281-AR	US-290-AR	US-288-AR
3/4	100	100	100	100	100	100	100	100	100	100	100
1/2	80	100	90.3	84.5	81	90.5	95	100	99	99.7	95.6
3/8	35	60	59.5	52.8	43	50.9	50	80	54.6	75.7	54.9
#4	1	20	10.1	6.6	15.5	3.2	0	8	5	7.9	4
#8	1	10	5.2	4.2	6.7	1.5	0	4	1.9	1.1	2.1
#200	1	4	2.3	2.4	2.2	1.1	0	4	1	0.6	0.8

The comparison of mixture properties and performance at different levels of densification was conducted on PMLC specimens, similar to the PMLC previously defined, from the US-59Y-PG and US-290-AR mixtures. These specimens have the same characteristics as those currently used for PFC mix design (TxDOT 2005). However, the HWTT and the OT required specimens compacted using the SGC to dimensions of 150 mm in diameter and 62 ± 2 mm and 57 mm in height, respectively.

6.4.3 Laboratory and Field Testing

The laboratory assessment was conducted on replicate PMLC specimens subjected to the following sequence of testing: G_{mb} measurement, X-ray CT scanning, water-accessible AV content determination, laboratory permeability test, and durability test. G_{mb} and water-accessible AV content computations and X-ray CT scanning were conducted on road cores.

The calculation of both G_{mb}, for total AV content computation, and water-accessible AV content (proportion of the total volume of a compacted mixture that is accessible to water) was performed using dimensional analysis as described by Alvarez, et al. (2009d). Dimensional analysis for G_{mb} calculation includes measurement of the dry weight and a direct geometrical computation of the total volume of the specimen using average height and diameter. In addition to these parameters, computation of water-accessible AV content requires measurement of the saturated weight of the specimen in water. The vacuum method (Alvarez et al. 2009d) was used to determine the total AV content of the PMLC specimens employed in the HWTT.

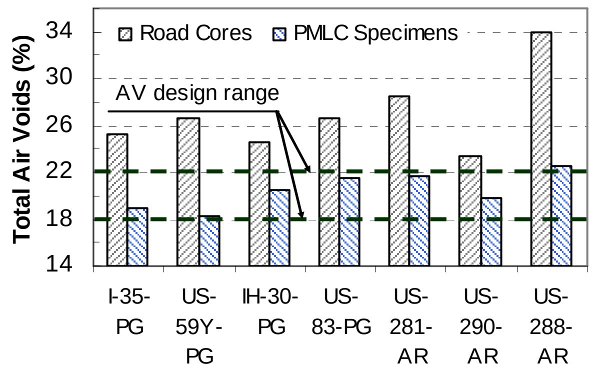
The X-ray CT system at Texas A&M University was used for nondestructive 2D imaging of the internal structure of compacted mixtures. Information on the principles of the X-ray CT system is documented elsewhere (Masad 2004). The evaluation of mixture durability included conducting the Cantabro loss test, the HWTT, and the OT. Alvarez et al. (2009e) summarizes details on the application of these tests in PFC mixtures. Drainability was determined in the laboratory by conducting falling head permeability tests in accordance with ASTM PS 129-01 (ASTM International 2001), and field assessments of drainability were conducted according to the Tex-246-F (TxDOT 2005) procedure.

6.5 RESULTS AND DISCUSSION

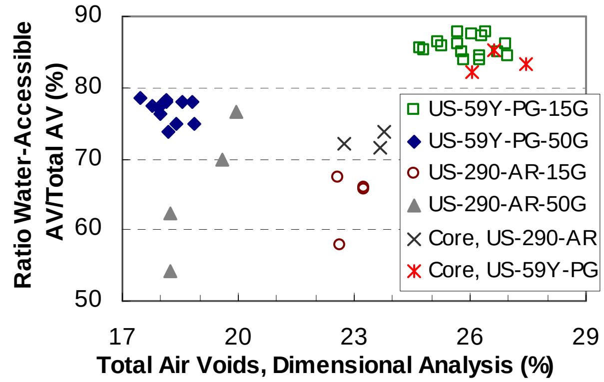
This section presents the comparison of total AV content for PMLC specimens and road cores and the evaluation of the effect of densification on PFC mixtures. The evaluation includes aspects related to: internal structure of compacted mixtures, stone-on-stone contact, density, durability, and functionality for two PFC mixtures fabricated with each asphalt system (PG and AR).

6.5.1 Comparison of Total Air Voids Content Obtained Under Field and Mix Design Compaction

The comparison of total AV content presented in Figure 6-1(*a*) shows that for both types of mixtures, AR and PG, higher average total AV contents were obtained in the field (road cores) than in the laboratory (PMLC specimens fabricated at 50 gyrations of the SGC). Whereas the total AV content of PMLC specimens were in the specified design range (18 to 22 %), the total AV content for road cores were, in general, higher than 25 %. These data suggest a potential problem of construction control leading to a poor reproduction of the mix design in the field. The differences in total AV content motivated the evaluation of PFC mixtures using PMLC specimens produced at two different levels of densification to: (*i*) reproduce the average total AV content (±1 %) computed for corresponding road cores and (*ii*) reproduce the total AV content obtained during mix design with 50 gyrations of the SGC.



(a)



(b)

Figure 6-1. Comparison of Total Air Voids (AV) Content for Road Cores and Plant Mixed-Laboratory Compacted (PMLC) Specimens (Mix Design) (a) and Effect of Densification on Air Voids Content (b)

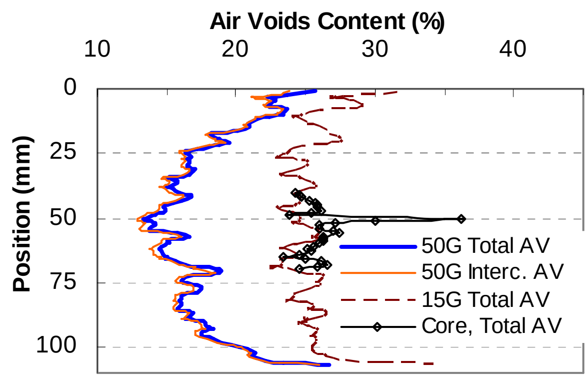
For both the US-59Y-PG and US-290-AR mixtures, the compaction energy required to reproduce (in PMLC specimens) the total AV content achieved in road cores corresponded to 12 to 15 gyrations of the SGC (Figure 6-1[*b*]). Specimens compacted at 12 and 15 gyrations are represented in Figure 6-1(*b*) as 15G and those compacted using the design compaction energy are represented as 50G. For the US-59Y-PG mixture not only the total AV content, but the ratio of water-accessible AV content to total AV content values computed for road cores were reproduced in the laboratory by applying 15 gyrations. However, for the US-290-AR mixture the total AV content was reproduced, but smaller ratios of water-accessible AV content to total AV content values were obtained compared to those computed for road cores. These results suggest the existence of discrepancies in the internal structure of laboratory- and field-compacted mixtures, which are discussed subsequently.

6.5.2 Internal Structure of Compacted Mixtures and Effect of Densification

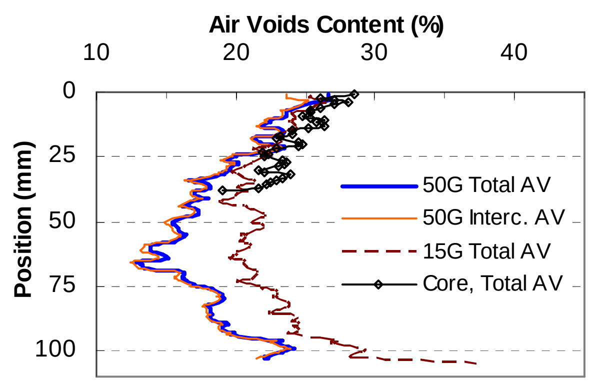
As suggested by Masad et al. (1999b), the internal structure of an asphalt mixture is related to the distribution of AV and the distribution, orientation, and contact of aggregates. In addition, previous research by Watson et al. (2004b) concluded that the AV size, determined using three dimensional image analysis, is related to the degree of packing (i.e., stone-on-stone contact) in the granular skeleton of PFC mixtures. Smaller AV sizes are expected as the AV are separated into smaller AV when the number of particle contacts and the packing increase.

In this study, the evaluation of the internal structure of PFC mixtures using X-ray CT and image analysis included determining the: (*i*) distribution of total AV, (*ii*) distribution of interconnected AV, and (*iii*) average AV radius (computed for AV included as part of the total AV content). The interconnected AV content corresponds to the proportion of AV (including surface voids) in the compacted mixture that form connected paths from top to bottom of the specimen and is related to the water-accessible AV content measured in the laboratory. However, different nomenclature was used to differentiate the calculation methods. The average AV radius (computed using 2D image analysis) was used as an indicator to compare stone-on-stone contact of PFC mixtures with different levels of densification. The parameters referred to previously were determined based on analysis of X-ray CT images, carried out as described by Alvarez et al. (2008b) using the software Image-Pro® Plus and Visual Fortran.

Results of the analysis of X-ray CT images showed higher AV contents at the top and bottom portions of all PMLC specimens. The characteristic AV distribution resembles a "C" shape, as shown in Figure 6-2 for specimens compacted at 15 (15G) and 50 gyrations (50G), and can be due to the restriction imposed by the top and bottom surfaces of the SGC during compaction. Similar distributions were reported for gyratory compacted specimens of dense-graded HMA (Masad et al. 1999b; Tashman et al. 2001). Substantial differences (up to 15 percentage points) between the central and the top and bottom portions of PMLC specimens were observed for both total and interconnected AV. The results of this analysis showed that total and interconnected AV distributions were parallel for specimens compacted at both 15 and 50 gyrations (Figure 6-2) which suggests that these parameters are directly proportional in PFC mixtures.



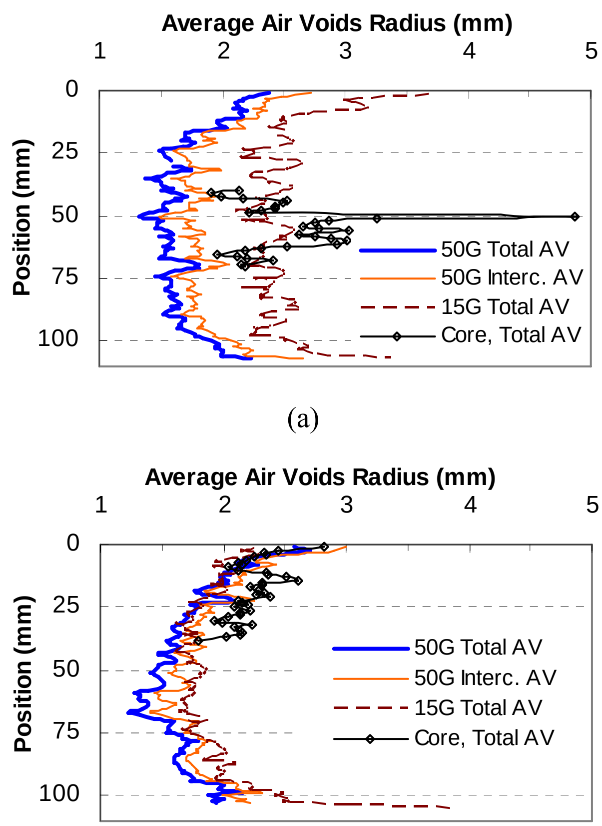
(a)



(b)

Figure 6-2. Total and Interconnected Air Voids (AV) Distribution for Plant Mixed-Laboratory Compacted (PMLC) Specimens and Road Cores of (a) US-59Y-PG and (b) US-290-AR Mixtures

Although the distribution of total and interconnected AV for road cores were also parallel, these distributions did not exhibit the "C" shape obtained for PMLC specimens (Figure 6-2). The distributions of average AV radius presented in Figure 6-3 lead to similar conclusions comparing PMLC specimens and road cores. In summary, the central portion of PMLC specimens contains fewer and smaller AV compared to their top and bottom portions, whereas road cores do not show these AV distribution characteristics. In conclusion, the total AV content computed for road cores was reproduced using PMLC specimens 115 mm in height, but the internal structure of AV was not reproduced. In addition, previous research by Tashman et al. (2001) reported differences in the AV distribution of dense-graded HMA specimens compacted at different heights. Based on these findings, it is expected that shorter specimens of PFC mixtures used for the HWTT and OT (61 mm and 58 mm in height, respectively) can exhibit different AV distributions compared to both road cores and the larger PMLC specimens evaluated in this study.



(a)

(b)

Figure 6-3. Average Air Voids (AV) Radius for Plant Mixed-Laboratory Compacted (PMLC) Specimens and Road Cores of (a) US-59Y-PG and (b) US-290-AR Mixtures

The aforementioned difficulties in reproducing the actual internal structure of field mixtures restrict the durability and functionality evaluations performed on specimens compacted using the SGC. Further analysis of the internal structure of road cores gathered from additional highway sections and comparison to the characteristics of PMLC specimens is required to recommend alternative protocols to fabricate laboratory specimens that better reproduce the AV characteristics of field-compacted mixtures. The selection of the number of gyrations as a compaction control parameter for PFC mixtures also requires further investigation. Previous research (Muraya 2007) suggested that it was not possible to use the number of gyrations to control the compaction of similar porous asphalt mixtures.

Results shown in Figure 6-3 provide evidence of modifications in the internal structure after reaching the state of densification corresponding to stone-on-stone contact. The next section discusses the corresponding verification of this condition. The increment in the level of densification induced by modifying the compaction energy from 15 to 50 gyrations produced smaller AV for the US-59Y-PG mixture. These results suggest that further mobilization of the granular skeleton occurred (besides the state of densification corresponding to stone-on-stone contact) and promoted additional inter-particle contact. Results from the US-290-AR mixture did not show substantial variations in the average AV radius after increasing the compaction energy, although both the total AV and interconnected AV contents were modified, but in smaller proportion than in the US-59Y-PG mixture. Furthermore, both types of mixtures exhibit approximately the same total AV content at 50 gyrations. However, the change in AV content was higher for the PG than for the AR mixture after reducing the compaction energy. These responses show differences in the compactibility of both types of mixture that may also be reflected during field compaction.

Subsequent sections discuss the effect of densification on the properties and performance of the US-59Y-PG and US-290-AR mixtures.

6.5.3 Effect of Densification on Changes in Density and Stone-on-Stone Contact

Figure 6-4 shows the change in the height of PMLC specimens between successive gyrations calculated based on the data reported by the SGC. NCAT reported data with similar tendencies for the compaction of OGFC mixtures fabricated using three different PG asphalts (Watson et al. 2003). Small differences in height were computed after 15 to 20 gyrations compared to those obtained prior to these numbers of gyrations (Figure 6-4). However, at 15 gyrations only 67 to 70 % of the total reduction in height induced by applying 50 gyrations was obtained. Approximate densities (computed using the volume of the specimen determined based on the height reported by the SGC) at 15 gyrations of 91 and 94 % of the densities computed at 50 gyrations for the US-59Y-PG and US-290-AR mixtures, respectively, were calculated. Subsequent discussion presents the effect of these reduced densities on the performance of these mixtures. The analysis suggests the necessity of further compaction in the flat zone of Figure 6-4 after reaching the state of densification corresponding to stone-on-stone contact to ensure proper functionality and durability.

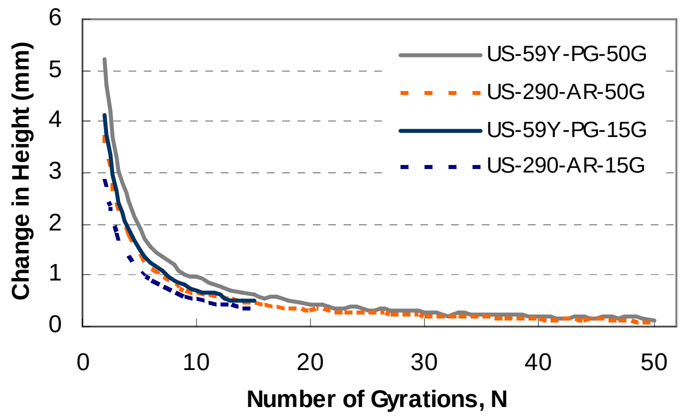


Figure 6-4. Compaction Curve for Plant Mixed-Laboratory Compacted (PMLC) Specimens

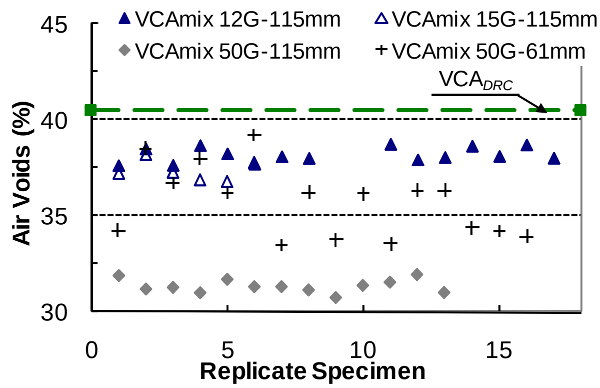
Previous research by Kandhal (2002) emphasized the necessity of obtaining stone-on-stone contact of the coarse aggregate to guarantee adequate resistance to permanent deformation in PFC mixtures. In addition, as previously discussed, raveling may also be favored by incomplete seating of aggregates that lead to poor aggregate interlock to resist the shear stresses induced by vehicle loads. Consequently, the stone-on-stone contact condition was analyzed for specimens fabricated at different levels of densification using the criterion suggested by NCAT (Kandhal 2002). According to this criterion, stone-on-stone contact is obtained when the volume of AV in the coarse aggregate of the compacted mixture (VCA_{mix}) is less than the volume of AV in the coarse aggregate calculated from the dry rodded unit weight (VCA_{DRC}). The coarse aggregate was defined as the fraction retained on a #4 (4.75 mm) sieve. This sieve was adopted as the critical breaking point sieve for both the US-59Y-PG and US-290-AR mixtures whose nominal maximum aggregate size (NMAS) corresponds to 19 mm and 12.5 mm, respectively (Kandhal 2002).

