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16. Abstract

Permeable friction course (PFC) mixtures are a special type of hot mix asphalt characterized by a high total air voids content to guarantee proper functionality and stone-on-stone contact of the coarse aggregate fraction to ensure adequate mixture stability. Thus, PFC mixtures constructed in a thin layer at the surface of a pavement structure produce several benefits in terms of economy, safety, and the environment. This project focused on the analysis of functionality (i.e., drainability), stone-on-stone contact, and mixture internal structure to propose improvements in these three aspects for PFC mix design and evaluation. The analysis was based on both a macroscopic assessment of mixture properties and a study of internal structure using X-ray Computed Tomography (X-ray CT) and image analysis techniques.

The assessment of drainability led to a recommendation to use the expected value of permeability (based on a modified Kozeny-Carman equation) for analytical prediction of permeability. The water-accessible AV content was also proposed as a surrogate of the total AV content for indirect assessment of permeability. In addition, field drainability of PFC mixtures can be evaluated in terms of the water flow value (outflow time). Proposed enhancements for the quantitative determination of stone-on-stone contact were established using the Discrete Element Method and image analysis techniques. This analysis allowed recommendation of: (*i*) a criterion to determine the breaking-sieve size (sieve size differentiating the coarse and fine aggregate fractions) and (*ii*) verification of stone-on-stone contact using a maximum voids in coarse aggregate (*VCA)* ratio of 0.9 over the current criterion (*VCA*=1.0). The analysis of mixture internal structure led to recommend reduction of the horizontal heterogeneity of total AV content by using road cores with a minimum 152.4 mm diameter and coring SGC specimens from 152.4 to 101.6 mm in diameter. In addition, limitations in comparing the vertical distribution of AV of field- and laboratory-compacted mixtures supported recommendation of field-compaction control and future analysis of mixtures produced accordingly.

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ADDRESSING SAFETY THROUGH EVALUATION AND OPTIMIZATION OF PERMEABLE FRICTION COURSE MIXTURES

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EXECUTIVE SUMMARY

This report summarizes the main findings and recommendations suggested for improvement of the mix design and evaluation of permeable friction course (PFC) mixtures in terms of: (*i*) evaluation of mixture drainability, (*ii*) assessment of stone-on-stone contact, and (*iii*) improved comparison of the mixture internal structure of field- and laboratory-compacted mixtures. Research results were presented in three journal papers (two of them submitted to the Journal of Materials in Civil Engineering and another submitted to the Construction and Building Materials journal) that treated independently each of these topics and constitute the body of this report. Based on this organization, the main aspects of the research conducted are subsequently summarized.

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 (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.

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 AV 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.

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 Computed Tomography 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 Superpave Gyratory Compactor (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 prepared 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.

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1. INTRODUCTION

Permeable friction course (PFC) mixtures are a special type of hot mix asphalt (HMA) characterized by a high total air voids (AV) content (i.e., 18 to 22% for Texas mixtures) to guarantee proper functionality and stone-on-stone contact of the coarse aggregate fraction to ensure adequate mixture stability. The use of PFC mixtures as surface courses provide advantages related to improvements in safety, economy, and the environment, which make PFC one of the safest, cleanest, and quietest alternatives currently available for surface paving [1].

This project focused on the improvement of PFC mix design based on the analysis and formulation of recommendations to enhance the assessment of drainability and stone-on-stone contact. In addition, the study included an analysis of mixture internal structure of laboratory- and field-compacted mixtures that aimed to improve the comparison of corresponding internal structures.

1.1 PROJECT PROBLEM STATEMENT AND RESEARCH OBJECTIVE

Mix design and construction practices for PFC mixtures can be further improved to better guarantee adequate performance of this type of HMA. The overall objective of this research was to enhance the current mix design procedure for PFC mixtures. Achievement of this objective included the determination and analysis of the internal structure of PFC mixtures using X-ray Computed Tomography (X-ray CT) and image analysis techniques to propose modifications in terms of: (*i*) determination of permeability for PFC mixtures including its analytical prediction and (*ii*) verification of stone-on-stone contact. In addition, modifications were proposed to enhance the comparison of mixture internal structure of field- and laboratory-compacted mixtures.

1.2 BACKGROUND

This section presents a general background based on previous related research on: (*i*) analysis of AV distribution and stone-on-stone contact in HMA based on X-ray CT and image analysis techniques and (*ii*) functionality (drainability) of PFC mixtures.

During the last decade X-ray CT along with image analysis techniques has been used to study the internal structure of HMA and other civil engineering materials. The internal structure of compacted HMA refers to the distribution of the mixture components: aggregates, mastic, and AV. This internal structure has been studied mainly in terms of the distribution of AV and the distribution, orientation, and contact of aggregates [2].

Non-uniform distributions of AV sizes (with larger AV at the top and bottom parts of a specimen) in gyratory compacted specimens of dense-graded HMA were reported in previous research [3]. This distribution of AV sizes was properly described using the Weibull model. In addition, Tashman et al. [4, 5] provided evidence of non-uniform distributions of AV content along the vertical and horizontal directions of gyratory compacted specimens. Similar analysis for corresponding road cores of dense-graded HMA indicated non-uniform distributions of AV content in the vertical direction and uniform distributions in the horizontal direction [4, 5].

These distributions of AV content were attributed to the restrictions imposed by the mold and the top and bottom surfaces of the Superpave Gyratory Compactor (SGC) in the laboratory and by the drum of a roller in the field, which restrain the mobility of particles during compaction. Masad et al. [6] concluded that the vertical distributions of temperature and AV content are coincident. However, the authors considered that the main aspect generating non-uniform distributions of AV (in dense-graded HMA) is the restriction induced by the mold and the top and bottom surfaces of the SGC. Voskuilen and Ven [7] also discussed this phenomenon (termed the "side effect") and indicated that the side effect of compacted specimens can be stronger for stone skeleton mixtures (Stone Matrix Asphalt) compared to that for dense-graded HMA.

X-ray CT and image analysis have also been applied to compare the internal structure of laboratory- and field-compacted mixtures. Tashman et al. [5] suggested that gyratory compacted specimens of dense-graded HMA could be used to obtain specimens with AV distributions similar to that of road cores. In addition, previous research concluded that similar aggregate structure distributions were obtained regardless of the field compaction pattern used [5, 8]. Furthermore, it was shown that the parameters used in the SGC: (*i*) substantially modify the mechanical properties of dense-graded HMA and (*ii*) can be modified to better reproduce the internal structure of road cores [8].

Previous research by Kandhal [9] emphasized the necessity of obtaining stone-on-stone contact of the coarse aggregate fraction to guarantee adequate resistance to permanent deformation in PFC mixtures. In addition, raveling (the distress most frequently reported as the cause of failure in these mixtures) may also be favored by incomplete seating of aggregates that lead to poor aggregate interlock to resist the shear stresses induced by vehicle loads. Quantification of stone-on-stone contact using X-ray CT and image analysis techniques was conducted by Watson et al. [10]. Three different methods, based on AV size distribution, level of contacts, and number of contacts, were applied to study aggregate packing in gyratory compacted specimens of Open Graded Friction Course mixtures (OGFC), mixtures similar to PFC. Future research integrating field compaction and performance was suggested to recommend a minimum value for the number of contacts. This research also suggested the modification of the breaking-sieve size selection for OGFC previously recommended by NCAT [9].

Drainability is believed to be integrated in most OGFC mix design procedures since total AV content is considered to be representative of drainability (i.e., permeability). Consequently, current mix design methods do not include laboratory verification of water-permeability, although previous research [11] defined minimum recommended water-permeability values. However, a few agencies specify a minimum field drainability value [1, 12], usually measured in terms of outflow time. These conditions motivate an investigation to determine whether the water-permeability values measured in the laboratory can be analytically predicted for both laboratory- and field-compacted mixtures to better engineer this important property of PFC mixtures.

1.3 REPORT ORGANIZATION

The body of this report is organized in three sections. Each section corresponds to a journal paper obtained as a result of the research conducted during the project on each one of the three topics aforementioned. Thus, the next chapter presents a paper related to the evaluation of drainability in PFC mixtures. This paper was already accepted for publication in the Journal of Materials in Civil Engineering-ASCE. The authors of this paper are Allex E. Alvarez, Amy Epps Martin, and Cindy Estakhri. The following chapter contains a paper related to the analysis of stone-on-stone contact in PFC mixtures, submitted for publication in the Journal of Materials in Civil Engineering-ASCE. The authors of this paper are Allex E. Alvarez, Enad Mahmoud, Amy Epps Martin, Eyad Masad, and Cindy Estakhri. The next chapter presents a paper written by Allex E. Alvarez, Amy Epps Martin, and Cindy Estakhri on the internal structure of PFC mixtures and published in the Construction and Building Materials journal.

2 DRAINABILITY OF PERMEABLE FRICTION COURSE MIXTURES[1]

2.1 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 (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.

2.2 INTRODUCTION

PFC mixtures 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 [1]. 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 [1]. 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

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(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.

At present, measurement of the coefficient of permeability (or permeability) is not directly included as part of PFC mix design [12], and most agencies do not specify evaluation of drainability during mix design [1]. 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. The National Center for Asphalt Technology (NCAT) [9] as well as ASTM International (D 7064-04) [13] 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 [1], 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 water flow value (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.

2.3 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.

2.4 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.

2.4.1 Mix Design and Material Requirements

Mix design was conducted according to the current Texas Department of Transportation (TxDOT) PFC mix design method [12]. Corresponding material specifications include master aggregate gradation bands for each of the following two types of asphalt binders allowed for PFC mixtures [14]:

- a Type I or II Asphalt Rubber (AR) with a minimum of 15 % by weight of asphalt of Grade C or Grade B crumb rubber.
- a Performance Grade (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 binder selected, master aggregate gradation bands are also provided in Item 342 [14].

2.4.2 Material Selection and Specimen Fabrication

Laboratory evaluations included in this study were conducted using road cores as well as plant mixed-laboratory compacted (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 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 1. Aggregate gradations for these specific mixtures are presented in Table 2.

Table 1. Description of Mixtures Included to Evaluate Drainability.

Mixture	TxDOT District	Asphalt Type	OAC, %	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%

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

Table 2. Aggregate Gradations for PG- and AR-Mixtures Included to Evaluate 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 [12]. The compaction temperature used was 149°C for both PG (76-22) and AR asphalts as recommended in the PFC mix design procedure [12] 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.

2.4.3 Laboratory and Field Testing

Falling head permeability tests were conducted in accordance with ASTM PS 129-01 [15] 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 [12] 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 [12].

The total AV content was computed in the laboratory based on dimensional analysis [16] to determine the bulk specific gravity of the compacted mixture (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 [16]. 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 [17]. 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 [18]. 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. [19] using Image-Pro® Plus:

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

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

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:

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

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.

2.5 ANALYTICAL COMPUTATION OF PERMEABILITY

Previous research [20] 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 [21] 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. [22] proposed Equation (4) to compute HMA permeability. Unlike the previous equations proposed, Equation (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 [22]:

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

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), Masad et al. [22] 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), which was adopted as a function of both the aggregate-particle size and the total AV content. All other variables included in Equation (4) were adopted as constants and $\overline{C}$ remained as an empirical coefficient to be determined by calibrating the expected value equation (Equation (5)) against permeability measurements. The expected value of permeability determined using a two-dimensional Taylor series approximation then becomes:

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

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:

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

Aggregate and asphalt parameters grouped in Equation (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:

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

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

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:

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

2.6 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.

2.6.1 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 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. [23] (for laboratory mixed-laboratory compacted specimens of open-graded friction courses (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 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. [23] and in this study, respectively.