Figure 6-5 shows the comparison of VCA_{mix} and VCA_{DRC} for specimens of two heights compacted by applying 12, 15, and 50 gyrations (12, 15, and 50G). Specimens fabricated for the HWTT and OT (61 mm and 58 mm in height, respectively) were grouped in Figure 6-5 as

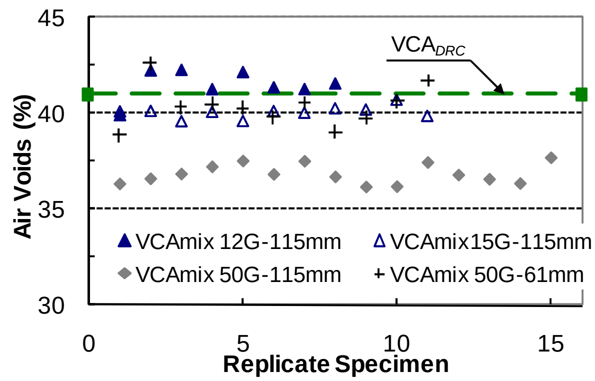
61 mm in height specimens. While all the US-59Y-PG mixture specimens met the requirement of VCA_{mix} less than VCA_{DRC} even at 12 gyrations, some of the specimens compacted at the same energy of compaction for the US-290-AR mixture marginally failed to meet that requirement. However, specimens of this AR mixture compacted at 15 gyrations met the stone-on-stone contact requirement while replicating the total AV content measured in corresponding road cores. The following considerations may lead to the conclusion that the US-290-AR mixture specimens compacted at 12 gyrations did meet the stone-on-stone contact requirements:

(*i*) Use the vacuum method to compute G_{mb} instead of using dimensional analysis. The VCA_{mix} values shown in Figure 6-5 were computed based on G_{mb} values determined by dimensional analysis. However, higher G_{mb} values (and corresponding smaller VCA_{mix} magnitudes) would be obtained by applying the vacuum method, which may lead to VCA_{mix} less than VCA_{DRC}.

(*ii*) Redefine the critical breaking point sieve size as the #8 (2.36 mm) sieve according to the alternate recommendations suggested by Watson et al. (2004b) based on the slope of the gradation curve. According to the same recommendations, the 4.75 mm sieve will still be the critical breaking point for US-59Y-PG mixture.



(a)



(b)

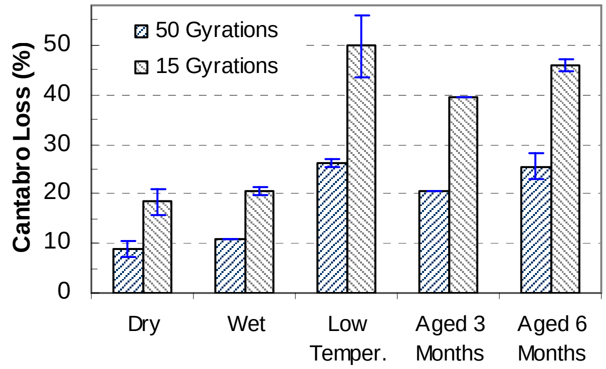
Figure 6-5. Comparison of Voids in Coarse Aggregate (*VCA*) for (a) US-59Y-PG and (b) US-290-AR Mixtures

Data shown in Figure 6-5 also suggest the possibility of decreasing the number of gyrations currently used for mix design (50) while still ensuring stone-on-stone contact. However, the modification in mixture durability and functionality, aggregate breakage, and the proper reproduction of the internal structure of field-compacted mixture needs to be assessed to validate this modification. In addition, specimen size seems to be an important variable to integrate in this analysis. Data shown in Figure 6-5 suggests higher variability in the volumetric properties of shorter specimens, which is coincident with the conclusions reported in previous research by Alvarez et al. (2009d).

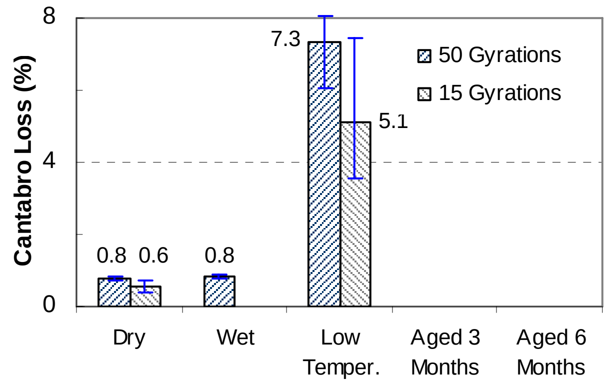
6.5.4 Effect of Densification on Durability

The effect of densification on durability was evaluated in the laboratory through Cantabro loss tests, HWTTs, and OTs performed on specimens compacted at both 15 and 50 gyrations in the SGC. The Cantabro loss test is conducted by subjecting a compacted specimen to 300 revolutions in the Los Angeles abrasion machine without using any abrasive load. The ratio of lost weight to initial weight (expressed as a percentage) is reported as the Cantabro loss. Previous research (Ruiz et al. 1990) concluded that the Cantabro loss was a suitable parameter to evaluate the resistance to disintegration (in terms of raveling) of similar porous asphalt mixtures with appropriate correlation to field performance. However, Nielsen (2006) reported more recently the lack of correlation for porous asphalt mixtures, especially those constructed using modified asphalts.

Figure 6-6 shows the average, maximum, and minimum Cantabro loss values determined on PMLC specimens subjected to five different conditioning processes (dry, wet, low temperature, and three and six months aging). The dry and wet conditioning processes were selected to evaluate the mixture response in its original state (dry-no aging) and after inducing moisture damage using controlled laboratory conditions (24 ± 0.5 hours in a water bath with a constant temperature of 60°C), respectively. The low temperature conditioning process (24 hours in a cool room at 3°C) allowed assessing the material response when the asphalt becomes stiffer and more susceptible to brittle fracture. Finally, the potential effect of asphalt aging on the loss of cohesion in PFC mixtures was investigated by subjecting compacted specimens to accelerated aging for three and six months in a temperature-controlled room at 60°C with heated air circulation.



(a)



(b)

Figure 6-6. Effect of Densification on Cantabro Loss for (a) US-59Y-PG and (b) US-290-AR Mixtures

The US-59Y-PG mixture exhibited a 100 % decrease in Cantabro loss when the energy of compaction was increased from 15 to 50 gyrations. Consequently, the response of this mixture may indicate an important improvement in mixture resistance to disintegration consistently observed in dry, wet, low temperature, and aged conditioned specimens. Since the PMLC specimens compacted at 15 gyrations developed stone-on-stone contact, this improvement in resistance to disintegration is mostly related to the increment in the level of densification that further modified both aggregate interlock and AV characteristics after reaching the state of densification corresponding to stone-on-stone contact.

In contrast, data corresponding to wet conditioned specimens for the US-290-AR mixture fabricated by applying 15 gyrations are not included in Figure 6-6(*b*) since they disintegrated during the water conditioning process (immersion at 60°C). However, specimens compacted at 50 gyrations and subjected to the same conditioning process did not show this type of premature failure. In addition, specimens fabricated by applying both 15 and 50 gyrations disintegrated after aging at 60°C for less than one month. The shape adopted by these aged- and water-conditioned specimens suggested that the material failed by creep when the asphalt viscosity was reduced due to the increased temperature.

The occurrence of the same type of failure in specimens compacted at both energies can be related to an excess of asphalt that facilitated the creep mechanism. Lack of confinement can also contribute to this failure. Although the draindown evaluation performed as part of the mix design did not show draindown susceptibility, asphalt binder deposited where the specimens were aged suggested excess asphalt in the US-290-AR mixture. In addition, smaller Cantabro loss values were obtained for specimens compacted at 15 gyrations and tested in both dry and low temperature conditions, compared to specimens compacted at 50 gyrations (Figure 6-6[b]). These results suggest a small effect on the Cantabro loss (conducted at these testing temperatures) of changes in the level of densification and AV characteristics induced after modifying the compaction energy. These responses may be explained by considering that at room and cold temperature the relatively high amount of asphalt bonding the granular particles improves the resistance to disintegration, but at the high temperature used for both wet and aging conditioning, the effect is reversed as the high asphalt content lubricates the particle contacts and reduces the mixture stability. However, these conclusions are limited by the large variability in the Cantabro loss values (Figure 6-6[b]), which is coincident with the Cantabro loss test variability reported in previous research (Alvarez et al. 2009e).

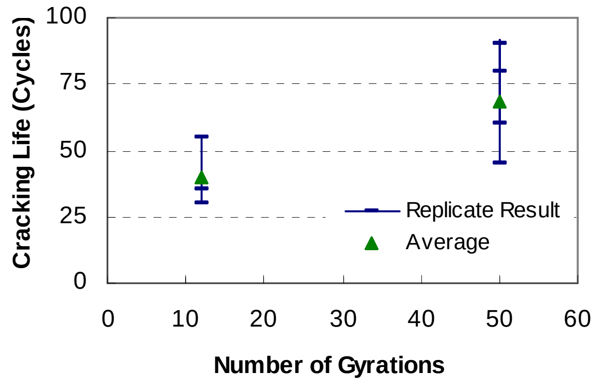
Table 6-3 shows the rut depth determined for the US-59Y-PG mixture after applying 20,000 load cycles in the HWTT and the number of cycles required to reach a rut depth of 12.5 mm for the US-290-AR mixture. These results illustrate the substantial improvement in rut resistance for PMLC specimens compacted at 50 gyrations compared to that determined on specimens compacted at 12 gyrations. Ultimately, these results provide evidence of the importance of controlling the density to ensure adequate permanent deformation resistance of PFC mixtures. This improvement in performance is a result of the reduced deformability of mixtures with fully developed stone-on-stone contact that lead to adequate interlock and a tight aggregate skeleton. As discussed subsequently, important reductions in drainability are associated with decreases in AV content. Since permanent deformation can lead to important reductions of AV content, providing a rut resistant mixture is fundamental to ensure not only mixture durability, but also mixture functionality.

Table 6-3. Effect of Densification on Hamburg Wheel-Tracking Test (HWTT) Results

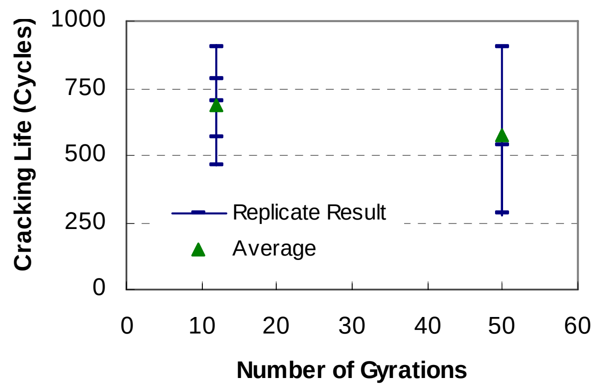
Mixture	Asphalt Content, %	Compaction Energy (SGC Gyrations)	Average Total Air Voids Content, %[a]	Cycles to Failure @ 12.5 mm	Rut Depth @ 20,000 Cycles, mm
US-290-AR	8.3	12	19.9	7,550	-
		50	16.9	16,700	-
US-59Y-PG	5.8	12	22	-	11.41
		12	22.3	-	8.96
		50	17.6	-	4.82
		50	16.2	-	5.43

[a]Computation based on the determination of G_{mb} using the vacuum method.

Results of OT shown in Figure 6-7 indicate the effect of densification on cracking life, a parameter expressing the number of cycles to failure of a specimen tested in a controlled-displacement mode to simulate the opening and closing of joints or cracks in old pavements beneath an overlay. For the US-59Y-PG mixture, cracking life is extended as specimens are compacted with 50 gyrations. This result can be related to the improvement of the fracture properties developed in a less deformable mixture with adequate aggregate interlock. The results obtained for the US-290-AR mixture did not exhibit this same tendency. Taking into account the variability, the cracking life determined for specimens compacted at 50 gyrations can be equal or even less than that calculated for specimens compacted at 12 gyrations. The high variability and the lack of defined trends in the results obtained for the AR mixture system indicate the limitations of the OT to capture the response of this particular material as suggested in previous research (Alvarez et al. 2009e). The amount, distribution, but probably most important, the ratio of AV size to sample dimensions (150-mm long by 75-mm wide by 38-mm high) probably have an important effect on the cracking life variability because the AV may be large enough to influence the development of cracking during the test.



(a)

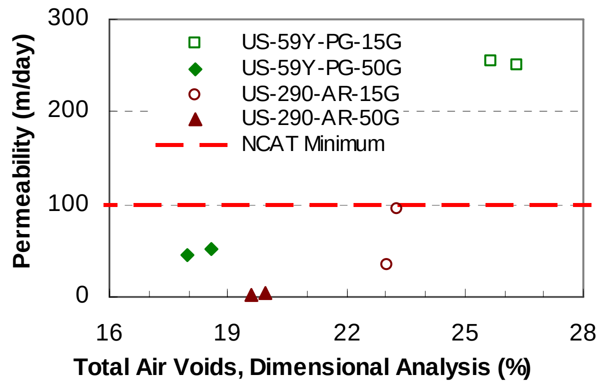


(b)

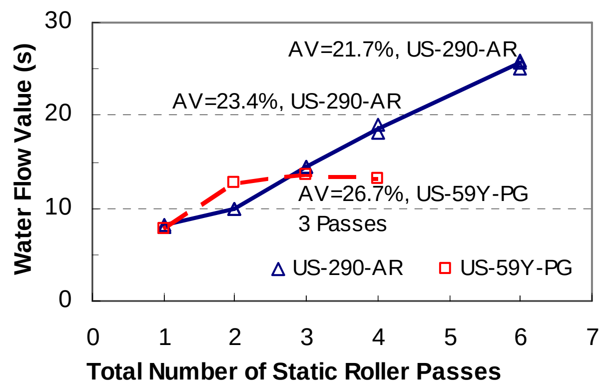
Figure 6-7. Effect of Densification on Cracking Life for (a) US-59Y-PG and (b) US-290-AR Mixtures

6.5.5 Effect of Densification on Functionality (Drainability)

Figure 6-8(*a*) shows the permeability values measured in the laboratory using PMLC specimens and the minimum permeability value recommended by NCAT (100 m/day) (Kandhal 2002). This minimum value can be adopted as a reference to compare the changes in permeability induced by modifying the level of densification. The complete loss of drainability encountered for the US-290-AR specimens compacted at 50 gyrations constitutes a remarkable aspect of this evaluation. Even though the total AV content of these specimens are right in the middle of the current AV design range, the permeability substantially decreased to the point of practically losing the distinctive drainage properties in these specimens. Similarly, the US-59Y-PG mixture reduced its permeability by approximately 80 % when the number of gyrations was increased from 15 to 50. This loss of drainability can be mostly related to the reduction of the size and proportion of total and interconnected AV, especially in the central zone of PMLC specimens (Figure 6-2 and Figure 6-3), induced by the increased compaction energy. Therefore, despite the fact that the total AV content of these specimens is still in the design range, their central portion became a bottleneck in terms of drainability.



(a)



(b)

Figure 6-8. Effect of Densification on Water-Permeability (a) and Effect of Field Compaction Pattern on Water Flow Number (WFV) (b)

Since verification of field drainability is the main control currently applied during construction of PFC mixtures, results from a field drainability evaluation performed to assess the effect of the compaction pattern were included in this study (Figure 6-8[*b*]). The total number of static roller passes reported in Figure 6-8(*b*) includes the passes made by the finish roller. Typically, two to four passes (within the adequate range of temperature) with an 8- to 9-ton tandem roller has been reported as appropriated to complete the compaction process on thin layers (20 mm) of OGFC (Alvarez et al. 2006). In addition, the Federal Highway Administration recommended one or two passes of an 8- to 10-ton static steel-wheel roller to compact OGFC. However, for compaction of porous asphalt mixtures in Britain, the application of at least five passes is recommended, but they typically use thicker (~50 mm) layers (Alvarez et al. 2006). PFC mixtures, placed in thicknesses of approximately 32 to 38 mm, are typically compacted by applying three to four passes with a flat-wheeled static roller (Alvarez et al. 2006).

The WFV data shown in Figure 6-8(*b*) correspond to the time, expressed in seconds, required to discharge a given volume of water channeled into the pavement surface with the use of a variable charge outflow meter 152 mm in diameter. The maximum WFV recommended for PFC mixtures is 20 seconds (TxDOT 2005). Data shown in Figure 6-8(*b*) for the US-290-AR mixture suggest that increasing the number of roller passes to four or five to increase the field density, and still achieve the maximum WFV recommended for PFC mixtures, is possible. However, this recommendation cannot be generalized since the tendencies of the curves and the differences in total AV content shown in Figure 6-8(*b*) suggest that the WFV is mixture dependent. In fact, the field mixture drainability can change as a function of aggregate gradation, asphalt content, fiber content (for PG mixtures only), aggregate shape properties, compaction temperature, and characteristics of the compaction equipment, among other factors.

6.6 CONCLUSIONS AND RECOMMENDATIONS

This paper presents an evaluation of the densification effect on the properties and performance of PFC mixtures fabricated using both an AR asphalt binder and a PG asphalt. The following conclusions are provided based on the analysis of laboratory and field-testing results gathered as part of this study:

- Laboratory reproduction of the total AV content computed for road cores from two mixtures showed that PMLC specimens compacted at 15 gyrations of the SGC met the field total AV content. However, the internal AV structure of road cores was not replicated. Although this fact constitutes a restriction on the evaluation of mixture properties and performance presented, the results from this evaluation provide evidence of the expected mixture response.
- High levels of densification (after reaching stone-on-stone contact) are required to obtain a granular skeleton with fully developed stone-on-stone contact that ensures proper mixture resistance to raveling and permanent deformation. Therefore, reductions in the level of

densification to increase the AV content should not be pursued. These findings suggest the necessity of: (*i*) checking the stone-on-stone contact condition during mix design and (*ii*) including density control during construction based on a reference equilibrium density that provides a proper balance between mixture durability and mixture functionality.

The following recommendations are drawn based on the analysis and conclusions previously indicated:

- Include a field density requirement in the specifications for PFC mixtures. The density corresponding to the OAC, computed during the mix design, may be used as reference to define the equilibrium density.
- Additional research is required to develop techniques (e.g., nondestructive methods) that effectively evaluate the field density of PFC mixtures and enforce a density specification. Since coring and patching PFC sections is cumbersome, and nondestructive techniques are not currently validated for PFC density control, increasing the efforts to establish appropriate roller patterns (based on road core density determined in a control strip) is recommended as an initial action to improve the compaction process.
- Perform additional research to improve the current laboratory compaction protocol used for PFC mixtures. The updated protocol may lead to laboratory specimens that: (*i*) better reproduce the characteristics of field-compacted mixtures and (*ii*) can be used to better define the equilibrium density.
- Evaluate long-term performance to determine the actual response of mixtures constructed at different levels of densification and obtain final recommendations to control field density.

7. STONE-ON-STONE CONTACT OF PERMEABLE FRICTION COURSE MIXTURES*

7.1 OVERVIEW

Stone-on-stone contact of the coarse aggregate fraction is one of the main characteristics of PFC asphalt mixtures that is required to provide adequate resistance to both raveling and permanent deformation. Currently, stone-on-stone contact is determined by comparing the air voids content in the coarse aggregate (*VCA*), assessed in both the dry-rodded condition (VCA_{DRC}) and the compacted PFC mixture (VCA_{mix}). The underlying assumption is that the coarse aggregate of a compacted PFC mixture with VCA_{mix} equal to VCA_{DRC} would develop a stone-on-stone contact condition equivalent to that existing in the dry-rodded aggregate. This study focused on proposing enhancements for the quantitative determination of stone-on-stone contact of PFC mixtures. The assessment supported on both laboratory testing and application of the Discrete Element Method and image analysis techniques, led to recommendation of a criterion to determine the breaking-sieve size. In addition, verification of stone-on-stone contact using a maximum *VCA* ratio of 0.9 was recommended to ensure the design and construction of PFC mixtures with fully developed stone-on-stone contact.