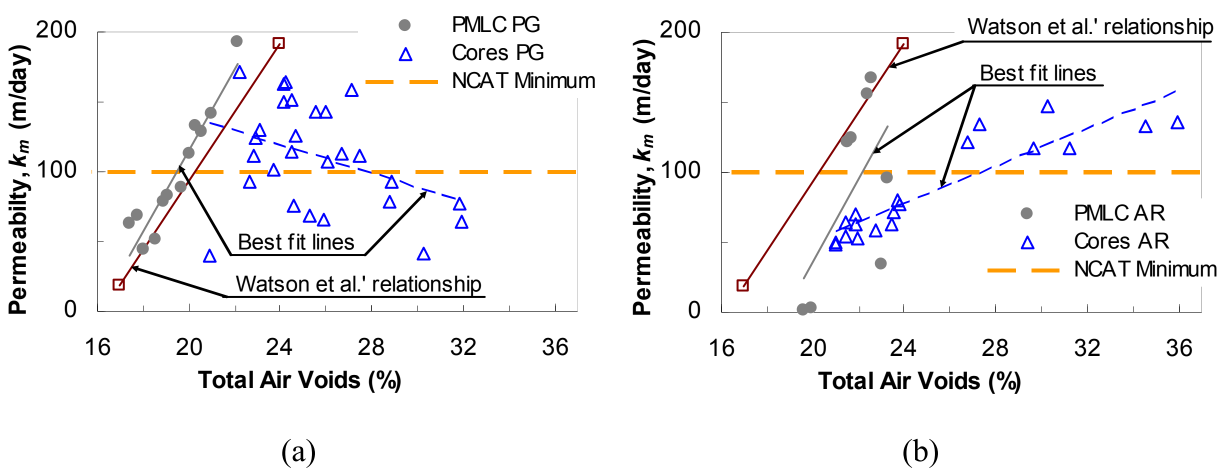


Figure 1. Comparison of Total Air Voids Content and Laboratory-Measured Permeability for (a) PG-and (b) AR-Mixtures.

Data shown in Figure 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 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.

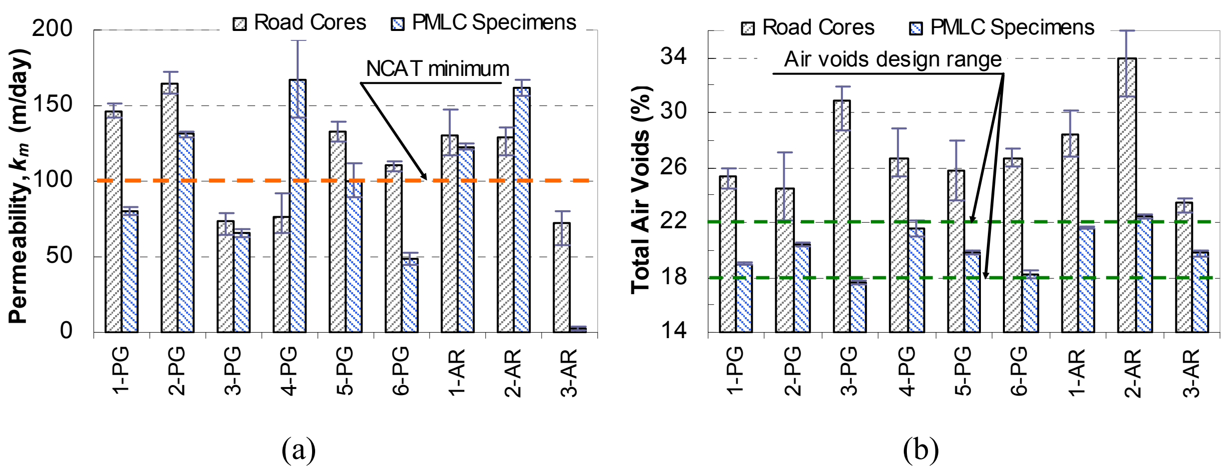


Figure 2. Comparison of Road Cores and PMLC Specimens in Terms of (a) Laboratory-Measured Permeability and (b) Total Air Voids Content.

Note: The total AV content of the 5-PG (US-59-PG) mixture was determined based on the vacuum method [7].

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 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 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 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 [24] 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 [2, 5].

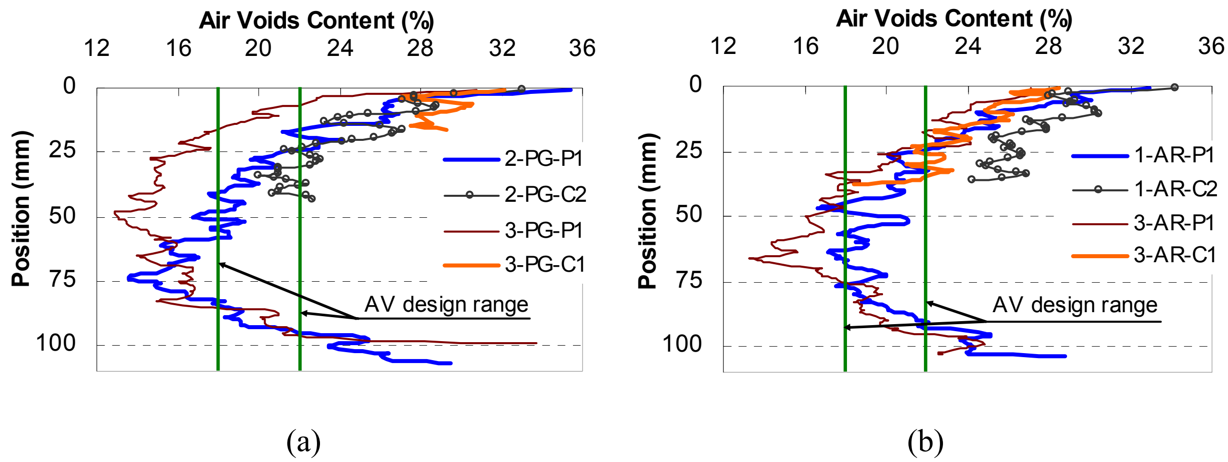


Figure 3. Vertical Distribution of Air Voids for (a) PG- and (b) AR-Mixtures.

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 [25].

Although the permeability values measured on road cores and PMLC specimens agree for the 3-PG mixture and also the 1-AR mixture (Figure 2(a)), the distribution of AV (Figure 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 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 [26] 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 [21] 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.

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

Coefficients of correlation shown in Table 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 1 for total AV content. Consequently, the data set presented in Table 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 3. Coefficients of Correlation for Air Voids 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 [27] can provide stronger correlation with permeability values than those computed using the vacuum method applied in this study.

2.6.3 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 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 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.

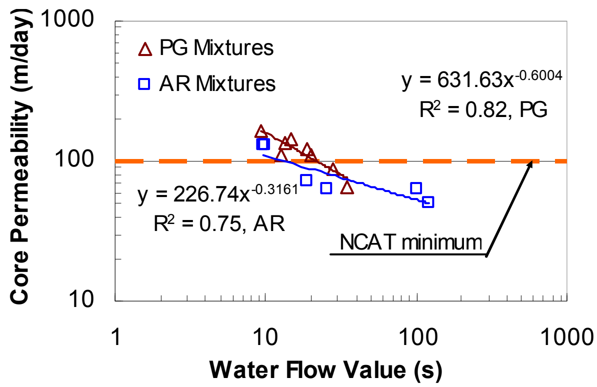


Figure 4. Relationship of Laboratory-Measured Permeability and Water Flow Value.

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 [24], 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 1 and Figure 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.

2.6.4 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 (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) 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 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). In fact, for PMLC specimens, the coefficient of correlation (CC) for values of laboratory-measured permeability and expected value of permeability was 0.93, whereas the CC for laboratory-measured and calculated permeability values was 0.69. However, the same comparison for road cores led to CC 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.

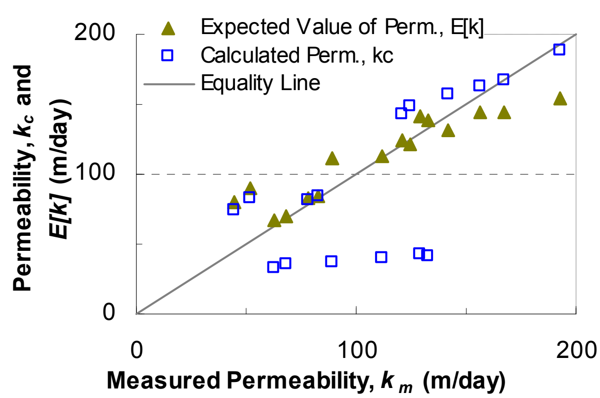


Figure 5. Comparison of Laboratory-Measured and Predicted Permeability for PMLC Specimens.

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 [27] 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 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 (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 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 6(b), which impedes definition of clear trends of the variability that can be expected in this type of specimen.

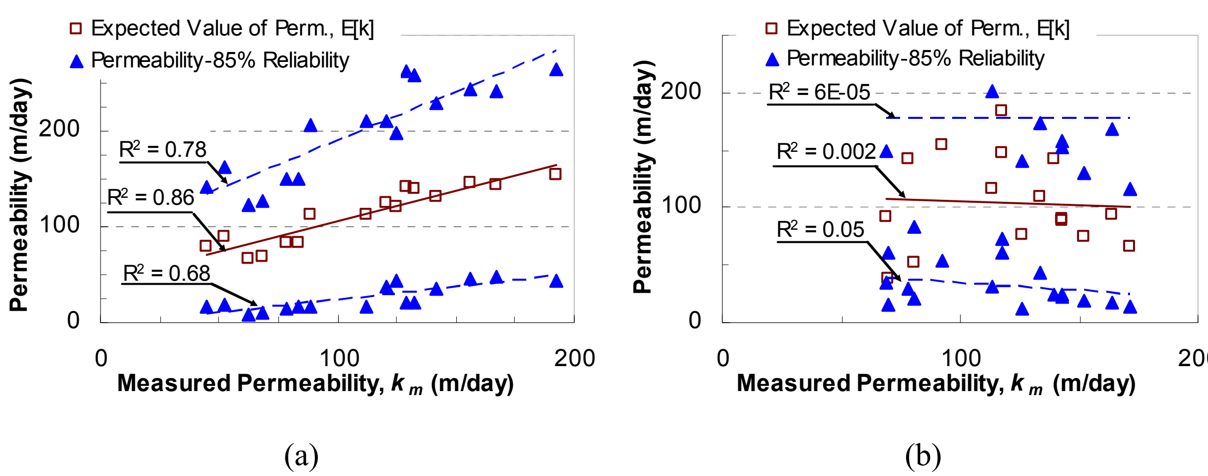


Figure 6. Expected Value of Permeability and Variability at 85% Reliability for (a) PMLC Specimens and (b) Road Cores.

Given the previously discussed advantages of using the expected value of permeability as an estimator of permeability, the practical application of this approach (Equations (5) to (9)) is subsequently discussed. Determination of the parameters clustered in Equation (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 ($\bar{n}$) of the vertical AV distribution as reported in previous research [27, 28] and confirmed in this study. In addition, the coefficient of variation (COV) of the total AV content distribution determined in this study was computed and associated with corresponding average total AV content values (Equations (10) and (11)). The CC obtained for PMLC specimens and road cores were -0.61 and -0.47, respectively.

$$COV_{PMLC} = -1.103 \times \bar{n} + 0.386 \tag{10}$$

$$COV_{Cores} = -0.393 \times \bar{n} + 0.177 \tag{11}$$

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.

2.7 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 (5)) proved to be a better estimator of the laboratory-measured permeability values as compared to the deterministic evaluation of Equation (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 (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.

3 STONE-ON-STONE CONTACT OF PERMEABLE FRICTION COURSE MIXTURES[2]

3.1 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 AV 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.

3.2 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 [1].

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

[2]Submitted for Publication in the *Journal of Materials in Civil Engineering, ASCE* (2009), by Allex E. Alvarez, Enad Mahmoud, Amy Epps Martin, Eyad Masad, and Cindy Estakhri.

raveling and permanent deformation [9, 24]. 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 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.