7.2 INTRODUCTION

PFC mixtures, or new generation OGFC, are HMA mixtures characterized by a high total AV content (minimum 18 %) as compared to the most commonly used dense-graded HMA. The use of these mixtures decreases splash and spray, fuel consumption, tire wear, and pavement noise; improves ride quality and visibility of pavement markings at night and in wet weather; and reduces the risk of hydroplaning and wet skidding (Alvarez et al. 2006).

One of the main characteristics of PFC mixtures is the existence of stone-on-stone contact in the coarse aggregate fraction, which is required to provide adequate resistance to both raveling and permanent deformation (Alvarez et al. 2009b; Kandhal 2002). Poor stone-on-stone contact can be related to inappropriate gradation (excessive amount of fine aggregate obstructing the contact of coarse aggregate particles) as well as low density in PFC mixtures. Low density leads to incomplete seating and poor interlock of aggregates to resist the shear stresses induced

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by traffic loads, creating a mixture whose response relies more on the cohesion provided by the asphalt. Consequently, a reliable methodology for quantitative determination of stone-on-stone contact in compacted PFC mixtures is required.

NCAT recommended verification of stone-on-stone contact for the mix design of new generation OGFC based on the comparison of *VCA* in the dry-rodded condition—VCA_{DRC}—and the *VCA* in the compacted mixture—VCA_{mix}—(Kandhal 2002). According to this method, a PFC mixture achieves stone-on-stone contact when the VCA_{mix}/VCA_{DRC} ratio (*VCA* ratio) is equal to one (1.0). This *VCA* method was supported by additional research (Watson et al. 2004b) based on analysis of stone-on-stone contact in digital images. However, further research is required to improve the determination of: (*i*) the breaking-sieve size (i.e., aggregate size that differentiates the fine- and coarse-aggregate fractions to compute the *VCA* ratio) and (*ii*) the existence of a fully developed stone-on-stone contact condition in compacted PFC mixtures that ensures adequate mixture durability.

Therefore, this paper compares the existing criteria, subsequently presented, proposed to determine the breaking-sieve size of PFC mixtures and presents results of analysis conducted by combining the Discrete Element Method and image analysis techniques (DEM-IA) (Mahmoud et al. 2009) to further recommend one of these criteria. The DEM-IA approach was selected because of the Discrete Element Method (DEM) capabilities of capturing interactions between the particles within the model. DEM can be used to model the different material phases of the mixture, thus differentiating between the aggregates and matrix. In addition, the DEM can be used to track the forces developing within the internal structure of the mixture. With these features, the DEM-IA approach was used to investigate the effect of certain aggregate fractions on the stone-on-stone contact of PFC mixtures. Thus, the study assessed the effect of removing certain aggregate fractions on the mechanical response of the mixture, which was computed in terms of the mixture strength, total energy, internal forces, and crack patterns.

In addition, the paper explores the verification of stone-on-stone contact using a maximum value of the *VCA* ratio to guarantee a fully developed stone-on-stone contact condition. This study included PFC mixtures fabricated, in both the laboratory and field, using PG asphalt and AR as well as aggregates with diverse gradation and origin representative of the granular materials employed to construct PFC mixtures in Texas. First, the experiment design is described, followed by a summary of the current approach used to determine stone-on-stone contact in PFC mixtures and the basis of the DEM-IA. Results and discussion as well as a summary and recommendations complete the paper.

7.3 OBJECTIVE AND METHODOLOGY

The objective of this paper is to propose enhancements (based on both laboratory testing and modeling of PFC mixtures using DEM-IA) for the quantitative determination of stone-on-stone contact of compacted PFC mixtures. The study was divided into the following tasks to achieve this objective:

- Comparison of stone-on-stone contact computations conducted based on the criteria currently suggested to determine the breaking-sieve size.
- Application of the DEM-IA to account for the effect of fine-aggregate fractions on stone-on-stone contact and formulation of corresponding recommendations to improve the determination of the breaking-sieve size.
- Recommendation of a maximum value for the *VCA* ratio that ensures obtaining PFC mixtures with fully developed stone-on-stone contact.

7.4 EXPERIMENTAL DESIGN

This section presents the experimental design defined for this study, which includes mix design, material requirements, material selection, specimen fabrication, and laboratory testing.

7.4.1 Mix Design and Material Requirements

Mix design was carried out according to the current TxDOT mix design method (TxDOT 2005). Corresponding material specifications define different master aggregate gradation bands for each of the following asphalts permitted for PFC mixtures (TxDOT 2004):

- a Type I or II AR with a minimum of 15 % by weight of virgin asphalt of Grade C or Grade B crumb rubber. The grades C and B refer to the gradation of the crumb rubber as defined in Item 300.2.G (TxDOT 2004).
- a PG asphalt with a minimum high temperature grade of PG76-XX with a minimum of 1.0 % by weight of dry aggregate of lime and a minimum of 0.2 % by weight of mixture of cellulose or mineral fibers.

7.4.2 Material Selection and Specimen Fabrication

As specified in Table 7-1, mixture evaluations included in this study were conducted using: (*i*) PMLC specimens, (*ii*) field mixed-field compacted specimens or road cores, (*iii*) LMLC specimens, and (*iv*) slab cores, extracted from laboratory-compacted slabs. The PMLC specimens (150 mm in diameter and 115 ± 5 mm in height) and LMLC specimens (100 mm in diameter and 150 ± 5 mm in height) were compacted by applying 50 gyrations of the SGC as specified for mix design (TxDOT 2005) and recommended in previous studies (Muraya 2007; Watson et al. 2003). In addition, fabrication of the PMLC specimens involved reheating the mixtures to the compaction temperature, which corresponded to 149°C for both AR and PG 76-22 asphalts as recommended by the AR supplier and in the PFC mix design procedure (TxDOT 2005), respectively. Road cores of 150 mm in diameter and 31 to 52 mm in height were used, except for the 3-PG and 4-PG mixtures, which had road cores of 19 to 25 mm in height. Table 7-1 shows details on the composition of each mixture, and Table 7-2 and Table 7-3 present corresponding aggregate gradations.

Table 7-1. Description of Mixtures Used to Assess Stone-on-Stone Contact

Mixture	Asphalt Type	OAC, %	Aggregate Type	Other Materials (L / CF)	Type and (Number) of Specimens Evaluated
I-35-PG or 1-PG	PG 76-22	6.1	Sandstone, Limestone	1 % / 0.3 %	PMLC (4), RC (3)
IH-30-PG or 2-PG	PG 76-22	6.6	Sandstone	1 % / 0.3 %	PMLC (6), RC (3)
IH-20-PG or 3-PG	PG 76-22	6.5	Limestone	1 % / 0.3 %	PMLC (4), RC (4)
US-83-PG or 4-PG	PG 76-22	6.4	Limestone	1 % / 0.3 %	PMLC (3), RC (3)
US-59-PG or 5-PG	PG 76-22	5.9	Granite, Limestone	1 % / 0.3 %	PMLC (7), RC (3)
US-59Y-PG or 6-PG	PG 76-22	5.8	Limestone	1 % / 0.3 %	PMLC (12), RC (3)
El Paso or 7-PG	PG 76-22	6.6	Granite	1 % / 0.4 %	LMLC (3)
Fordyce or 8-PG	PG 76-22	6.8	Gravel	1 % / 0.4 %	LMLC (1)
Brownwood-1 or 9-PG	PG 76-22	5.1	Limestone	1 % / 0.4 %	LMLC (3)
Brownlee-1 or 10-PG	PG 76-22	5.5	Sandstone	1 % / 0.4 %	LMLC (1)
Beckman-1 or 11-PG	PG 76-22	7.1	Limestone	1 % / 0.4 %	LMLC (4)
Brownwood-2 or 12-PG	PG 76-22	6.4	Limestone	1 % / 0.3 %	SC (7)
Brownlee-2 or 13-PG	PG 76-22	6.0	Sandstone	1 % / 0.2 %	SC (8)
Beckman-2 or 14-PG	PG 76-22	6.0	Limestone	1 % / 0.3 %	SC (8)
US-281-AR or 1-AR	Type II AR, Grade B (AC-10 w/16 % CR)	8.1	Sandstone, Limestone	0 % / 0 %	PMLC (5), RC (5)
US-290-AR or 3-AR	Type II AR, Grade B (AC-10 w/17 % CR)	8.3	Sandstone	0% / 0%	PMLC (15), RC (3)

Note: OAC = optimum asphalt content; L= lime; CF = cellulose fibers; CR = crumb rubber; RC = road core; SC= slab core.

Table 7-2. Aggregate Gradations for PG Mixtures (Percentage Passing) Used to Assess Stone-on-Stone Contact

Sieve	Specifi-cation	1-PG	2-PG	3-PG	4-PG	5-PG	6-PG	7-PG, 8-PG, 9-PG, 10-PG, 11-PG	12-PG	13-PG	14-PG
¾	100-100	100	100	100	100	100	100	100	100	100	100
½	80-100	90.3	81	85.3	90.5	80.2	84.5	90	100	90.3	84.5
3/8	35-60	59.5	43	59.4	50.9	57.7	52.8	47.5	80	59.5	52.8
#4	1-20	10.1	15.5	18.6	3.2	15.9	6.6	10.5	8	11.4	6.6
#8	1-10	5.2	6.7	2	1.5	6	4.2	5.5	4	5.4	4.2
#200	1-4	2.3	2.2	1.6	1.1	2.1	2.4	2.5	4	2.2	2.4

Table 7-3. Aggregate Gradations for AR Mixtures (Percentage Passing) Used to Assess Stone-on-Stone Contact

Sieve	Specification	1-AR	3-AR
¾	100-100	100	100
½	95-100	99	99.7
3/8	50-80	54.6	75.7
#4	0-8	5	7.9
#8	0-4	1.9	1.1
#200	0-4	1	0.6

Laboratory Testing

The bulk specific gravity of the compacted mixture was computed using both dimensional analysis and the vacuum method as described by Alvarez et al. (2009d). Dimensional analysis includes both determination of the dry specimen weight and direct geometrical computation of the total volume of the specimen using average height and diameter measurements. In the vacuum method, the compacted specimen is wrapped in a plastic bag, subjected to and sealed with a vacuum, and the buoyancy principle is used to determine the total volume of the wrapped specimen. The bulk specific gravity and the dry-rodded unit weight of coarse aggregate were determined in accordance with AASHTO T 85-91 and AASHTO T 19M/T 19-00, respectively. These two tests were conducted on independent sets of coarse aggregate fraction specimens prepared by adopting the No. 4 (4.75 mm) sieve and the No. 8 (2.36 mm) sieve, separately, as the breakpoint-sieve size and the corresponding aggregate gradation of each mixture listed in Table 7-1.

Five PG mixtures (7-PG to 11-PG) were analyzed using DEM-IA. A previous study (Reyes et al. 2008) characterized these mixtures using Indirect tensile tests, as well as corresponding aggregates based on Indirect tensile, Elastic modulus, and Compressive strength tests. The indirect tensile test on PFC mixtures was carried out on cylindrical specimens (10 cm in diameter and 5 cm height) compacted to a target density of 80 ± 2 %. In addition, Indirect tensile as well as Compressive strength tests were conducted on cylindrical cores from rock masses to determine, respectively, the tensile strength and compressive strength of the aggregates. Elastic modulus of aggregate was obtained using ultrasonic testing (V-meter), which is a nondestructive testing procedure.

Table 7-4 summarizes the experimental results of the tests conducted on both aggregates and mixtures. Since gravel consists of loose material, it was not possible to perform the aggregate tests. However, individual particles of all aggregate types were tested under compressive loading (Mahmoud and Masad 2009), and the results were related to the rock core test results. Accordingly, gravel properties were estimated using the relationship between the single aggregate crushing and rock core test results (Mahmoud 2009).

Table 7-4. Experimental Results for Aggregates and Corresponding PFC Mixtures

Mixture	Aggregate Type	Aggregate Compressive Strength, kN/m^2	Aggregate Tensile Strength, kN/m^2	Aggregate Elastic Modulus, MN/m^2	Mixture Tensile Strength at Failure, kN/m^2
7-PG	Granite	96761 (7 %)	7322 (23 %)	46098 (6 %)	421
8-PG	Gravel		Not Feasible		400
9-PG	Hard Limestone	71892 (38 %)[a]	9735 (20 %)	71209 (13 %)	455
10-PG	Sandstone	96196 (31 %)	11563 (11 %)	59702 (7 %)	538
11-PG	Soft Limestone	48056 (8 %)	4702 (-)[b]	37735 (11 %)	345

[a]Numbers in the parentheses are the coefficients of variation from triplicate tests.
[b]Only one specimen was tested for the soft limestone.
Source: Adapted from Mahmoud et al. 2009

7.5 CURRENT APPROACH USED TO DETERMINE STONE-ON-STONE CONTACT IN PFC MIXTURES

According to the pass/fail criterion suggested by NCAT (Kandhal 2002), stone-on-stone contact is achieved in PFC mixtures when:

$$\frac{VCA_{mix}}{VCA_{DRC}} < 1 \tag{7-1}$$

where VCA_{mix} and VCA_{DRC} are calculated as follows:

$$VCA_{DRC} = \left[\frac{(G_{CA} \times \gamma_w) - \gamma_s}{G_{CA} \times \gamma_w}\right] \times 100 \quad \text{(7-2a);} \qquad VCA_{mix} = \left[1 - \frac{G_{mb} \times P_{CA}}{G_{CA}}\right] \times 100 \quad \text{(7-2b)}$$

where G_{CA} and γ_s are the bulk specific gravity and the dry-rodded unit weight of the coarse aggregate fraction, respectively, γ_w is the unit weight of water, and G_{mb} corresponds to the bulk specific gravity of the compacted PFC mixture. The percent of coarse aggregate by weight of total mixture, P_{CA}, is computed as:

$$P_{CA} = \left(\frac{\%R_{BS}}{100}\right) \times \left(1 - \frac{P_b}{100}\right) \tag{7-3}$$

where $\%R_{BS}$ is the percent of aggregate retained on the breaking-sieve, and P_b is the percent of asphalt content by total weight of the mixture.

The coarse aggregate fraction (i.e., fraction retained on the breaking-sieve size) is the portion of aggregate forming the granular skeleton with stone-on-stone contact and particle interlock, while the remaining fine-aggregate fractions fill the AV structure attained by the coarse aggregate in a compacted PFC mixture. Thus, proper determination of the breaking-sieve size is required to ensure that the coarse aggregate fraction included in the *VCA* computations is the fraction that actually contributes to develop stone-on-stone contact in the mixture. Criteria suggested to determine the breaking-sieve size of PFC mixtures include:

- Criterion No. 1: select the No. 4 sieve for all PFC mixtures (ASTM International 2006; Kandhal 2002). Currently, this criterion is the most widely applied for mix design of PFC and OGFC.
- Criterion No. 2: select the sieve size at which the slope of the gradation curve below this size begins to flatten out (Watson et al. 2004b), and
- Criterion No. 3: select the finest sieve size in which a minimum of 10 % of total aggregate is retained (Watson et al. 2004b).

Previous research (Brown and Mallick 1995) originally proposed the criterion presented in Equation (7-1) to evaluate stone-on-stone contact in stone-matrix asphalt mixtures. According to this criterion, since the *VCA* in the dry-rodded condition is associated with a stone-on-stone contact condition, the coarse aggregate of a compacted SMA mixture with VCA_{mix} equal to VCA_{DRC} would develop a stone-on-stone contact condition equivalent to that existing in the dry-rodded aggregate. This criterion for verifying stone-on-stone contact is also currently used to assess PFC mixtures. However, the dry-rodded unit weight corresponds to a particular density that is not necessarily related to the density required in the coarse aggregate of a compacted PFC mixture to guarantee the proper balance of mixture durability and drainability. In addition, previous research (Alvarez et al. 2009b) provided evidence of the necessity of continuing the compaction process after reaching the threshold stone-on-stone contact condition (VCA ratio $=1.0$) to attain a granular skeleton with fully developed stone-on-stone contact that ensures adequate durability in terms of both permanent deformation and resistance to raveling. Therefore, as subsequently presented, this study explores recommending a maximum value for the *VCA* ratio that ensures the design and construction of PFC mixtures with fully developed stone-on-stone contact.

7.6 DISCRETE ELEMENT METHOD AND IMAGE ANALYSIS TECHNIQUES (DEM-IA)

The DEM is a finite difference scheme used to study the interaction among discrete particles (Cundall 1971). The DEM is based on successive solution of Newton's second law (law of motion) and the force-displacement law for each discrete particle in the model. Newton's second law is integrated by applying an explicit time-stepping scheme with a given set of contact forces acting on each particle. As a result, the particle velocity and position are updated and with the new positions, the relative displacement among particles is computed and used to calculate the contact forces (PFC2D 2004). The DEM has been applied to model different types of geotechnical problems and to analyze asphalt mixture response under static and cyclic loadings (You and Buttlar (2004), Abbas (2004), and the PFC2D (2004)).

This study used a DEM code called *Particle Flow Code in 2-Dimensions, Version 3.1* (PFC2D 2004) in order to assess the effect of different aggregate size fractions on the development of stone-on-stone contact in the internal structure of PFC mixtures. The X-ray Computed Tomography (X-ray CT) system at Texas A&M University was used to obtain images of the mixture internal structure, which allowed differentiating between aggregate particles and the matrix (asphalt and aggregate particles finer than 0.24 mm). Subsequently, digital image processing techniques were used to transfer the internal structure of asphalt mixtures to the geometry of the model in the PFC2D software. The asphalt mixture discrete element model included three types of contacts: aggregate-to-aggregate contact, matrix-to-matrix contact, and aggregate-to-matrix contact.

The inputs for the discrete element model were the bond strength and contact stiffness for the three different types of contacts. These input parameters were determined following a calibration technique that was presented by Mahmoud et al (2009). In this technique, the bond strength and stiffness input parameters for the aggregate-aggregate contacts were determined based on matching the results of DEM simulations of the three aggregate tests previously described (indirect tensile strength, compressive strength, and elastic modulus) with the experimental results from these tests. The input parameters for the matrix-to-matrix contact and matrix-to-aggregate contact were determined based on matching the DEM simulations and experimental measurements of indirect tensile tests of the five PFC mixtures used in this study (Mahmoud et al. 2009).

In order to analyze the effect of different aggregate size fractions on stone-to-stone contact, it was necessary to develop a method to identify individual aggregate particles that belong to each aggregate size group. For this purpose, the *Image-Pro® Plus* software was used to convert the grayscale X-ray CT images of the mixture to black (aggregate particles) and white (matrix) images. Then, a FORTRAN program was written to recognize the outline pixels of each aggregate particle and add all the pixels inside the outline to the same aggregate particle (Abbas 2004). The second step was to determine the size of each aggregate particle. A Matlab code was written to measure the dimensions of each aggregate particle and each aggregate particle was assigned to the appropriate aggregate-fraction size group (sieve size) based on its shortest dimension.