The NCAT recommended verification of stone-on-stone contact for the mix design of new generation OGFC based on the comparison of the voids in coarse aggregate (*VCA*) in the dry-rodded condition (VCA_{DRC}) and the *VCA* in the compacted mixture (VCA_{mix}) [9]. 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 [10] 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) [29] to further recommend one of these criteria. The DEM-IA approach was selected because of the DEM capabilities of capturing interactions between the particles within a model of asphalt mixture internal structure. DEM can be used to model the different material phases of the mixture, thus differentiating between the aggregates and matrix. In addition, the DEM is capable of tracking the forces developing within the internal structure of the mixture. In this study, 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 Performance Grade (PG) asphalt and Asphalt Rubber (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.

3.3 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.

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 [12]. Corresponding material specifications define different master aggregate gradation bands for each of the following asphalts permitted for PFC mixtures [14]:

- 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 [14].
- 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

As specified in Table 4, mixture evaluations included in this study were conducted using: (*i*) PMLC specimens, (*ii*) field mixed-field compacted specimens or road cores, (*iii*) laboratory mixed-laboratory compacted (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 [12] and recommended in previous studies [30, 31]. 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 [12], 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 4 shows details on the composition of each mixture, and Table 5 and Table 6 present corresponding aggregate gradations.

Table 4. Description of Mixtures Included to Evaluate 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 5. Aggregate Gradations for PG-Mixtures (Percentage Passing) Included to Evaluate Stone-on-Stone Contact.

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

Table 6. Aggregate Gradations for AR-Mixtures (Percentage Passing) Included to Evaluate 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

3.4.3 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. [16]. 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 4.

Five PG mixtures (7-PG to 11-PG) were analyzed using DEM-IA. A previous study [32] 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 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 [33], 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 [34].

Table 7. 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

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

According to the pass/fail criterion suggested by NCAT [9], stone-on-stone contact is achieved in PFC mixtures when:

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

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

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

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:

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

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 [9, 13]. 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 [10], and
- Criterion No. 3: select the finest sieve size in which a minimum of 10% of total aggregate is retained [10].

Previous research [35] originally proposed the criterion presented in Equation (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 [24] 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.

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

The discrete element method (DEM) is a finite difference scheme used to study the interaction among discrete particles [36]. 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 [37]. The DEM has been applied to model different types of geotechnical problems and to analyze asphalt mixture response under static and cyclic loadings [37-39].

This study used a DEM code called Particle Flow Code in 2-Dimensions, Version 3.1 [37] 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 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. [29]. 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 [29].

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 [39]. 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 [34] 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.

3.7 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 determine 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.

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

Figure 7 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 [9] 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.

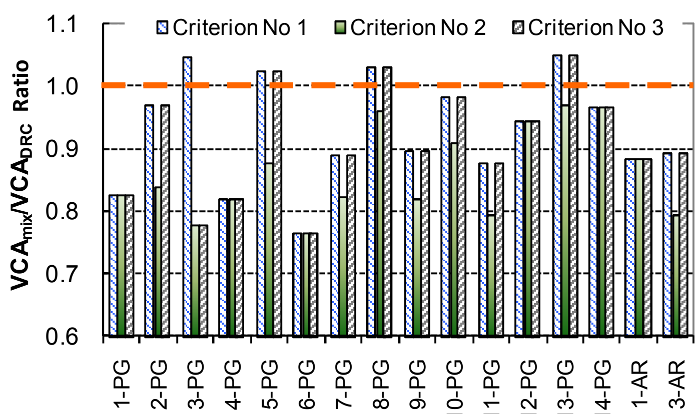
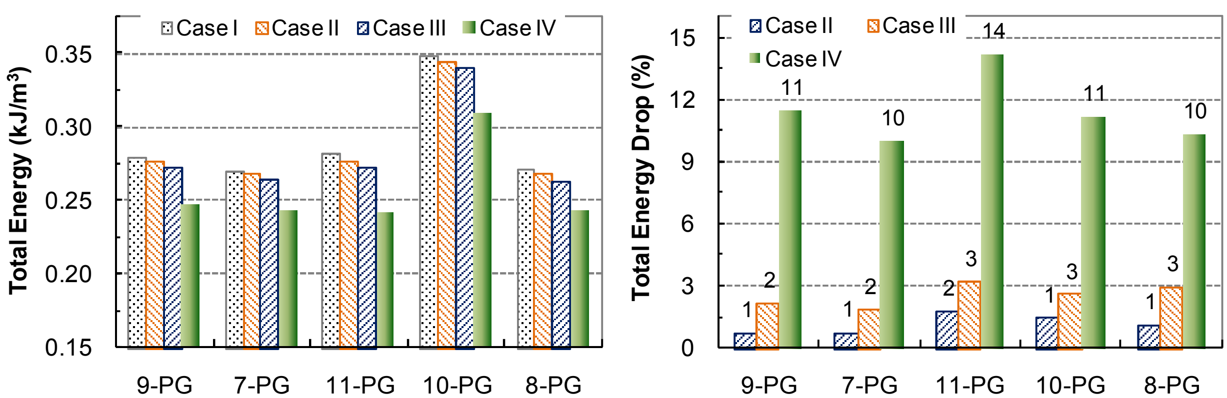


Figure 7. Comparison of the VCA_{mix}/VCA_{DRC} Ratio Calculated Using Different Criteria to Determine the Breaking-Sieve Size.

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.

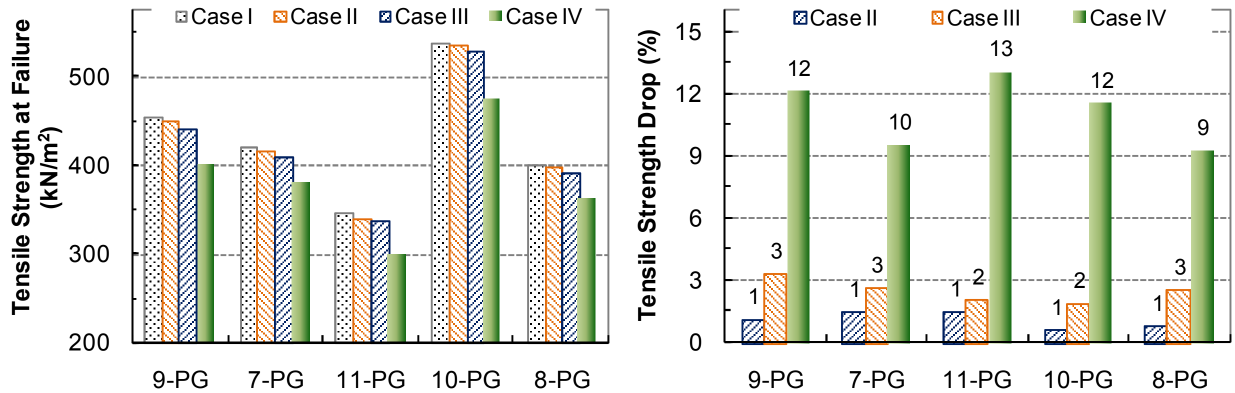
3.7.2 Analysis of Breaking-Sieve Size Determination Based on the Discrete Element Method and Image Analysis Techniques (DEM-IA)

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 8 and Figure 9 show the values and changes in the total energy and the indirect tensile strength, respectively.



(a) (b)

Figure 8. Comparison of Total Energy.

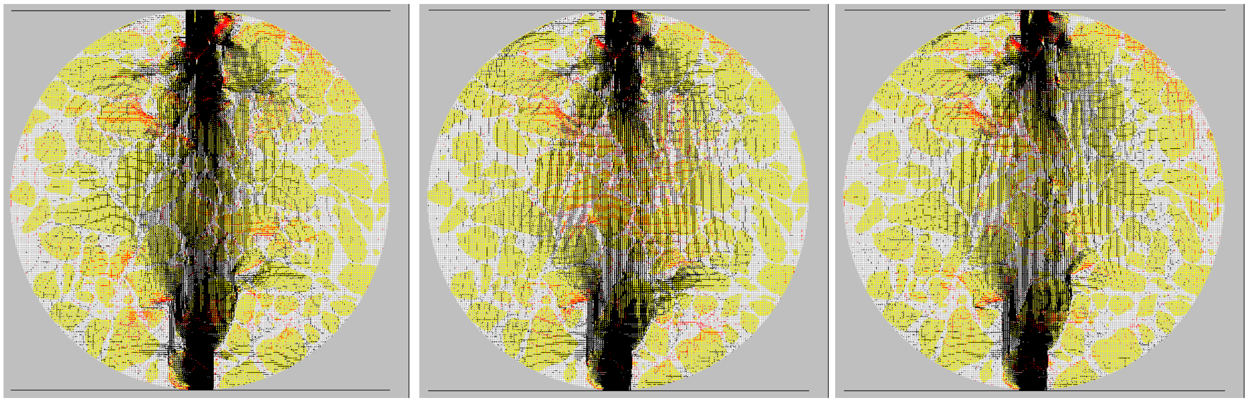


(a) (b)

Figure 9. 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 8(a) and Figure 9(a)). Figure 8(b) and Figure 9(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 10. 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 10(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 10(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 10. Stress Concentration for Cases II (a), III (b), and IV (c).

Figure 11 summarizes the cracking results for all the mixtures. Figure 11(a) and Figure 11(c) show the percent of interface (adhesive) cracking and percent of matrix (cohesive) cracking, respectively, while Figure 11(b) and Figure 11(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.

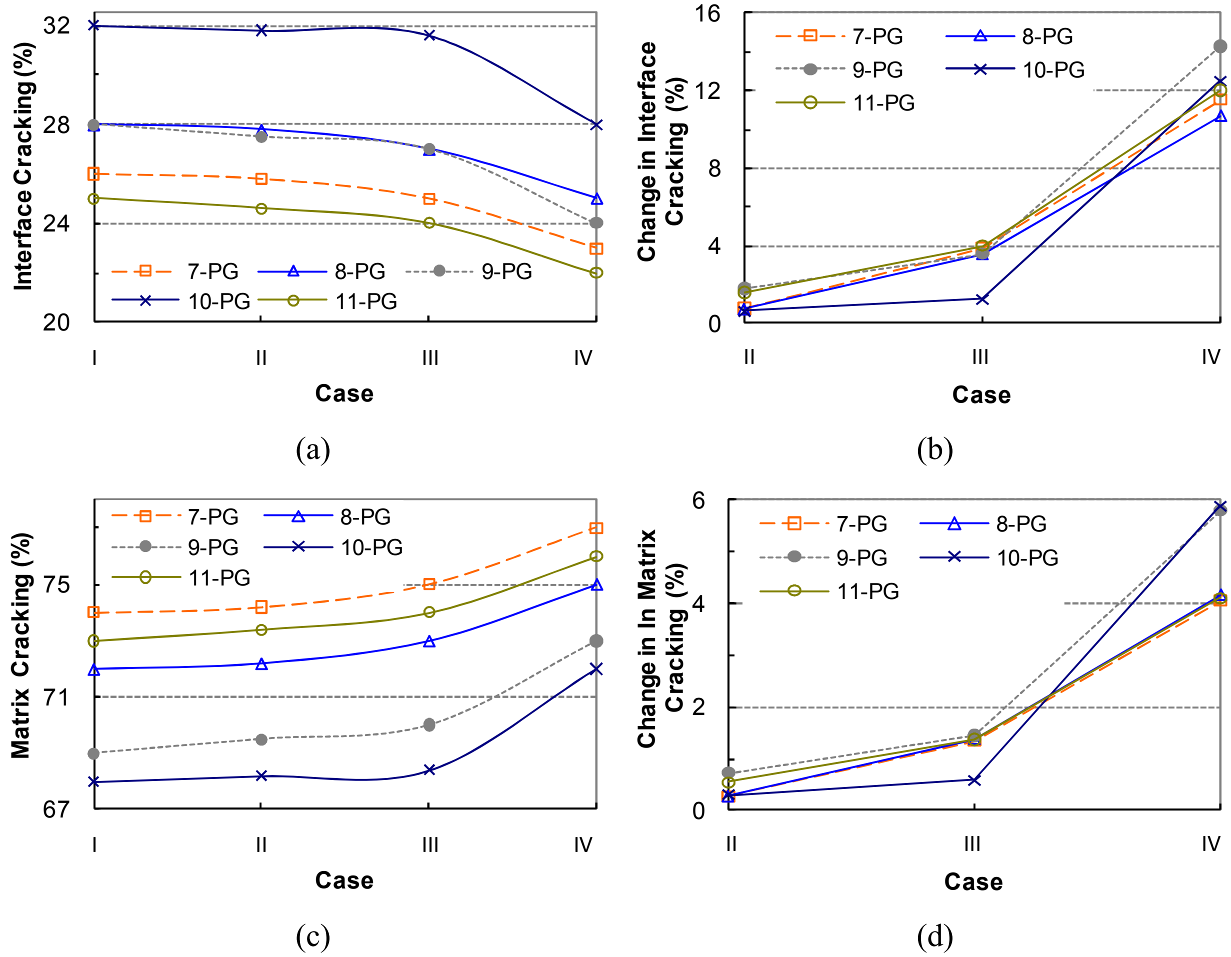


Figure 11. Comparison of Interface and Matrix Cracking.