With aggregate particles within the model grouped based on sieve sizes, the DEM model was used to determine whether aggregate fractions finer than the No. 4 sieve contribute toward development of stone-on-stone contact in PFC mixtures, or if these fractions mostly act by filling the AV structure attained by the aggregate retained on the No. 4 sieve. The aggregate fractions finer than the No. 4 sieve included in the analysis corresponded to those passing the No. 4 sieve and retained on the No. 8 sieve (or P4-R8 fraction) and passing the No. 8 sieve and retained on the No. 16 sieve (or P8-R16 fraction). The computational analysis was conducted by comparing the mixture mechanical response (DEM model outputs) of PFC mixtures for the following cases:

- I: all aggregate fractions used for mix design (P ¾-R60 (0.24 mm)),
- II: all aggregate fractions retained on the No. 16 sieve (exclusion of fractions P16-R60),
- III: all aggregate fractions retained on the No. 8 sieve (exclusion of fractions P8-R60), and
- IV: all aggregate fractions retained on the No. 4 sieve (exclusion of fractions P4-R60).

In order to exclude any sieve size from the PFC mixture analysis, that specific size was switched to the matrix phase. For instance, to study the PFC mixture with aggregate fractions retained on the No. 4 sieve, all the aggregate particles passing the No. 4 sieve were switched to the matrix phase.

The DEM model evaluated the mixture mechanical response in terms of the following indicators: (*i*) total energy, (*ii*) indirect tensile strength (derived from the load-displacement curve), (*iii*) cracking patterns within the mixture, and (*iv*) internal forces developed within the aggregate particles. Total energy is defined as the area under the stress strain diagram up to the failure point (maximum load) and the tensile strength is a representation of the maximum load. Mahmoud (2009) studied the different crack patterns developing within the mixture in DEM by tracking the loss of bond between two discrete elements. Based on the type of the two elements between which the bond was broken, three cracking patterns were identified: cohesive cracking within aggregate particles, cohesive cracking within the matrix phase, and adhesive cracking at the interface between the aggregate and matrix phases. The discrete element model was used to determine the percentage of the total cracking that occurred within the matrix and at the interface between the matrix and aggregate at the peak load.

In summary, the inputs of the model are an image of the mixture internal structure and calibrated aggregate- and matrix-parameters. The model output is the mechanical response of the mixture computed in terms of the load-displacement curve, internal forces at different loading stages, and the cracking patterns. The main concept behind the analysis using the DEM-IA approach is that the PFC mixture gain its strength (mechanical response) through stone-to-stone contact, and thus with the removal of certain aggregate size fraction(s), there will be a modification of stone-to-stone contact. The drop in these contacts (and in the mechanical response) will depend on how much that certain aggregate size is contributing to the stone-to-stone contact. Therefore, the highest mixture strength is expected for case I, followed by cases II and III, and case IV should be the weakest. However, the significance of excluding certain aggregate size from the mixture can be assessed by comparing the change in the mechanical response of the mixture from one case to another. For example, the change in the mixture response between case II and case III is attributed to the contribution of aggregate of the size fraction P8-R16, and so the effect of certain sieve size is assumed to be significant if the change due to its exclusion is the highest compared to the effect of other sieve sizes.

7.7 RESULTS AND DISCUSSION

This section includes results and discussion on: (*i*) evaluation of the criteria currently suggested to select the breaking-sieve size, (*ii*) application of the DEM-IA to analyze the determination of the breaking-sieve size, (*iii*) recommendation of a criterion to select the breaking-sieve size, and (*iv*) recommendation of a maximum value for the *VCA* ratio.

7.7.1 Evaluation of Criteria Currently Used to Determine the Breaking-Sieve Size

Figure 7-1 shows a comparison of *VCA* ratios, computed using average G_{mb} values obtained from dimensional analysis and the three criteria currently suggested to determine the breaking-sieve size. Results are compared to the current pass/fail criterion (*VCA* ratio=1.0) suggested by NCAT

(Kandhal 2002) to determine the existence of stone-on-stone contact. As subsequently discussed, application of the criteria suggested to determine the breaking-sieve size led to either the No. 4 or No. 8 sieve for all the mixtures studied. Thus, either the inclusion or the exclusion of the P4-R8 fraction in the computation of both VCA_{mix} and VCA_{DRC} corresponds to the differences in the three assessed criteria.

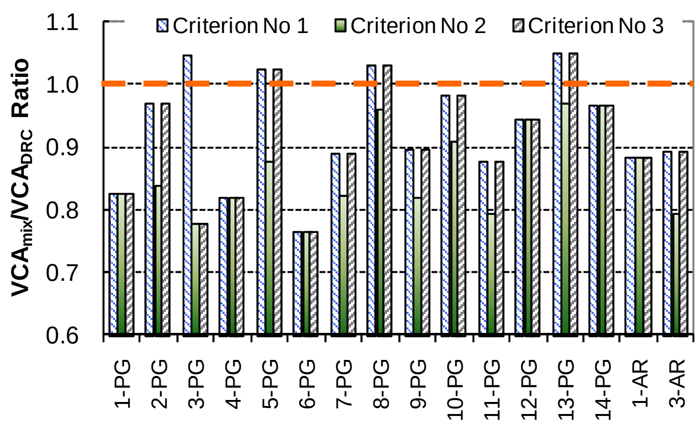


Figure 7-1. Comparison of the VCA_{mix}/VCA_{DRC} Ratio Calculated Using Different Criteria to Determine the Breaking-Sieve Size

These criteria showed coincident outputs (resulting in similar values of the *VCA* ratio) in six out of sixteen mixtures studied. For the remaining mixtures, however, there are differences in both the values of the *VCA* ratio and corresponding conclusions on the existence of stone-on-stone contact. These differences are generated by changes in the *VCA* computations related to the fractions that were included as coarse aggregate according to each criterion to determine the breaking-sieve size. These conclusions provided evidence of the necessity of further analysis to unify the criterion used to determine the breakpoint-sieve size.

7.7.2 Analysis of Breaking-Sieve Size Determination Based on the Discrete Element Method and Image Analysis Techniques (DEM-IA)

As previously discussed, the effect of aggregate fractions passing the No. 4 sieve was studied by excluding certain sieve sizes from the mixture gradation (cases I, II, III, and IV) in the DEM-IA analysis. The total energy and indirect tensile strength were compared for the different cases.

Figure 7-2 and Figure 7-3 show the values and changes in the total energy and the indirect tensile strength, respectively.

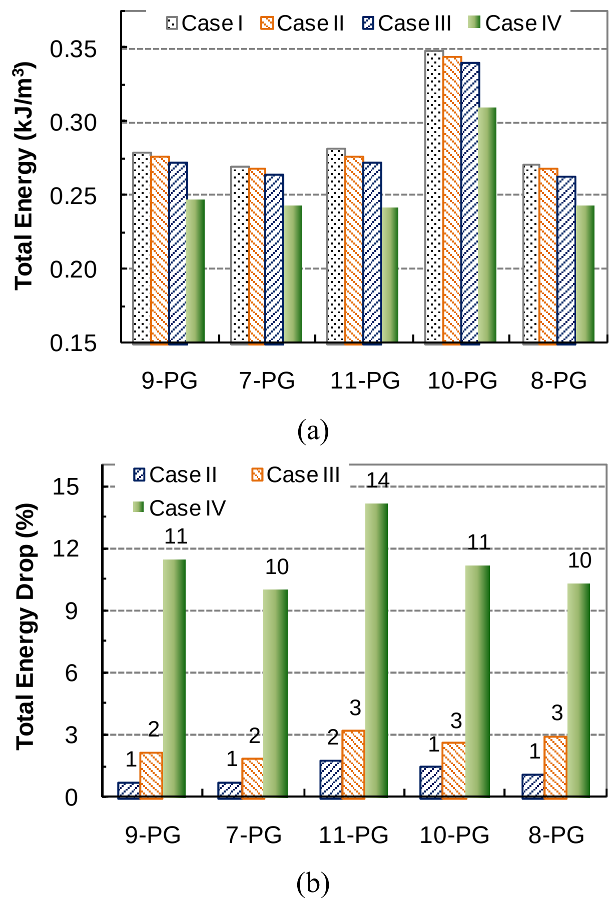
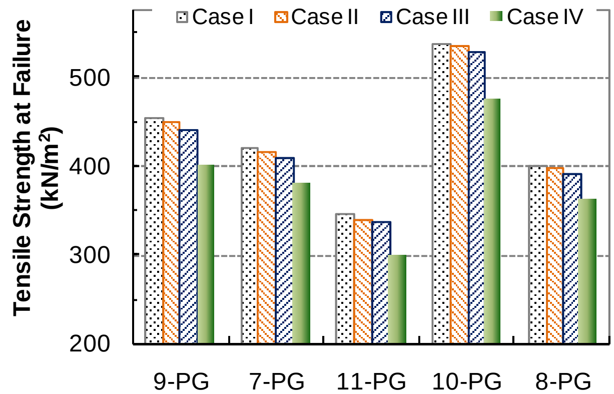
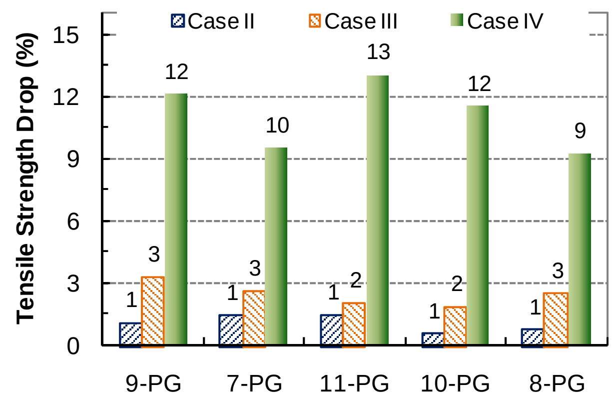


Figure 7-2. Comparison of Total Energy



(a)

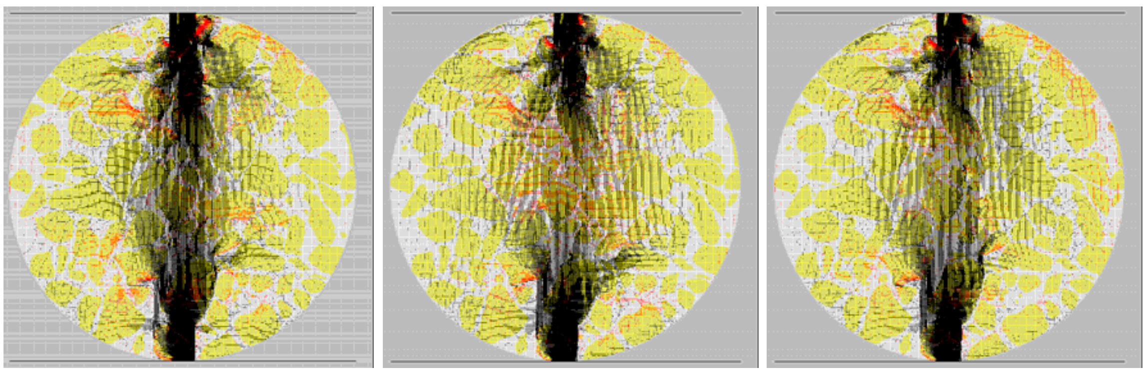


(b)

Figure 7-3. Comparison of Indirect Tensile Strength

All the different mixtures had similar trends, as both the energy and tensile strength were the highest for the full gradation (case I), followed by cases II, III, and IV (Figure 7-2[a] and Figure 7-3[a]). Figure 7-2(b) and Figure 7-3(b) show, respectively, the change in total energy and tensile strength for cases II to IV as compared to case I. It can be seen that the drop for cases II and III was not as significant as the drop in case IV. These results indicate that the aggregate fraction P8-R16 and P16-R60 can be considered part of the matrix without much effect on the mixture behavior. The drop in case IV is attributed to the exclusion of aggregate fraction P4-R8, and this high change in energy and strength in comparison to case I indicate that this fraction is playing an important role in influencing the mixture's ability to sustain loads.

Stress concentrations for cases II, III, and IV are shown in Figure 7-4. In this figure the internal forces developed within the mix are represented by black (compression) and red (tension) colored lines. All the pictures are scaled to the same force, which means that similar thickness represent similar internal forces across the three cases. Furthermore, the three cases correspond to the application of the same load level. Figure 7-4(*c*) (case IV) shows how the internal forces are more spread and less concentrated in the aggregate structure as compared to both cases II and III (Figure 7-4[*a*] and [*b*]), which indicates that the removal of the aggregate fraction P4-R8 affected the development of stone-on-stone contact.



(a) (b) (c)

Figure 7-4. Stress Concentration for Cases II (a), III (b), and IV (c)

Figure 7-5 summarizes the cracking results for all the mixtures. Figure 7-5(*a*) and (*c*) show the percent of interface (adhesive) cracking and percent of matrix (cohesive) cracking, respectively, while Figure 7-5(*b*) and (*d*) show the changes of cases II through IV as compared to case I. The decrease in the interface cracking and the increase in the matrix cracking followed the same order as for the energy and strength cases. The changes were again significant for case IV but not for cases II and III, which further supports the hypothesis that the aggregate fraction P4-R8 contributes to the development of stone-on-stone contacts in PFC mixtures and not only to fill the AV structure attained by the aggregate retained on the No. 4 sieve.

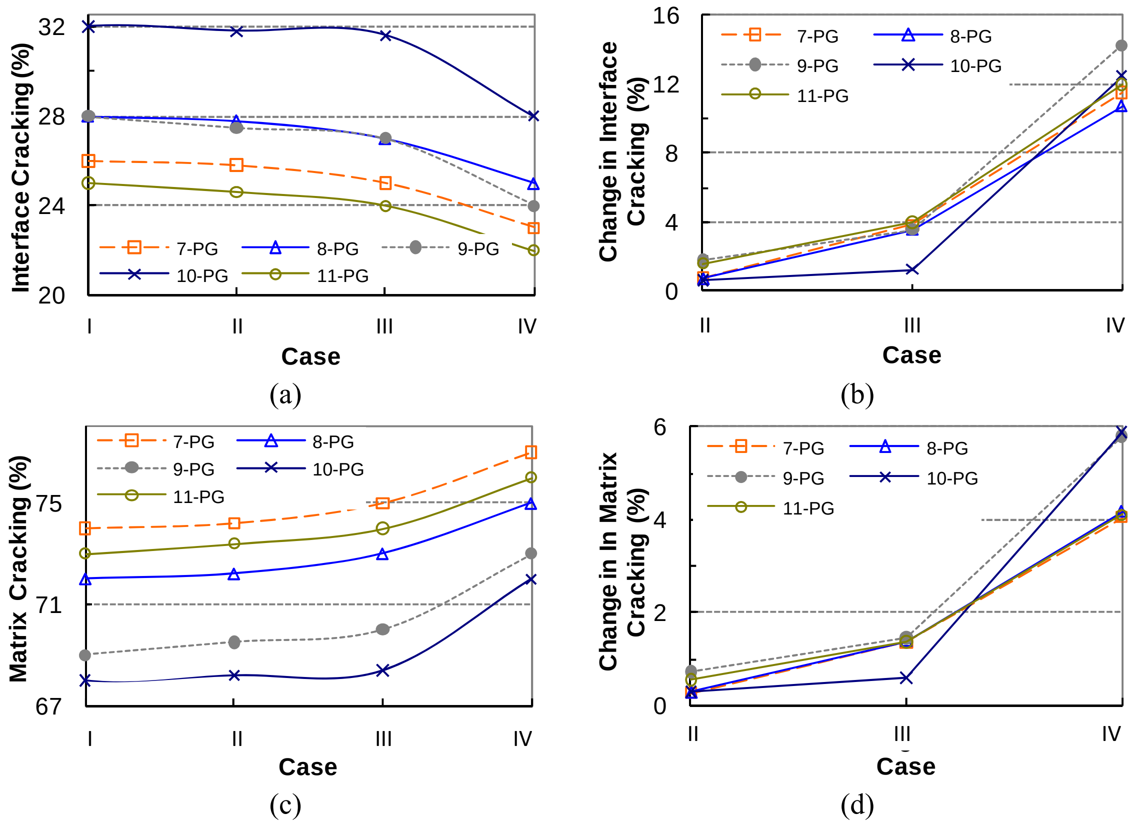


Figure 7-5. Comparison of Interface and Matrix Cracking

In order to link the responses obtained for strength/energy and cracking pattern, as related to the effect of the aggregate fraction P4-R8, the DEM-IA method was applied to compare the distribution of internal forces within the aggregate particles for each mixture studied. Figure 7-6 shows the cumulative frequency distribution for the 9-PG mixture. A similar trend was observed for all the other mixtures included in this study. According to these results, the internal forces within the aggregate particles decreased for case IV as compared to cases I, II, and III, which means that the aggregate particles left after excluding the P4-R8 fraction are carrying less load. This indicates that the P4-R8 fraction supports the distribution of internal forces within the PFC mixtures by creating additional stone-on-stone contact.

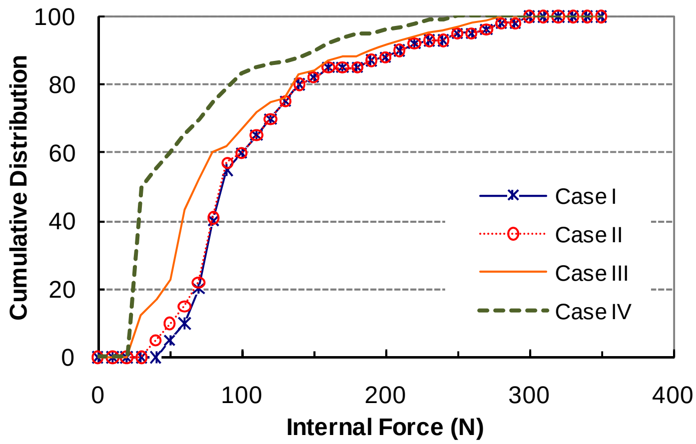


Figure 7-6. Comparison of Internal Forces Distribution for the 9-PG Mixture (Hard Limestone Aggregate)

7.7.3 Recommended Criterion to Determine the Breaking-Sieve Size

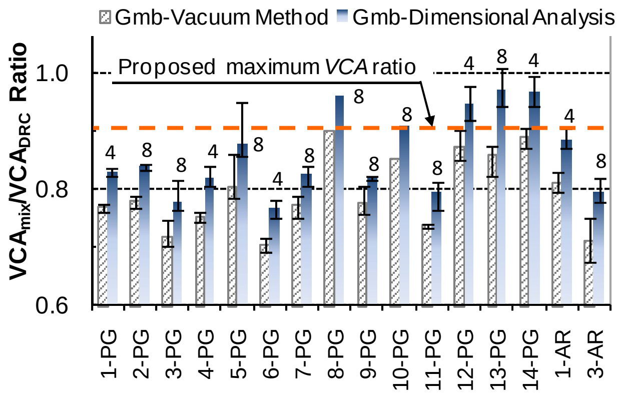
The three different analyses carried out using the DEM-IA method showed that in the mixtures analyzed the aggregate fraction P4-R8 contributes to the strength of the PFC mixture by carrying part of the load and transporting the load through stone-on-stone contact associated with the presence of this fraction. Therefore, results of the DEM-IA supported the inclusion of the P4-R8 fraction as part of the coarse aggregate fraction forming the granular skeleton with stone-on-stone contact.

In addition, based on the master aggregate gradation bands currently specified for PFC mixtures (Table 7-2 and Table 7-3), as the proportion of the P4-R8 fraction becomes larger, the slope of the gradation curve begins to flatten out at the No. 8 sieve (instead of at the No. 4 sieve). Under these conditions, according to criterion No. 2 to determine the breaking-sieve size, the P4-R8 fraction would be included as coarse aggregate to determine the existence of stone-on-stone contact. Thus, high proportions of this fraction (between the limits of the aggregate gradation bands) should contribute to the creation of a granular skeleton with stone-on-stone contact. Criterion No. 3 always leads to the No. 4 sieve as breaking-sieve (which is coincident with criterion No. 1) for the AR mixtures given the aggregate gradation bands specified for these mixtures. For the PG mixtures, the breaking-sieve can correspond to either the No. 4 or No. 8 sieve, although for most of the mixtures analyzed this criterion led to the No. 4 sieve, which is again coincident with criterion No. 1.

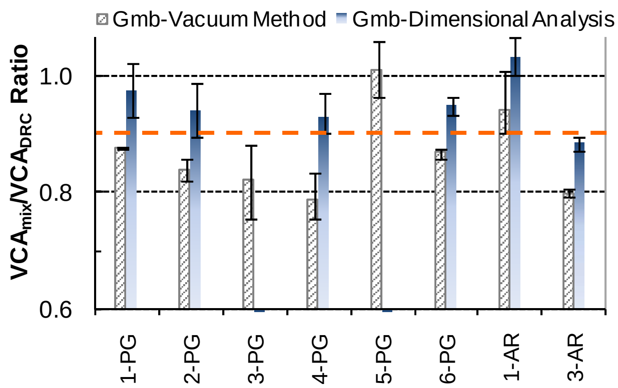
The previous discussion suggests that the results obtained by applying criterion No. 2 to determine the breaking-sieve size are coincident with DEM-IA results. Agreement of these two analyses support recommendation of criterion No. 2, based on the slope of the gradation curve, to determine the breaking-sieve size for PFC mixtures. Additional research may be required to quantify the effect of the aggregate fractions studied in mixtures produced at different levels of compaction as well as in mixtures designed with aggregate gradations close to the coarse and fine sides of the master aggregate gradation band.

7.7.4 Maximum Value of the Voids in Coarse Aggregate Ratio (VCA Ratio)

The two factors included to study the *VCA* ratio were: (*i*) the criterion used to select the breaking-sieve size and (*ii*) the method used for measuring G_{mb} (i.e., dimensional analysis and the vacuum method). Based on the recommendations previously stated on the determination of the breaking-sieve size, criterion No. 2 was used in the study of the maximum value of the *VCA* ratio. Application of this criterion led to the inclusion of the P4-R8 fraction in several mixtures, which constituted the main difference with respect to the current practice of stone-on-stone contact evaluation. In addition, recent research (Alvarez et al. 2009d) recommended dimensional analysis (over the vacuum method) to compute G_{mb} for PFC mixtures and did not support the interchangeable use of these methods for mix design based on different corresponding minimum total AV content values. However, data for both methods were collected in this study for comparison reasons, since the vacuum method is still employed for mix design (Alvarez et al. 2009d). Incidentally, according to ASTM D 7064-04 (ASTM International 2006) evaluation of G_{mb} (to determine the total AV content) for OGFC mix design can be conducted by applying either the vacuum method or dimensional analysis. Results of the *VCA* ratio obtained for the mixtures studied, including both average values and the range, are shown in Figure 7-7, which also shows the corresponding breaking-sieves.



(a)



(b)

Figure 7-7. Average and Range of the Voids in Coarse Aggregate (*VCA*) Ratio for (a) Laboratory- and (b) Field-Compacted Mixtures (Road Cores)

As expected, the inclusion of all surface AV in the dimensional analysis led to smaller G_{mb} values and, therefore, to higher values of the *VCA* ratio, as compared to those computed using the vacuum method. In addition, the variability shown in Figure 7-7 is associated with the VCA_{mix} as a function of the G_{mb} variability evaluated using the number of specimens specified in the Table 7-1. This was considered the main source of variability in the computation of the *VCA* ratio, since the variability of the other inputs involved in this calculation (G_{CA} and γ_s) met the maximum values specified for the corresponding laboratory tests (in accordance with AASHTO T 85-91 and AASHTO T 19M/T 19-00 for G_{CA} and γ_s, respectively).

However, even taking into account the maximum values of the *VCA* ratio, computed based on G_{mb} determined using either dimensional analysis or the vacuum method, most of the mixtures compacted at 50 gyrations of the SGC exhibited a *VCA* ratio smaller than 0.9 (Figure

7-7[*a*]). As compared to the corresponding laboratory-compacted mixtures, the field-compacted mixtures consistently showed higher values of the *VCA* ratio, which indicates lower compaction levels achieved in the field (Figure 7-7[*b*]). In fact the total AV content of these mixtures (except for the 3-PG mixture), measured using dimensional analysis, was in the range of 23.4 % to 29.2 %, whereas the design range used to produce the SGC laboratory-compacted mixtures corresponds to 18 to 22 %. Additional differences in the *VCA* ratio evaluated for field- and laboratory-compacted mixtures can be related to discrepancies in their internal structure. Previous research presents additional discussion on these differences (Alvarez et al. 2009c).

In addition, research conducted by Watson et al. (2003) on OGFC mixtures, indicated that between 30 and 45 SGC gyrations were required to achieve the threshold stone-on-stone contact condition (*VCA* ratio =1.0). At 30 gyrations, however, the VCA_{mix} values were slightly higher than the VCA_{DRC} values. Results shown in Figure 7-8 also suggest that this condition can be reached in PFC mixtures at low compaction levels, corresponding to approximately 12 gyrations of the SGC (Alvarez et al. 2009b). Furthermore, corresponding mixtures compacted at 50 gyrations of the SGC showed both reduced *VCA* ratio (Figure 7-8) and improved performance (i.e., durability evaluated in the laboratory) as compared to those compacted at the number of gyrations required to obtain the threshold stone-on-stone contact condition. Consequently, this previous research recommended requiring a *VCA* ratio higher than 1.0 to obtain PFC mixtures with fully developed stone-on-stone contact.

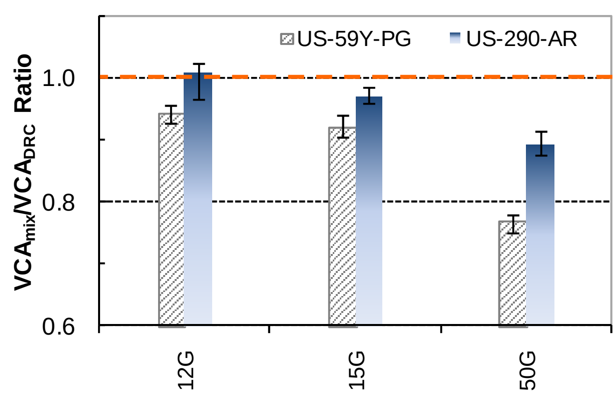


Figure 7-8. Average and Range of the Voids in Coarse Aggregate (*VCA*) Ratio Values for PFC Mixtures Compacted at 15 and 50 Gyrations of the Superpave Gyratory Compactor (SGC) (Adapted from Alvarez et al. (2009b))

Furthermore, previous research (Alvarez et al. 2009e) used the Cantabro loss, an index of mixture resistance to disintegration measured in the laboratory, to evaluate the durability of the 1-PG to 6-PG, 1-AR, and 3-AR mixtures used in this study. The evaluation was conducted using PMLC specimens compacted at 50 gyrations of the SGC and provided evidence of adequate resistance to disintegration for these mixtures, except for the 4-PG mixture. The inadequate durability response of this mixture, however, can be associated with a poor combination of materials.

Therefore, the necessity of ensuring a fully developed stone-on-stone contact condition in PFC mixtures leads to: (*i*) ratification of the inclusion of stone-on-stone contact verification in the PFC mix design that was proposed in previous research (Alvarez et al. 2009b), and (*ii*) proposal of corresponding verification based on a maximum value of the *VCA* ratio of 0.9. Data shown in Figure 7-7(*a*) as well as the previous discussion on the enhanced performance of mixtures (produced according to the current PFC mix design procedure and material specifications) compacted to obtain values of the *VCA* ratio smaller than 1.0, supports the adoption of a maximum value for the *VCA* ratio of 0.9. However, future evaluation of field performance is required to corroborate the adequacy of this maximum *VCA* ratio. In addition, as suggested in recent research (Alvarez et al. 2009b), a field density requirement should be included in the specifications for PFC mixtures, to better reproduce in the field the mix design determinations and allow validation of the proposed maximum *VCA* ratio.

7.8 SUMMARY AND CONCLUSIONS

This paper presents an evaluation of PFC mixtures conducted to improve the quantitative assessment of stone-on-stone contact for this type of asphalt mixtures. The evaluation included both laboratory tests and an analysis based on Discrete Element Method and image analysis techniques (DEM-IA). The following conclusions are provided based on the results and analysis conducted as part of this study.

- Application of the three criteria currently proposed to determine the breaking-sieve size gave different results in terms of the existence of stone-on-stone contact in the mixtures studied. Consequently, this study developed a unified criterion to determine the breaking-sieve size and to assess the presence of stone-on-stone contact in PFC mixtures.

- The DEM-IA results provided evidence of the adequacy of including the P4-R8 aggregate fraction as part of the coarse aggregate phase forming the granular skeleton with stone-on-stone contact.
- The criterion based on the slope of the gradation curve is recommended to determine the breaking-sieve size of PFC mixtures. This recommendation is supported by the agreement in the results obtained based on this criterion and those obtained using the DEM-IA analysis.
- A maximum value of the VCA ratio of 0.9 is recommended, over the current pass/fail criterion (VCA ratio=1.0), to guarantee the design and construction of PFC mixtures with fully developed stone-on-stone contact. However, the long-term performance of mixtures fabricated according to this recommendation should be assessed to determine final recommendations on the maximum value of the VCA ratio.

8. INTERNAL STRUCTURE OF COMPACTED PERMEABLE FRICTION COURSE MIXTURES*

8.1 OVERVIEW

Durability and functionality (i.e., noise reduction effectiveness and drainability) of PFC mixtures depend on the characteristics of the AV contained in the mixture. This study analyzes the internal structure of PFC mixtures, assessed in terms of AV characteristics, determined using X-ray CT and image analysis techniques. Corresponding results showed: (*i*) heterogeneous distributions of AV in the horizontal direction of both field-compacted mixtures (road cores) and specimens compacted using the SGC and (*ii*) limitations to compare their vertical AV distributions. Recommendations to reduce the horizontal heterogeneity included using road cores with a minimum 152.4 mm diameter and coring SGC specimens to 101.6 mm in diameter. Implementation of field-compaction control and future analysis of mixtures produced accordingly was recommended to determine the pattern of vertical AV distribution that should be reproduced in SGC specimens and corresponding modifications required for fabrication of these specimens.

8.2 INTRODUCTION

PFC, also termed new generation OGFC, are HMA mixtures characterized by a high total and interconnected (or effective) AV content. These AV contents are directly related to the main advantages conferred by these mixtures, as compared to dense-graded HMA, that include: reduction in the risk of wet skidding and hydroplaning; decrease of pavement noise and splash and spray; and enhancement in the visibility of pavement markings at night and in wet weather (Alvarez et al. 2006). Therefore, proper determination of the AV content of both field and laboratory-compacted mixtures constitutes an important aspect for mix design, construction, and evaluation of performance including both functionality (noise reduction effectiveness and drainability) and durability. Although previous research (Alvarez et al. 2009a; Alvarez et al. 2009d; Crouch et al. 2003; Watson et al. 2004a; Watson et al. 2003) focused on studying the macroscopic assessment of the AV content, limited information is currently available on the internal structure of PFC mixtures.

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* Submitted for Publication in the *Construction and Building Materials* journal (2009), by Allex E. Alvarez, Amy Epps Martin, and Cindy Estakhri.

Masad et al. (Masad et al. 1999b) proposed characterizing the internal structure of HMA in terms of the distribution, orientation, and contact of aggregates as well as the distribution of AV. In addition, during the last decade, the use of nondestructive techniques based on X-ray CT and image analysis led to additional insight into the internal structure of field- and laboratory-compacted dense-graded HMA. Similar studies addressed PFC mixtures (Alvarez et al. 2009b; Muraya 2007), even though additional work is still required to characterize field-compacted mixtures and to determine whether the internal structure of these mixtures is reproduced in laboratory-compacted mixtures. The specific characteristics of PFC mixtures (as compared to those of dense-graded HMA) and the relationship between the AV characteristics and both mix design and performance (Alvarez et al. 2008a; Alvarez et al. 2009e) encourage further examination of the mixture internal structure.

The specific characteristics of PFC mixtures include: (*i*) use of an open-graded aggregate (to create a coarse-aggregate granular skeleton with stone-on-stone contact, while the fine fraction fills the AV structure formed by the coarse aggregate), (*ii*) high asphalt content (6 to 10 %) and AV content (18 to 22 %), (*iii*) reduced thickness of field-compacted mixtures (25 to 50 mm), and (*iv*) mixture construction without a compaction control. In addition, current mix design of PFC mixtures (ASTM International 2006; TxDOT 2005) suggests selection of the optimum asphalt content based on a target laboratory density (between 78 and 82 %) that is evaluated on specimens compacted using the SGC.

Some of the limitations of this practice rely on the lack of field-compaction control to validate the mix design determinations and the poor relationship that can exist between the internal structure of both field-compacted mixtures and SGC specimens (Alvarez et al. 2009b). Further examination of the PFC mixture internal structure is also encouraged by: (*i*) the direct relationship between mixture durability and both total- and interconnected-AV content (Alvarez et al. 2009e; Khalid and Pérez 1996; Pérez and Gordillo 1990) and the discrepancies in permeability values computed for field- and laboratory (SGC)-compacted mixtures identified in previous research and attributed to differences in the distribution of AV (Alvarez et al. 2008a). Thus, additional examination of the internal structure is warranted, since drainability constitutes the main reason for employing PFC mixtures as the surface course in asphalt pavements in the United States.

Consequently, additional analysis to ensure the proper reproduction of the internal structure of field-compacted mixtures in SGC specimens is still needed. Corresponding results can provide further assurance that the mix design and evaluations conducted in the laboratory using this type of specimens represent the actual properties and response of PFC mixtures. This approach is promoted by the conclusions of previous research conducted on dense-graded HMA indicating that portions of SGC specimens can be used to obtain specimens with similar distributions of total AV content (Peterson et al. 2004; Tashman et al. 2001) as well as mechanical properties (Peterson et al. 2004) to those obtained in the field. This paper assesses the internal structure of field- and laboratory-compacted PFC mixtures, in terms of the horizontal variability and the vertical distribution of the AV characteristics. In addition, modifications in the fabrication of SGC specimens are explored to improve the comparison with the internal structure of field-compacted mixtures. The paper includes a description of the experiment design, describes the analysis conducted to study the AV characteristics of PFC mixtures, followed by results and discussion. Conclusions and recommendations complete the paper.

8.3 OBJECTIVE AND METHODOLOGY

The objectives of this study are to assess and compare the internal structure (evaluated in terms of AV characteristics) of field- and laboratory-compacted PFC mixtures and propose the required enhancements in the fabrication of laboratory-compacted specimens to better reproduce the AV characteristics of field-compacted mixtures. X-ray CT and image analysis techniques were applied to achieve this objective according to the following tasks:

- Analysis of horizontal variability of total AV content and size of AV for both field-compacted mixture specimens (road cores) and specimens produced in the laboratory (SGC compacted).
- Analysis of vertical distribution of both total AV content and size of AV for both road cores and SGC specimens.

8.4 EXPERIMENTAL DESIGN

The experimental design defined for this study is presented in this section and includes mix design and material requirements, material selection, and specimen fabrication as well as laboratory testing.

8.4.1 Mix Design and Material Requirements

Mixtures included in this study were designed according to the current PFC mix design method specified by TxDOT (TxDOT 2005). Material specifications for PFC mixtures (TxDOT 2004) include the following two types of asphalt binders and corresponding master aggregate gradation bands:

- a PG asphalt (minimum high temperature grade of PG76-XX) with a minimum of 1.0 % by weight of dry aggregate of lime and a minimum of 0.2 % by weight of mixture of mineral or cellulose fibers.
- a Type I or II AR with a minimum of 15 % by weight of asphalt of Grade C or Grade B crumb rubber.

8.4.2 Material Selection and Specimen Fabrication

The assessment of internal structure included plant mixed-laboratory compacted—produced using the SGC—specimens and corresponding road cores gathered from eleven PFC mixtures produced in the field and used in diverse highway projects (Table 8-1). Thus, this study included mixtures fabricated using the two types of asphalt binders specified as well as aggregates of diverse geological origins and gradations covering the entire master aggregate gradation bands specified for both AR and PG mixtures (Table 8-2).

Table 8-1. Description of Mixtures Used to Assess Mixture Internal Structure

Mixture	Asphalt Type	OAC, %	Aggregate Type	Other Materials (L / CF)	Type and (Number) of Specimens Evaluated
I-35-PG or 1-PG	PG 76-22	6.1	Sandstone, Limestone	1 % / 0.3 %	SGC (2), RC-T (2)
IH-30-PG or 2-PG	PG 76-22	6.6	Sandstone	1 % / 0.3 %	SGC (2), RC (2)
IH-20-PG or 3-PG	PG 76-22	6.5	Limestone	1 % / 0.3 %	SGC (2), RC-T (1)
US-83-PG or 4-PG	PG 76-22	6.4	Limestone	1 % / 0.3 %	SGC (2), RC-T (2)
US-59-PG or 5-PG	PG 76-22	5.9	Granite, Limestone	1 % / 0.3 %	SGC (2)
US-59Y-PG or 6-PG	PG 76-22	5.8	Limestone	1 % / 0.3 %	SGC (2), RC (1)
US-281-AR or 1-AR	Type II AR, grade B (AC-10 w/16 % CR)	8.1	Sandstone, Limestone	0 % / 0 %	SGC (2), RC (2)
US-288-AR or 2-AR	Type II AR, grade B (AC-10 w/17 % CR)	8.0	Granite, Limestone	0 % / 0 %	SGC (2), RC (2)
US-290-AR or 3-AR	Type II AR, grade B (AC-10 w/17 % CR)	8.3	Sandstone	0 % / 0 %	SGC (2), RC (2)
SH-6-AR or 4-AR	Type II AR, grade B (AC 10 w/17 % CR)	8.2	Granite	0 % / 0 %	RC (7)-T
IH-35-AR or 5-AR	Type II AR, grade B (AC-10 w/17 % CR)	8.4	Sandstone, Limestone	0 % / 0 %	RC (2)-T

Note: OAC = optimum asphalt content; L= lime; CF = cellulose fibers; CR = crumb rubber; RC = road core taken after mixture compaction; RC-T = road core taken after 1 to 2 years of traffic.