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 12 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.

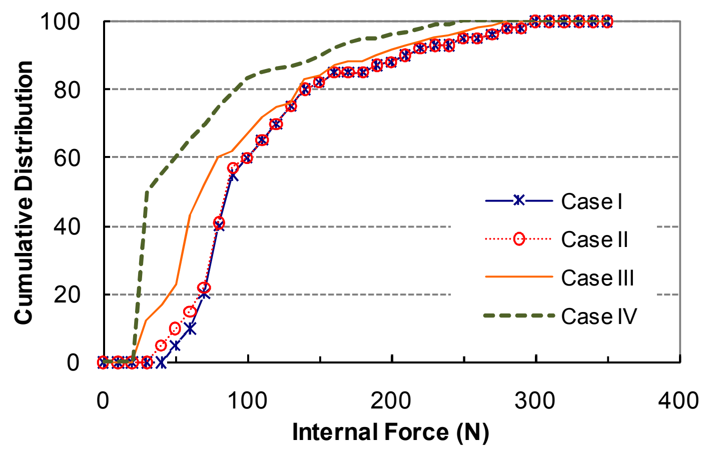


Figure 12. Comparison of Internal Forces Distribution for the 9-PG Mixture (Hard Limestone Aggregate).

3.7.3 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.

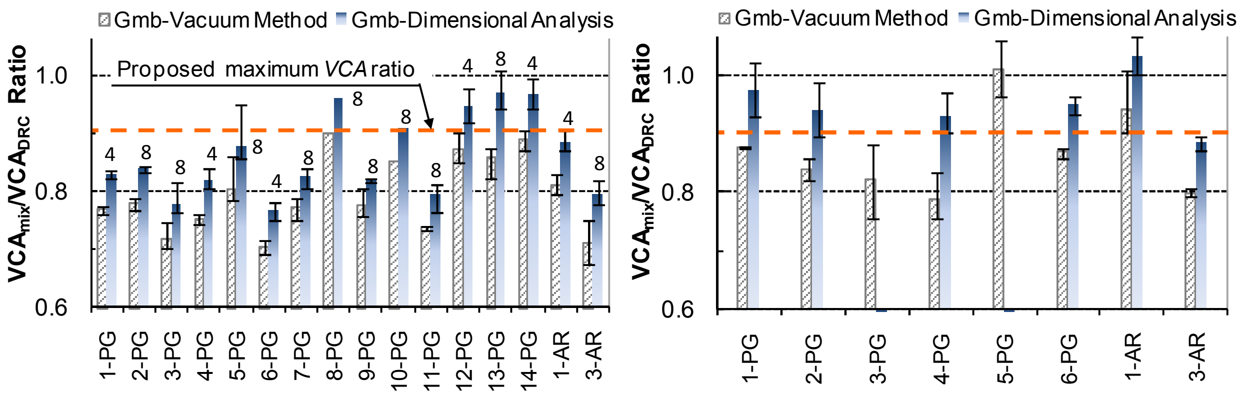
In addition, based on the master aggregate gradation bands currently specified for PFC mixtures (Table 5 and Table 6), as the proportion of the P4-R8 fraction becomes larger, the slope of the gradation curve begins to flatten out at the No. 8 sieve (instead of at the No. 4 sieve). Under these conditions, 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.

3.7.4 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 [16] 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 [16]. Incidentally, according to ASTM D 7064-04 [13] 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 13, which also shows the corresponding breaking-sieves.



(a) (b)

Figure 13. Average and Range of the *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 13 is associated with the VCA_{mix} as a function of the G_{mb} variability evaluated using the number of specimens specified in the Table 4. 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 13(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 13(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 [25].

In addition, research conducted by Watson et al. [31] 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 14 also suggest that this condition can be reached in PFC mixtures at low compaction levels, corresponding to approximately 12 gyrations of the SGC [24]. Furthermore, corresponding mixtures compacted at 50 gyrations of the SGC showed both reduced *VCA* ratio (Figure 14) 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.

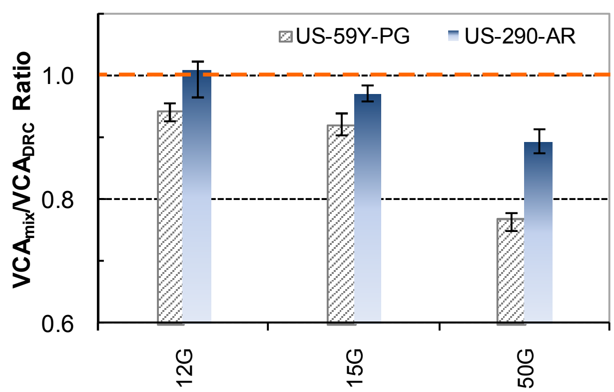


Figure 14. Average and Range of the *VCA* Ratio Values for PFC Mixtures Compacted at 15 and 50 Gyrations of the SGC (Adapted from Alvarez et al. [24]).

Furthermore, previous research [40] 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 [24], and (*ii*) proposal of corresponding verification based on a maximum value of the *VCA* ratio of 0.9. Data shown in Figure 13(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 [24], 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.

3.8 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.

4 INTERNAL STRUCTURE OF COMPACTED PERMEABLE FRICTION COURSE MIXTURES[3]

4.1 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 prepared 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.