Table 8-2. Aggregate Gradations for PG and AR Mixtures (Percentage Passing) Used to Assess Mixture Internal Structure

Sieve	Specifi-cation	1-PG	2-PG	3-PG	4-PG	5-PG	6-PG	Specifi-cation	1-AR	2-AR	3-AR	4-AR	5-AR
¾	100-100	100	100	100	100	100	100	100-100	100	100	100	100	100
½	80-100	90.3	81	85.3	90.5	80.2	84.5	95-100	99	95.6	99.7	95.7	98.9
3/8	35-60	59.5	43	59.4	50.9	57.7	52.8	50-80	54.6	54.9	75.7	68.7	54.6
#4	1-20	10.1	15.5	18.6	3.2	15.9	6.6	0-8	5	4	7.9	6.5	5
#8	1-10	5.2	6.7	2	1.5	6	4.2	0-4	1.9	2.1	1.1	2.2	2
#200	1-4	2.3	2.2	1.6	1.1	2.1	2.4	0-4	1	0.8	0.6	0.4	1

The compaction temperature for fabrication of SGC specimens was 149°C for both AR and PG 76-22 asphalts. Compaction was achieved by applying 50 gyrations (1.25°, 600 kPa, 30 rev/min) of a ServoPac SGC, as currently specified for mix design (TxDOT 2005), to obtain

152.4 mm in diameter and 115 ± 5 mm in height specimens. Road cores of 152.4 mm in diameter and 16 to 54 mm in height (average height 41 mm) were recovered from the field projects constructed according to the current TxDOT construction specifications (TxDOT 2004). The road cores obtained after mixture compaction were used in the analysis of vertical and horizontal distribution of AV, whereas those taken from mixtures subjected to one to two years of traffic were used only in the analysis of horizontal distribution of AV, since some AV clogging could reduce the AV content. However, the road cores from the 1-PG, 3-PG, and 4-PG mixtures were taken at the road shoulder, which reduced the probability of AV clogging.

8.4.3 Laboratory Testing

Computation of bulk specific gravity of the compacted mixture, G_{mb}, was conducted by dimensional analysis (Alvarez et al. 2009d), which required determination of: (*i*) average height and diameter of the specimen, based on direct measurements, for a geometrical computation of total volume and (*ii*) the weight of the compacted specimen in air. The X-ray CT system at Texas A&M University was used for nondestructive 2D imaging of compacted mixtures. A description of the X-ray CT imaging system principles is documented elsewhere (Masad 2004; Shashidhar 1999). The next section describes the corresponding image analysis conducted to assess the PFC mixture internal structure.

8.5 APPLICATION OF X-RAY COMPUTED TOMOGRAPHY AND IMAGE ANALYSIS TECHNIQUES TO ANALYZE MIXTURE INTERNAL STRUCTURE

Each specimen analyzed was subjected to X-ray CT scanning to obtain computerized grayscale images, representing successive scanned planes perpendicular to the vertical axis of the specimen, with a gap of 1 mm. Since the pixel size was approximately 0.17 mm, a voxel size of 0.17 by 0.17 by 1 mm was obtained. The grayscale images were first analyzed using the Image-Pro® Plus software to obtain black (air void) and white (aggregate and asphalt mastic) images. This iterative process allowed matching: (*i*) the specimen total AV content value computed based on volumetric laboratory determinations and (*ii*) the mean total AV content value computed for the corresponding set of images. The mixture internal structure was then analyzed based on the computation of the following AV characteristics on black and white images:

- total AV content, which corresponds to the mean total AV content value from image analysis,
- size, quantified in terms of mean AV radius, and

- connectivity, analyzed in terms of interconnected AV content, for a specific subset of specimens.

Computation of these parameters for each black and white image allowed subsequent analysis of the *vertical distribution* of total AV content, mean radius of AV, and interconnected AV content for each specimen. Based on an application for image analysis, developed by Masad et al. (Masad et al. 2007) using Image-Pro® Plus, the total AV content of an individual image, AV_i, and the mean total AV content value for the set of images representing a specimen, AV_s, were determined as follows:

$$AV_i = \frac{A_{vi}}{A_T} \quad \text{(8-1a)}; \qquad AV_s = \frac{\sum_{i=1}^{n} AV_i}{N} \quad \text{(8-1b)}$$

where A_{vi} corresponds to the area of AV in image i, A_T is the cross-sectional area of image i, and N is the total number of images. These computations included the surface AV (AV that are in contact with the external circumference of the specimen) in each image as suggested in previous research (Alvarez et al. 2009a). In addition, the mean radius of AV ($\bar{r}_i$) in image i is computed as:

$$\bar{r}_i = \sqrt{\frac{A_{vi}}{\pi M_i}} \qquad \text{(8-2)}$$

where M_i is the number of AV in each image. The radius of AV was included in this analysis since it is associated with the degree of packing of the granular skeleton of PFC mixtures (Watson et al. 2004b). Thus, for a particular mixture, increasing the particle contacts and packing leads to smaller sizes of AV. The interconnected AV content is defined as the proportion of the total volume that forms void-connected paths from top to bottom in a compacted specimen (Alvarez et al. 2009a). This parameter was computed using a FORTRAN-built algorithm to determine connected paths for the stack of images associated with a particular specimen. Additional details on this computation are reported elsewhere (Alvarez et al. 2009a).

The horizontal variability of the total AV content and mean radius of AV for road cores and SGC specimens was studied based on the analysis of: (*i*) concentric electronically cored specimens (or *e-cores*) of different diameters and (*ii*) three independent concentric zones of equal volume (or *e-rings*). E-cores 10, 20, 30, 40, 50, 60, 76.2, 84.3, 101.6, 127, 146.1, and 152.4 mm in diameter were analyzed to evaluate the variability of the AV characteristics. The analysis employed the software ImageJ 1.38x to crop the stack of black and white images (originally 152.4 mm in diameter) to the diameter of each e-core along with Image-Pro® Plus to compute the AV characteristics as previously described. The three concentric zones of equal volume correspond to the stack of images processed using ImageJ 1.38x to obtain: (*i*) an internal e-ring 84.3 mm in diameter, (*ii*) an intermediate e-ring, 84.3 mm in internal diameter and 119.2 mm in external diameter, and (*iii*) an external e-ring, 119.2 mm in internal diameter and 146.1 mm in external diameter. Image-Pro® Plus was also used to determine the total AV content of the images stack obtained for each e-ring.

The diameter of the internal e-ring was selected based on the variability analysis of AV characteristics performed using e-cores, subsequently discussed, to ensure a representative assessment. The maximum diameter of the e-rings was reduced from 152.4 to 146.1 mm to avoid including AV that can be generated during the image processing. These AV may be created since the analysis is conducted using a constant diameter value for all images representing the specimen, which imposes difficulties to capture all geometrical deviations of the specimen (i.e., surface irregularities not associated with those created by the surface AV).

8.6 RESULTS AND DISCUSSION

This section presents results and discussion on: (*i*) analysis of horizontal variability of total AV content and mean radius of AV, and (*ii*) analysis of vertical distribution of both total AV content and mean radius of AV for both road cores and SGC specimens.

8.6.1 Analysis of Horizontal Variability of Total Air Voids Content and Mean Radius of Air Voids

The analysis of e-cores, computed for one road core and one SGC specimen of each mixture analyzed, is summarized in Figure 8-1. For each e-core obtained from a particular mixture, the results are expressed in terms of the mean (AV_s) and COV of the vertical distribution of total AV content values (or vertical AV distribution). This distribution was obtained from the values of total AV content (AV_i) determined for the black and white images associated with a specific e-core. The tendencies of the mean and COV values computed for e-cores of different diameters led to identification of three homogeneous regions (delimited by vertical lines and identified as R1, R2, and R3 in Figure 8-1[*a*] and [*c*]) in each data set obtained for SGC specimens and road cores.

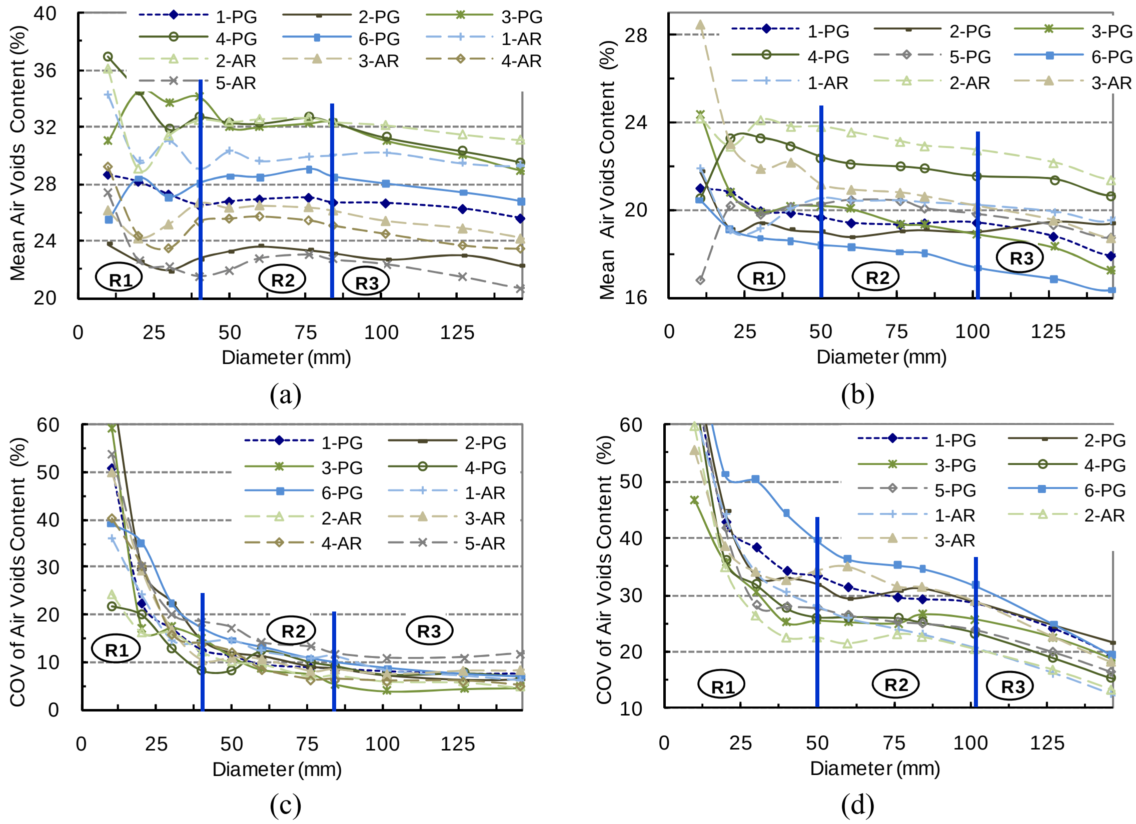
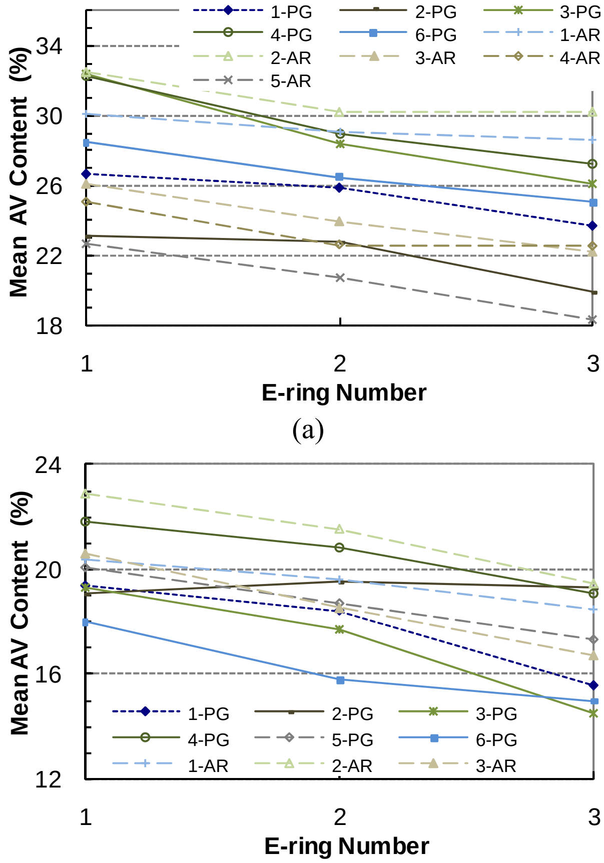


Figure 8-1. Mean Total Air Voids (AV) Content for E-cores Obtained from Road Cores (a) and Superpave Gyratory Compactor (SGC) Specimens (b), and Coefficient of Variation (COV) of Total AV Content for E-cores Obtained from Road Cores (c) and SGC Specimens (d)

In the case of road cores, big fluctuations of the mean and high values of the COV characterized the first region (R1) that included e-cores 10 to 40 mm in diameter. These results are associated with small-scale heterogeneity as described by Romero and Masad (Romero and Masad 2001), since the small area included in the analysis leads to areas composed of mostly aggregate-asphalt mastic and areas formed mostly by AV. The second region, R2 (e-cores 40 to 84.3 mm in diameter), corresponds to a transition region with small fluctuations in the mean and COV values that decreased as the diameter increased. On the contrary, the third region, R3 (e-cores 84.3 to 146.1 mm in diameter), presents approximately constant values of the COV, which suggests that corresponding determinations of total AV content are not affected by the small-scale heterogeneity. However, the mean total AV content values decreased as the diameter increases providing evidence of a non-uniform distribution of AV in the horizontal direction. In conclusion, this analysis suggests that road cores at least 84 mm in diameter, should be used to study the properties of PFC mixtures. However, additional discussion on this topic is subsequently presented based on the analysis of e-rings.

Figure 8-1(*b*) and (*d*) suggest that for SGC specimens (compacted at 50 gyrations) the first region, R1, affected by small-scale heterogeneity, includes e-cores up to 50 mm in diameter. The second region, R2, includes e-cores 50 to 101.6 mm in diameter, and is characterized by approximately constant COV values and decreasing mean total AV content values. The tendency for the mean values extends into the third region, R3, that includes e-cores 101.6 to 146.1 mm in diameter, where a decreasing tendency for the COV values is shown. These results provide evidence of a non-uniform distribution of total AV content for SGC specimens in the horizontal direction and lead to a recommendation that SGC specimens 100 mm in diameter be used for evaluating PFC mixture properties. Additional discussion on this aspect is also subsequently provided based on the analysis of e-rings.

The mean total AV content values computed for the internal, intermediate, and external e-rings (identified as e-ring number 1, 2, and 3, respectively) are shown in Figure 8-2. For road cores, the COV calculated for the vertical AV distribution of the three e-rings was approximately equal and the COV values for the radius of AV were, in general, higher for the internal e-ring. For SGC specimens, the highest and the smallest COV values for both total AV content and mean radius of AV were obtained, respectively, for the internal and the external e-rings. These results were consistent for both AR- and PG-mixtures. Examples of the vertical distribution of both total AV content and radius of AV values obtained for e-rings are shown in Figure 8-3, which uses the same convention used in Figure 8-2 to identify the e-rings.

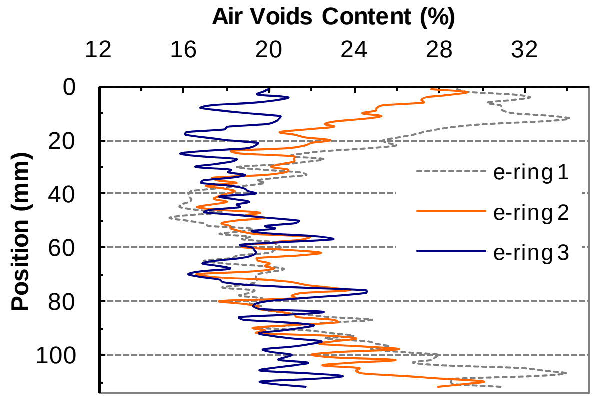


(a)

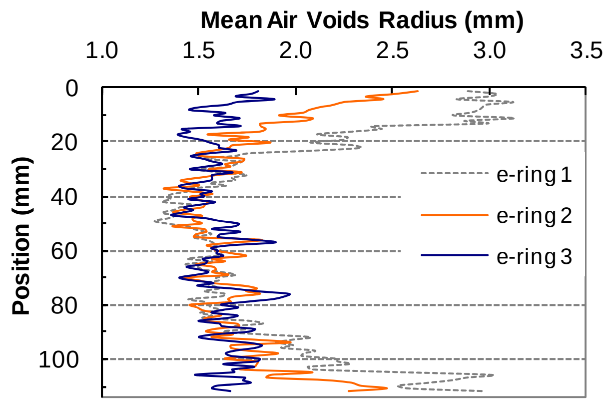
(b)

Figure 8-2. Mean Total Air Voids (AV) Content for E-rings Obtained from Road Cores (a) and Superpave Gyratory Compactor (SGC) Specimens (b)

These results are coincident with those shown in Figure 8-1(*b*) and (*d*), since the reduction in both the mean and COV values of e-cores 101.6 to 146.1 mm in diameter is explained by the smaller mean values and more homogeneous vertical AV distribution of the external e-ring in SGC specimens. On the contrary, previous research (Tashman et al. 2001; Thyagarajan et al. 2009; Voskuilen and van de Ven 2004) concluded that the outer portion of SGC specimens (135 mm in height) of dense-graded HMA exhibit higher total AV content values as compared to the corresponding inner core. However, Tashman et al. (2001) reported smaller values of total AV content in the outside region for short SGC specimens (i.e., 50 mm in height).



(a)



(b)

Figure 8-3. Typical Vertical Distribution of Total Air Voids (AV) Content (a) and Mean Radius of AV (b) for E-rings Obtained from Superpave Gyratory Compactor (SGC) Specimens

Q-Q plots proved that the distribution of total AV content values of all e-rings evaluated matched reasonably well to the normal distribution. Thus, the null hypothesis of equal means for the mean total AV content values computed for the internal, intermediate, and external e-rings was assessed by applying Analysis of Variance (ANOVA) at a significance level of 0.05. These analyses, conducted using the SPSS Statistics 17.0 software, included all the specimens listed in Table 8-1. Corresponding results showed that for one road core, out of 23 analyzed, the mean total AV content values of the three e-rings were statistically equivalent. The same conditions were valid for two SGC specimens out of 18 studied. Therefore, identification of significantly different means was conducted based on the following tests for multiple comparisons between means: Tukey's honestly significant difference, Tukey's b, and Bonferroni *t* test. Table 8-3 presents the conclusions of this statistical analysis expressed as the number of specimens and corresponding proportion (with respect to the total number of specimens analyzed) of specimens that were classified in a specific category defined according to the e-rings that exhibited equivalent mean total AV content values.

Table 8-3. Summary of Comparisons of Mean Total AV Content Values Computed for E-rings

E-rings with Statistically Equivalent Means, $\alpha=0.05$	Number and (Percentage) of Road Cores	Number and (Percentage) of SGC Specimens
All	1 (4)	2 (11)
Intermediate and External	6 (26)	1 (6)
Internal and Intermediate	8 (35)	9 (50)
None	8 (35)	6 (33)

In summary, results from the analysis conducted for both e-cores and e-rings are consistent and provide evidence of the heterogeneous horizontal distribution of total AV content values in road cores as well as in SGC specimens. For these two types of specimens, the external e-ring has smaller mean total AV content values as compared to the inner and intermediate e-rings. The variability of the vertical AV distribution is similar for all three e-rings in road cores and smaller in the external zone of SGC specimens as compared to the internal and intermediate e-rings. The differences in total AV content for the three e-rings assessed were probed to be statistically significant and are deemed of practical importance for PFC mix design, construction control, and performance evaluation.

The drilling and handling required to obtain road cores may be the main cause generating the heterogeneous horizontal distribution of total AV content, since the friction and heat induced during this process can distort the granular skeleton and the AV of the external zone. Data shown in the two bottom rows of Table 8-3 suggest that this phenomenon affected 70 % of the road cores analyzed and included PFC mixtures fabricated using different gradations and both AR and PG asphalts. In addition, the analysis of seven replicate road cores, gathered from the 4-AR mixture, along with the comparison of the replicate road cores analyzed for each mixture (Table 8-1) , led to the conclusion that this heterogeneous distribution of AV is not a mixture dependent phenomenon.

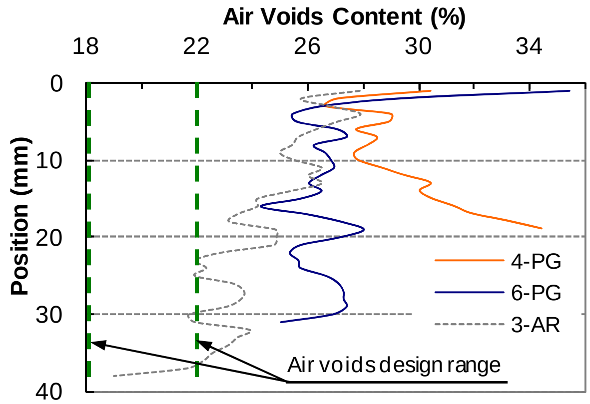
Previous research (Tashman et al. 2002; Tashman et al. 2001; Voskuilen and van de Ven 2004) reported homogeneous horizontal distributions of total AV content for road cores of dense-graded HMA. Even though the same response was expected for PFC mixtures, the results of this study do not support this expectation. The open structure of PFC mixtures can be more susceptible to rearrangement during coring as compared to that of dense-graded HMA, leading to the horizontal heterogeneity discussed. Although the analysis of e-cores led to the recommendation that road cores be at least 84 mm in diameter, road cores 152.4 mm in diameter are recommended based on the analysis of e-rings to minimize the disturbance induced by sampling. In addition, these results suggest that current assessment (e.g., permeability and total AV content measurements) of field-compacted PFC mixtures based on road cores can lead to unreliable results and ultimately suggests the necessity of alternative nondestructive evaluation tools.

In the case of SGC specimens, the horizontal heterogeneity is attributed to: (i) the irregular distribution of compaction energy applied by the SGC and (ii) the restriction induced by both the compaction mold and top and bottom surfaces of the SGC to the movement of aggregate particles during compaction (Thyagarajan et al. 2009). An irregular temperature profile can also be a factor generating heterogeneity in PFC mixtures. Even though research on dense-graded HMA (Masad et al. 2009) concluded that the effect of temperature is secondary as compared to the restriction imposed by the surfaces of the SGC, the effect of temperature can be different in PFC mixtures given the faster cooling of these mixtures, as compared to dense-graded HMA, that was observed in this study. Data shown in the two bottom rows of Table 8-3 allows the conclusion that for 83 % of these SGC specimens, taking out the external e-ring (1/3 of the specimen volume) will lead to a more homogeneous horizontal distribution of AV. In addition, the results obtained for e-cores (Figure 8-1[b] and [d]) and e-rings (Figure 8-2[b]) obtained from SGC specimens suggests that the external zone, can be approximated by an external ring 100 mm in internal diameter and 146.1 mm in external diameter.

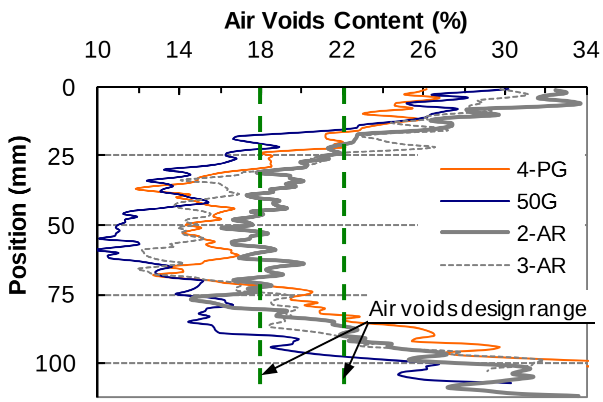
Therefore, coring the SGC specimens from 152.4 mm to 101.6 mm in diameter is recommended taking into account that: (i) it will increase the homogeneity of AV distribution in the horizontal direction, (ii) this diameter is more than five times the maximum aggregate size used in PFC mixtures, and (iii) the required equipment is readily available. However, the proposed coring can have some disadvantages that include: (i) increased variability of the vertical AV distribution, (ii) rearrangement of the granular skeleton and the AV, similar to that discussed for road cores, and (*iii*) sealing of surface AV (leading to problems to evaluate both functionality and volumetric properties such as the effective AV content). Comparison of the vertical AV distribution of e-cores 101.6 and 146.1 mm in diameter supports this increment of variability. Additional research is required to further assess all of the aforementioned aspects and validate the recommendation of coring SGC specimens to 101.6 mm in diameter. Previous research (Muraya 2007) conducted on European porous asphalt, similar to PFC mixtures, recommended coring SGC specimens (152 mm in diameter) to 65 mm in diameter to obtain a homogeneous horizontal AV distribution. However, the recommendation also included using specimens 121 mm in height, which are taller than those used for PFC mix design and evaluation.

8.6.2 Analysis of the Vertical Distribution of Total Air Voids Content

The patterns of vertical distributions of total AV content values (computed for e-cores 101.6 mm in diameter according to the previous recommendations) consistently obtained for all SGC specimens are shown in Figure 8-4(*b*). The distributions are similar to those reported by Thyagarajan et al. (Thyagarajan et al. 2009) for short SGC specimens (i.e., maximum of approximately 120 mm in height) of dense-graded HMA. The patterns of vertical AV distribution for road cores (calculated from e-cores 146.1 mm in diameter) can be grouped either as (Figure 8-4[*a*]): (*i*) an approximately homogeneous distribution, with higher AV contents in the zone adjacent to the pavement surface (e.g., 6-PG mixture) or (*ii*) a distribution with a positive slope (e.g., 3-AR mixture). However, for short road cores (approximately 25 mm in height), the pattern resembles either the vertical AV distribution shown for the 6-PG mixture or the "C" shape distribution obtained for SGC compacted specimens (e.g., 4-PG mixture). Since only two mixtures with small thickness were studied, additional information is required to better characterize them. For both road cores and SGC specimens, the patterns obtained for the vertical distribution of mean AV radius resembled the corresponding patterns obtained for the vertical AV distribution.



(a)



(b)

Figure 8-4. Vertical Distribution of Total Air Voids (AV) Content for (a) Road Cores and (b) Superpave Gyratory Compactor (SGC) Specimens

Dissimilarities in the patterns of vertical AV distribution obtained for road cores can be associated with two factors: (*i*) heterogeneous vertical distribution of temperature in the mixture during compaction and (*ii*) the field-compaction pattern employed. Faster cooling of the PFC mixture surface (as compared to dense-graded HMA) can be generated by both the construction of thin layers (Estakhri et al. 2008) and the open gradation that allows a faster loss of heat, specially at the pavement surface. In addition, even though previous research (Tashman et al. 2001) concluded that differences in the field-compaction pattern did not lead to discrepancies in the vertical AV distribution of dense-graded HMA, there is no evidence of the same response for PFC mixtures . The use of different compaction patterns to construct the mixtures included in this study impeded further analyzing the effect of this factor. Therefore, additional research is required to determine the effect of both the compaction pattern and the temperature profile.

A formal comparison of the vertical AV distribution of field- and laboratory-compacted PFC mixtures is limited by differences in: (*i*) the patterns of vertical AV distribution, previously discussed and (*ii*) the mean values of total AV content. While the mean total AV content value of SGC specimens was 20.4 % (COV=8.8 %), which met the mean value of the currently specified AV design range, the mean total AV content value for road cores was 26.8 % (COV=13.8 %). Although the distortion induced by coring, previously discussed, can bias the evaluation of total AV content for road cores, this assessment suggests the need for a field-compaction specification to meet the total AV content determined in the mix design. A similar conclusion was obtained in a previous study that addressed the effects of compaction in PFC mixtures (Alvarez et al. 2009b).

Evaluation of field sections constructed under a compaction control is required to determine the pattern of AV distribution that should be reproduced in SGC specimens, because the internal structure of mixtures compacted at lower AV content values, as compared to the values reported in this study, can differ from those reported in Figure 8-4(*a*). Additional compaction in the field can promote further rearrangement in the granular skeleton and modifications in the internal structure of the mixture. For example, an analysis conducted on road cores obtained from two sections of the 3-AR mixture, compacted at different AV content using the same compaction equipment, preliminarily suggests that additional compaction led to a more homogeneous vertical AV distribution. In addition, a previous laboratory evaluation suggested that low compaction levels (as compared to those specified for mix design, but similar to those obtained in the road cores included in this study) significantly modified both the macroscopic response and the internal structure of PFC mixtures (Alvarez et al. 2009b). In addition, research conducted on Danish porous asphalt (Nielsen 2007), reported a homogeneous and a "C" shape vertical AV distribution for road cores 72 and 45 mm in thickness, respectively. The total AV content of these road cores (100 mm in diameter) was 20.4 %, although the mixtures evaluated differed in both gradation and asphalt content as compared to PFC mixtures.

Based on the previous discussion, a strict comparison of SGC and road cores was not further pursued in this study. However, the data presented in Figure 8-4 allows for the conclusion that restrictions in the validity of laboratory tests conducted for mix design and performance evaluation using SGC specimens (fabricated according to the current specifications) can be expected. Therefore, subsequent analysis explores some modifications that can be applied in the fabrication of SGC specimens to improve the comparison with road cores taking into account the advantages and disadvantages of different AV distributions.

A homogeneous distribution of AV can favor mixture durability, since previous studies (Khalid and Pérez 1996; Pérez and Gordillo 1990) based on macroscopic response assessment provided evidence of a direct relationship between the AV content and the mixture resistance to disintegration (i.e., raveling). However, a performance assessment of Danish Porous Asphalt (Bendtsen et al. 2002) concluded that clogging of AV took place in the top 10 to 25 mm of the mixture and negatively affected both permeability and noise reduction effectiveness. Ongoing research by the authors preliminarily suggests that PFC clogging occurs in the top 25 mm. Therefore, as long as durability problems (i.e., raveling) do not arise, mixtures with higher AV content in the zone adjacent to the pavement surface (with a positive slope or increasing vertical AV distribution) can be desirable from the point of view of functionality. A higher volume of voids close to the pavement surface may extend the time required to lose the mixture functionality. Thus, additional research is required to evaluate the performance of mixtures with different AV distributions and the effect of other mixture and operational variables (e.g., aggregate gradation, AV size, AV connectivity, asphalt aging, and traffic speed).

The modifications for fabrication of SGC specimens can include: (*i*) reduction of the compaction energy (i.e., number of SGC gyrations), (*ii*) cutting sections of the currently compacted specimens, and (*iii*) modification of the specimen height. Figure 8-5 shows the vertical AV distribution of SGC specimens (obtained from e-cores 101.6 mm in diameter) compacted at both 50 (50G) and 15 (15G) gyrations of the SGC. The distributions of total and interconnected AV content are parallel for specimens fabricated at a particular compaction energy, suggesting that the degree of connectivity is not modified by the modification to the compaction energy. However, specimens compacted at the lowest energy showed a more homogeneous AV distribution. Further analysis of 15G-SGC specimens based on tests for multiple comparisons between means (Tukey's honestly significant difference, Tukey's b, and Bonferroni *t* test) led to the conclusion that the mean total AV content values of the internal and intermediate e-rings are statistically equivalent at a significance level of 0.05. Therefore, the horizontal variability of AV was not eliminated by decreasing the compaction energy.

This analysis does not intend to recommend any energy of compaction, but to illustrate the potential effect of this factor on the AV distribution. A previous study indicated that the total AV content of field-compacted OGFC (Watson et al. 2003) mixtures was comparable to that obtained in SGC specimens compacted at 50 gyrations and recommended this number of gyrations based on a macroscopic study of density, stone-on-stone contact, and aggregate breakdown of SGC specimens. However, the analysis of mixture internal structure presented in this study and the conclusions of previous research by Muraya (Muraya 2007), indicating that the number of gyrations does not constitute an effective parameter to control the SGC compaction of similar porous asphalt, encourage further research on the effect of compaction energy.

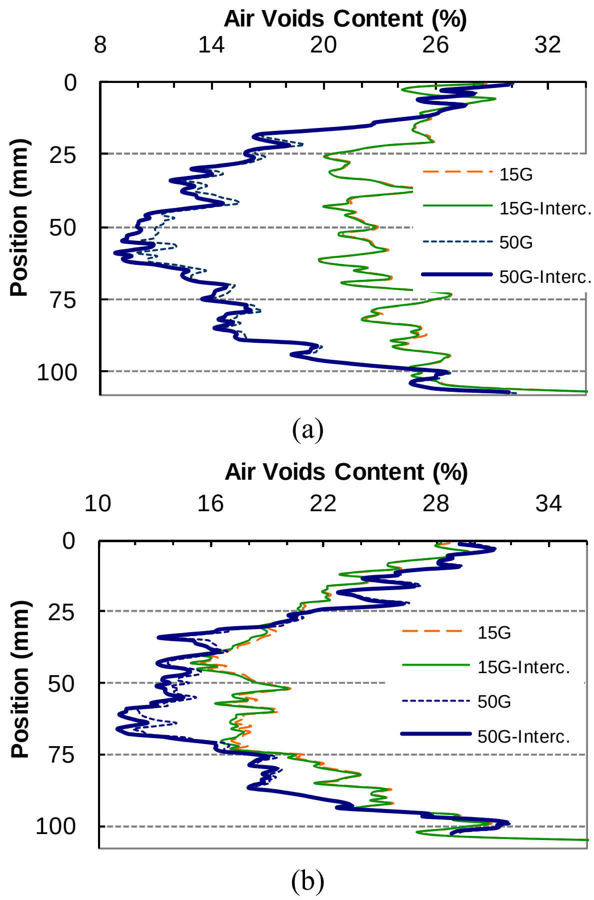


Figure 8-5. Vertical Distribution of Total Air Voids (AV) Content for Superpave Gyratory Compactor (SGC) Specimens of the (a) 6-PG and (b) 3-AR Mixture

Sections of the currently compacted SGC specimens can be used to represent the vertical AV distribution of road cores. For example, cutting 25 mm at top and bottom of the SGC specimens can produce specimens with a more homogeneous vertical AV distribution as compared to that of 115 mm in height specimens. Similarly, the top half or bottom half sections of the SGC specimens can reproduce a positive slope vertical AV distribution (Figure 8-4). Incidentally, computations based on the vertical AV distribution of SGC specimens showed that they are not symmetric. The differences were up to 2.75 percentage points between the top and bottom halves, with the highest total AV content values in the top half. Modification of the specimen height can also induce different AV distributions. This aspect, documented in previous studies (Peterson et al. 2004; Tashman et al. 2001), is mostly related to the distribution of the compaction energy in the SGC specimen as discussed in detail by Thyagarajan et al. (2009).

8.7 CONCLUSIONS AND RECOMMENDATIONS

This paper presents a study of the internal structure of PFC mixtures, assessed in terms of AV characteristics, computed for both field-compacted mixture specimens (road cores 152 mm in diameter) and specimens produced in the laboratory using the SGC (152 mm in diameter and 115 ± 5 mm in height). Results and analyses achieved in the study led to the following conclusions:

- The study of variability of AV characteristics provided evidence of heterogeneous distributions of AV in the horizontal direction for both road cores and SGC specimens.
- Recommendations to reduce the horizontal heterogeneity of AV content, according to the currently available testing methods, include using road cores with a minimum 152.4 mm diameter and coring SGC specimens from 152.4 mm to 101.6 mm in diameter. However, further research should be employed to propose alternative nondestructive field-evaluation tools to avoid the negative effects that coring can have on PFC mixtures. Further assessment of the effects of coring (e.g., sealing of surface AV and rearrangement of the granular skeleton and AV) on the internal structure of SGC specimens is also required for full validation of the corresponding coring recommendation.
- Differences in: (*i*) patterns of vertical AV distribution and (*ii*) mean values of total AV content limited the comparison of the internal structure of road cores and SGC specimens. The second aspect probably relates to the lack of a field-compaction requirement in the specifications for PFC mixtures. In addition, this aspect constitutes the main limitation encountered to define recommendations for enhancing the comparison of the internal structure of field- and laboratory-compacted mixtures.

- The limitations in the comparison of the internal structure of PFC mixtures led to the recommendation of implementation of field-compaction control. Future analysis on the internal structure of mixtures fabricated by applying compaction control is required to define the pattern of AV distribution that should be reproduced in SGC specimens. Reproduction of this pattern may require changes in the current specification for fabrication of SGC specimens, which can include: (*i*) modification of the compaction energy, (*ii*) cutting of top and bottom sections of the specimens, and (*iii*) modification of the specimen height.

9. CONCLUSIONS, RECOMMENDATIONS, AND FUTURE RESEARCH

This section summarizes the main findings of this research study, corresponding recommendations to improve the PFC mix design method and construction (regarding mixture compaction), and future research suggested to further improve the aspects treated in this study. First, an improved mix design method is presented, which synthesizes the main recommendations gathered in the study. These recommendations are further explored in a second section that also contains detailed conclusions, and corresponding suggestions for future research. The final section discusses additional topics that were not treated in this study but require additional research for improvement of the proposed PFC mix design.

9.1 IMPROVED MIX DESIGN METHOD

Current PFC mix design—as defined by TxDOT—focuses on guaranteeing mixture functionality by specifying a minimum total AV content (18 %). This approach accounts indirectly for durability in terms of accessibility to air and water that may cause, respectively, excessive aging or moisture damage. Thus, no durability test is currently included in the mix design method to assess compacted PFC mixtures. The “boiling test” is used to evaluate potential moisture damage problems, and a draindown test completes the mixture evaluation.

Figure 9-1 shows an improved mix design method proposed for PFC mixtures. This proposal is based on the guidelines of the current mix design method applied by TxDOT and the recommendations obtained in this study to enhance the determination of volumetric properties (density, total AV content, and water-accessible AV content) and the evaluation of drainability, durability, and stone-on-stone contact. Recommendations obtained based on the analysis of both the effects of densification and mixture internal structure were also integrated. In Figure 9-1, dashed-lined boxes indicate the procedures modified as compared to those included in the current TxDOT mix design method.

Straightforward implementation of both testing procedures and design criteria included in the improved mix design method can proceed because they are simple and the required equipment is readily available. However, complete implementation and validation of this mix design method requires future evaluation of performance (including functionality and durability) of mixtures fabricated as recommended in the improved method.

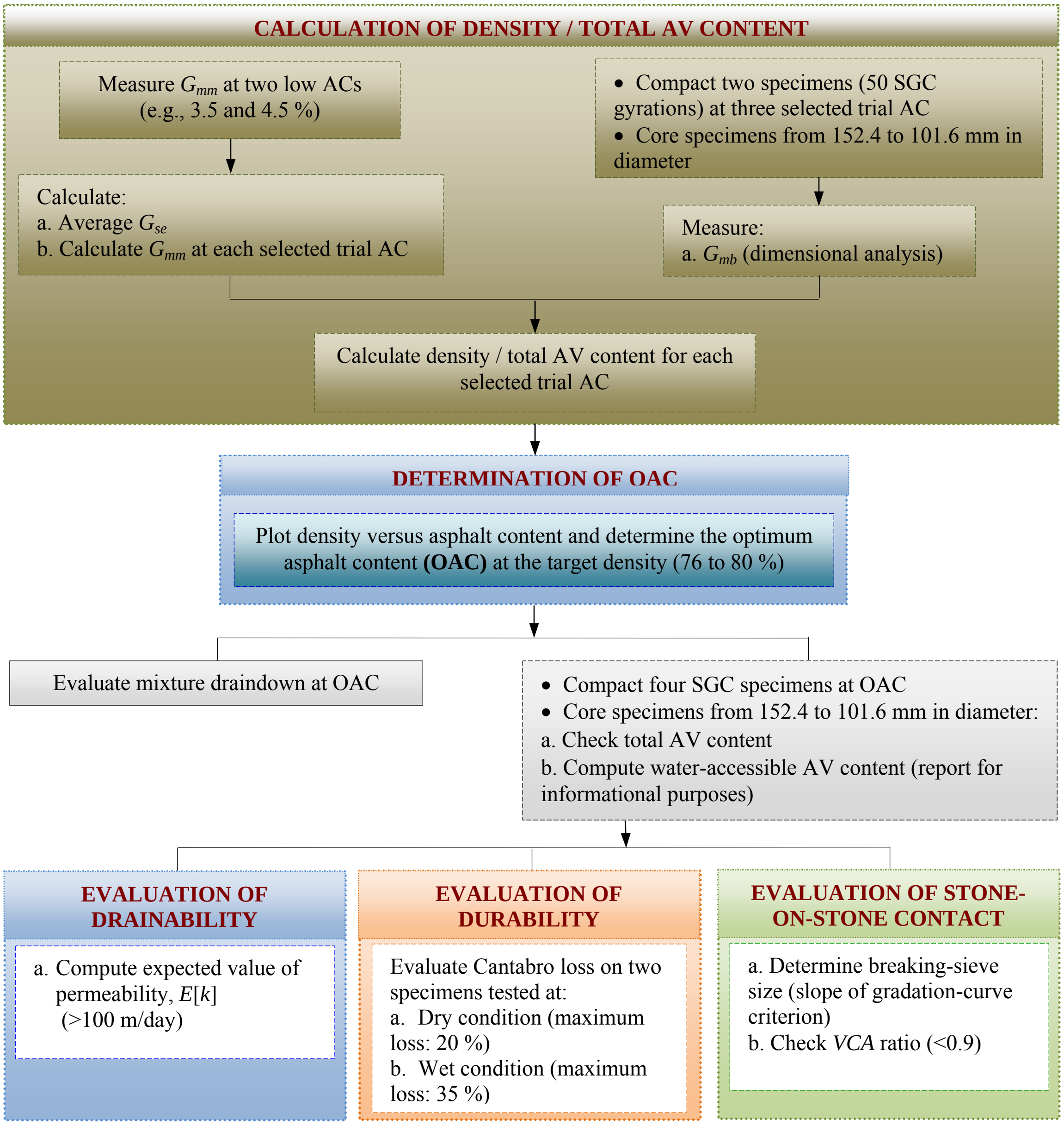


Figure 9-1. Summary of Improved Mix Design Method for PFC Mixtures
Note: AC = asphalt content.

9.2 DETAILED CONCLUSIONS, RECOMMENDATIONS, AND FUTURE RESEARCH

This section presents detailed conclusions and recommendations regarding the determination of volumetric properties and the evaluation of drainability, durability, effects of densification, stone-on-stone contact, and mixture internal structure. Discussion on the aspects that require additional research is also included.

9.2.1 Mixture Volumetric Properties

The assessment of volumetric properties of PFC mixtures led to the conclusions and recommendations subsequently presented. Future research to further improve this assessment is also suggested.

- Dimensional analysis—based on direct measurement of the specimen dimensions to compute the total volume—is recommended over the vacuum method to compute G_{mb}. However, additional research is recommended to assess the variability of the dimensional analysis method. The difficulties encountered to account for the differences in total AV content computed based on dimensional analysis and the vacuum method led to recommend only dimensional analysis to determine G_{mb} as a way to guarantee consistent evaluations of total AV content.
- Higher accuracy and reliability led to recommendation of using calculated G_{mm} values over G_{mm} values measured at the design asphalt binder content. The recommended method includes measuring G_{mm} at two low asphalt binder contents (3.5 % and 4.5 % are suggested) to determine the average G_{se} of the aggregate, and then calculating G_{mm} at the actual asphalt binder content at the design range (6 to 10 %) to compute the total AV content.
- Given the differences in total AV content computed using the recommended methodologies (dimensional analysis for G_{mb} and calculated G_{mm}) and the methodologies currently used (vacuum method and dimensional analysis for G_{mb}, and measured G_{mm}), corresponding density specifications for mix design should be modified from 78-82 % to 76-80 %. Adequate drainability and durability are expected for mixtures designed using this modified specification. However, future research is recommended to verify the adequacy of this specification on laboratory- and field-compacted mixtures.
- Inclusion of durability mixture testing in PFC mix design is recommended in addition to the current assessment of volumetric criteria, because the modifications necessary to meet volumetric criteria (e.g., changes in aggregate gradation or in fiber content) also affect durability.
- The connected AV content (termed water-accessible AV content and interconnected AV content, respectively, when computed based on volumetric determinations and application of X-ray CT and image analysis techniques) was assessed as a surrogate of the total AV content for mix design and evaluation. Computation of the water-accessible AV content based on dimensional analysis—conducted in the laboratory with application of vacuum to determine the saturated weight of the specimen in water—is recommended over the vacuum method.

Additional research is required to further study the testing procedure for measuring the specimen saturated weight.

- The strong linear correlation obtained for values of water-accessible AV content and interconnected AV content suggests that the corresponding techniques used can provide comparable results in terms of average connected AV content values.
- In addition to average values of interconnected AV content, X-ray CT and image analysis can provide nondestructive characterization of the mixture internal structure (e.g., location, size, and distribution of AV), which constitute a primary advantage of this computational technique as compared to the macroscopic laboratory determinations. This characterization of the mixture internal structure can be applied to study both functionality and durability of PFC mixtures. Additional research should be conducted to investigate the use of connected AV content as an alternative parameter to integrate within mix design as well as in laboratory and computational evaluation of PFC mixtures.
- Additional research is also required to minimize the random error associated with determinations of average mixture density values on replicate SGC specimens. This mixture density—required to establish the OAC—is currently computed using two replicate specimens produced at each trial asphalt binder content.

9.2.2 Mixture Drainability

Conclusions, recommendations, and future research proposed based on the study of mixture drainability are subsequently indicated.

- The current approaches used to evaluate drainability in PFC mixtures are based on either achieving a minimum total AV content or measuring permeability on laboratory-compacted specimens. The results gathered in this study suggest that these approaches do not constitute effective ways to evaluate whether adequate drainability is achieved in the field.
- The expected value of permeability, $E[k]$, determined using a modified version of the Kozeny-Carman equation, was recommended to analytically predict permeability for mix design and evaluation purposes. However, additional research should be conducted to further improve the estimation of permeability for field-compacted mixtures based on the assessment of SGC specimens. Differences in the internal structure of laboratory- and field-compacted mixtures may constitute the main limitation to successful estimation of permeability.

- The relationship determined for water flow value (WFV) and laboratory-measured permeability values of road cores suggests that the WFV constitutes a practical alternative to assess the field drainability of PFC mixtures. An important limitation of this parameter is that it does not allow for computation of a permeability coefficient that can be compared to other permeability measurements determined in the field (using different devices) or in the laboratory. Additional research is required to: (*i*) further evaluate the variability of the WFV, (*ii*) better support the maximum WFV threshold, (*iii*) recommend a minimum WFV to prevent the construction of low density mixtures that lead to mixture-durability problems, and (*iv*) evaluate if a unified WFV can be recommended for both AR and PG mixtures.
- The relationship between laboratory-measured permeability and water-accessible AV content values determined for SGC specimens preliminarily indicate that this AV content may be used as a surrogate of the total AV content to indirectly evaluate permeability in PFC mixtures. However, improvements in the comparison of mixture internal structure of field- and laboratory-compacted mixtures are required before pursuing the determination of a useful relationship between permeability and water-accessible AV content.
- The permeability evaluation included in this study focused on determining the initial drainability of PFC mixtures. However, future research should be performed to evaluate the AV clogging rate, service (functional) life, and corresponding alternatives to extend the service life of PFC mixtures (e.g., technical and economical appraisal of cleaning techniques versus a nonintervention alternative or the use of different gradation combinations).

9.2.3 Mixture Durability

The assessment conducted to recommend a laboratory test that can be used to evaluate PFC durability produced the following conclusions, recommendations, and suggested future research.

- Using the Cantabro test in both dry- and wet-conditions to evaluate mixture durability during the mix design stage (i.e., selection of the final OAC) and production is recommended. Since temperature variation is an important source of variability in the Cantabro loss, conducting the test in a controlled temperature environment at 25°C is also recommended. Since no field performance data are available at present to define maximum Cantabro loss values, 20 and 35 % are suggested, respectively, as limits for Cantabro loss in dry and wet conditions based on previous research. Thus, further research is required to evaluate these suggested limits.

• However, the trends and the variability in Cantabro loss values obtained for the mixtures included in this study suggest that the Cantabro test may not provide enough sensitivity to become a definitive tool for selecting the OAC of PFC mixtures. In the absence of any analytical model or any other test to evaluate PFC durability, the Cantabro test can be used to corroborate the suitability of the OAC defined based on volumetric determinations. In addition, future studies are required to assess field performance (service life and failure mechanisms) and its relationship with the Cantabro loss.

• The Hamburg Wheel-Tracking test (HWTT) and the Overlay test (OT) are not suggested for mixture evaluation because of the high variability of the corresponding test results.

• The limitations of the durability tests evaluated lead to recommend additional research to develop an improved methodology, supported by material properties and analytical models, to evaluate the durability of PFC mixtures in both dry- and wet-conditions. Potential advantages of this type of approach include less variability as compared to that reported for the tests evaluated in this study, better understanding of material response (especially for the AR mixtures), improved relationship with field performance, and possible integration of mixture durability predictions in performance models.

9.2.4 Effects of Densification and Stone-on-Stone Contact

The following conclusions and recommendations are provided based on the study of both the densification effect on the properties and performance of PFC mixtures and the analysis conducted to enhance the quantitative determination of stone-on-stone contact for these mixtures. Corresponding future research suggested by these results is also indicated.

• High levels of densification after reaching stone-on-stone contact—when the VCA_{mix}/VCA_{DRC} ratio (or *VCA* ratio) is equal to one (1.0) according to the current practice —are required to obtain a granular skeleton with fully developed stone-on-stone contact that ensures proper mixture resistance to raveling and permanent deformation. Therefore, reductions in the level of densification to increase the AV content and mixture drainability should not be pursued.

• The analysis conducted supports recommendation of: (*i*) verification of stone-on-stone contact during mix design and (*ii*) inclusion of a field compaction control in the specifications for PFC mixtures based on a reference *equilibrium density* that provides a proper balance between mixture durability and mixture functionality.

- A maximum value of the *VCA* ratio of 0.9—over the current pass/fail criterion (*VCA* ratio=1.0)—was recommended for verification of stone-on-stone contact during mix design and guarantee of the production of PFC mixtures with fully developed stone-on-stone contact. However, the long-term performance of mixtures fabricated according to this recommendation should be assessed to determine final recommendations on the maximum value of the *VCA* ratio.
- The criterion based on the slope of the gradation curve is recommended to determine the breaking-sieve size of PFC mixtures. This sieve size differentiates the fine- and coarse-aggregate fractions to determine the existence of stone-on-stone contact based on the computation of the *VCA* ratio. In a compacted PFC mixture, the coarse aggregate fraction is the portion of aggregate forming the granular skeleton with stone-on-stone contact and particle interlock, while the remaining fine-aggregate fraction fills the AV structure attained by the coarse aggregate.
- Inclusion of a field compaction control for PFC mixtures is supported by the limitations encountered when comparing the internal structure of laboratory- and field-compacted PFC mixtures. In addition, since the current design practice for selecting the OAC in several agencies is still based only on volumetric mixture properties, reproduction of mix-design density in the field should be required. Current practice in most agencies does not include a field compaction control, because compaction is generally considered a process without major issues in this type of mixture.
- The density corresponding to the OAC, computed during the mix design, may be used as a reference to define the *equilibrium density*. However, evaluation of the long-term performance of mixtures constructed at different levels of densification is required to define final recommendations to control field density.
- Additional research is required to develop techniques (e.g., nondestructive methods) that effectively evaluate the field density of PFC mixtures to enforce a density specification. Since coring can affect the internal structure of the mixture, patching PFC sections is cumbersome, and nondestructive techniques are not currently validated for PFC density control, increasing the efforts to establish appropriate roller patterns (based on road cores density determined in a control strip) is recommended as an initial step to improve the compaction process.

9.2.5 Mixture Internal Structure

Conclusions, recommendations, and future research proposed based on the analysis of the internal structure of compacted PFC mixtures are subsequently presented.

- Recommendations to reduce the horizontal heterogeneity of AV content identified in this study, according to the currently available testing methods, include using road cores with a minimum 152.4 mm diameter and coring SGC specimens (115 ± 5 mm in height) from 152.4 mm to 101.6 mm in diameter. However, further research should be conducted to propose alternative nondestructive field-evaluation tools to avoid the negative effects that coring can have on PFC mixtures. Further assessment of the effects of coring (e.g., sealing of surface AV and rearrangement of the granular skeleton and AV) on the internal structure of SGC specimens is also required for full validation of the corresponding coring recommendation.
- Differences in: (*i*) patterns of vertical AV distribution and (*ii*) mean values of total AV content limited the comparison of the internal structure of road cores and SGC specimens. The second aspect probably relates to the lack of a field compaction requirement in the specifications for PFC mixtures. In addition, this aspect constitutes the main limitation encountered to define recommendations for enhancing the comparison of the internal structure of field- and laboratory-compacted mixtures.
- Future analysis of the internal structure of mixtures fabricated by applying a field compaction control is required to define the pattern of AV distribution that should be reproduced in SGC specimens. Reproduction of this pattern may require changes in the current specification for fabrication of SGC specimens, which can include: (*i*) modification of the compaction energy, (*ii*) cutting of top and bottom sections of the specimens, and (*iii*) modification of the specimen height.
- Further research should focus on studying the effect of compaction energy to improve the comparison of field- and laboratory-compacted mixtures. A fixed compaction energy corresponding to 50 SGC gyrations is currently specified for mix design. The effect of surface properties and gradation of aggregates, as well as differences in the compaction of AR- and PG-mixtures should be integrated in this research.

9.3 ADDITIONAL FUTURE RESEARCH FOR IMPROVEMENT OF THE PROPOSED PFC MIX DESIGN METHOD

The analysis conducted allowed identification of the aspects subsequently discussed, not included in this study, that require additional investigation to further improve the proposed PFC mix design method.

- Tools for optimizing the selection and combination of asphalt binder and aggregates for fabrication of PFC mixtures are required. Analysis of mixture durability—based on Cantabro loss values—performed in this study suggested that mixture resistance to disintegration is affected more by aggregate properties than by those of the asphalt binder. Therefore, improvements in mixture durability (i.e., resistance to both disintegration and moisture damage) can be expected by optimizing the selection of materials. The surface free energy of both asphalt binders and aggregates along with computations of work of adhesion can be included as part of a material selection system.
- Assessment of aggregate degradation due to breakage during laboratory- and field-compaction needs to be addressed. Preliminary evidence of this phenomenon, that can affect negatively the mixture durability and functionality, was observed in this study.
- Evaluation of the effect of asphalt binder aging on mixture durability requires investigation. Differences in the susceptibility to oxidative aging for PFC mixtures and dense-graded HMA may be expected given the differences in their internal structure (e.g., total AV content, and distribution, size, and connectivity of AV). Asphalt binder aging can favor mixture raveling, which is the distress most frequently reported as the cause of failure in PFC mixtures.
- Assessment of mixtures properties related to noise reduction effectiveness and surface friction should be integrated in the mix design method. Although PFC mixtures are mainly intended to improve safety during wet conditions, evaluation of surface friction is not integrated in the mix design. Similarly, noise reduction capacity of PFC mixtures is becoming an important feature, which suggests the necessity of additional studies to optimize the material response by integrating the properties associated with noise reduction effectiveness in the mix design method. Long-term performance in terms of noise reduction capacity should also be monitored to better define the functional life of these mixtures.
- A methodology for optimizing the gradation of PFC mixtures should be integrated as part of the mix design. This process could be conducted to maximize drainability, noise reduction

effectiveness, and simultaneously the stone-on-stone contact of the granular skeleton to enhance durability.

- The effect of both the quality and amount of filler used in the mixture requires assessment. PFC mixtures are characterized by including a small proportion of filler. However, given the absence of sand-size particles, the effect of the filler in stiffening the asphalt binder and providing stability to the mixture can be even more important than in dense-graded HMA.

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