4.2 INTRODUCTION

PFC mixtures, also termed new generation OGFC, are HMA characterized by a high total and interconnected (also referred as 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 [1]. Therefore, proper determination of the AV content of both field- and laboratory-compacted mixtures constitutes an important aspect for mixture design, construction, and evaluation of performance including both functionality (noise reduction effectiveness and drainability) and durability. Although previous research [16, 23, 27, 31, 41] focused on studying

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the macroscopic assessment of the AV content, limited information is currently available on the internal structure of PFC mixtures.

Masad et al. [2] 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 [24, 30], 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 mixture design and performance [40, 42] 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 mixture design of PFC mixtures [12, 13] 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 mixture design determinations and the poor relationship that can exist between the internal structure of both field-compacted mixtures and SGC specimens [24]. 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 [11, 40, 43] 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 [42]. 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 mixture 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 [5, 44] as well as mechanical properties [44] to those obtained in the field. This paper assesses the internal structure of PFC mixtures and includes a description of the experiments and analysis conducted to study this internal structure in terms of AV characteristics, followed by results and discussion. Conclusions and recommendations complete the paper.

4.3 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 prepared 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.

4.4 EXPERIMENTAL DESIGN

This section presents the experiments defined for this study including mixture design and material requirements, material selection, and specimen fabrication as well as laboratory testing.

4.4.1 Mixture Design and Material Requirements

Mixtures included in this study were designed according to the current PFC mixture design method specified by the TxDOT [12]. Material specifications for PFC mixtures [14] 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. The mixtures included in this study were prepared using Type II (grade B) AR as specified in next section.

These high stiffness binders are specified to ensure high cohesion in the PFC mixture with expected benefits in terms of mixture durability. In addition, PFC mixtures are fabricated with asphalt contents between 6 to 7% for PG and 8 to 10% for AR [12]. The high asphalt contents provide thicker asphalt films that may also improve durability (in terms of resistance to aging and moisture damage), but increase the probability of draindown issues, especially in PG mixtures. Therefore, mineral and cellulose fibers are added to satisfactorily prevent this problem. In addition, lime is currently used to minimize moisture susceptibility in PG mixtures. PFC mixtures fabricated with AR do not incorporate lime, fibers, or any other agent to improve performance.

4.4.2 Material Selection and Specimen Fabrication

The assessment of internal structure included plant mixed-laboratory compacted (SGC) specimens and corresponding road cores gathered from eleven PFC mixtures prepared in the field and used in diverse highway projects (Table 8). 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 9). These materials, as well as the additives used (lime and fibers), met the specifications indicated in Item 342 of the 2004 TxDOT Standard Specifications book [14].

Table 8. Description of Mixtures Included to Evaluate Internal Structure.

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

Note: PG = Performance Grade; AR = Asphalt rubber; AC = Asphalt cement; CR = Crumb rubber; OAC = Optimum asphalt content; L= Lime; CF = Cellulose fibers; SGC = Superpave Gyratory Compactor; RC = Road core taken after mixture compaction; RC-T = Road core taken after 1 to 2 years of traffic.

Table 9. Aggregate Gradations for PG- and AR-Mixtures (Percentage Passing) Included to Evaluate Internal Structure.

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

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 mixture design [12], 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 [14]. 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.

4.4.3 Laboratory Testing

Computation of bulk specific gravity of the compacted mixture (G_{mb}) was conducted by dimensional analysis [16], 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 [18, 45]. The next section describes the corresponding image analysis conducted to assess the PFC mixture internal structure.

4.5 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 voids) 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. [19] 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:

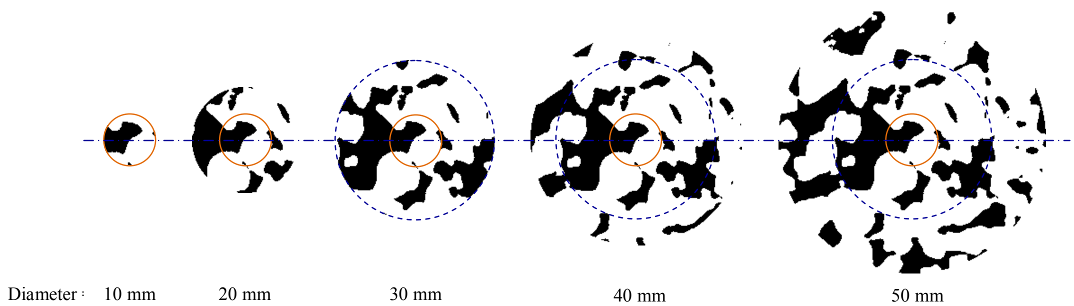
$$AV_i = \frac{A_{vi}}{A_T} \quad \text{(1a);} \qquad AV_s = \frac{\sum_{i=1}^{n} AV_i}{N} \quad \text{(1b)}$$

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 [27]. In addition, the mean radius of AV ($\bar{r}_i$) in image *i* is computed as:

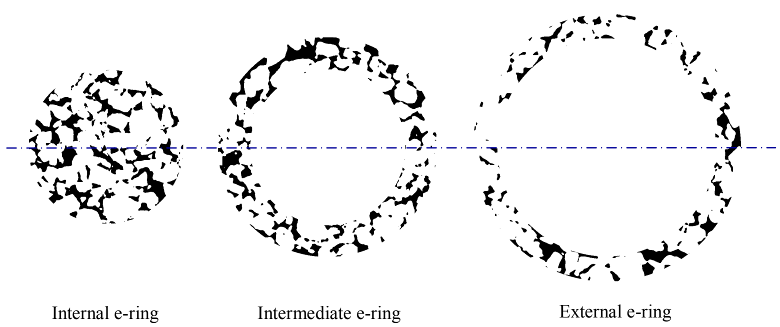
$$\bar{r}_i = \sqrt{\frac{A_{vi}}{\pi M_i}} \qquad (2)$$

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 [10]. 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 [27]. 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 [27].

The horizontal variability of the total AV content and mean radius of AV for both 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*) (Figure 15). 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 V1.38x 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 V1.38x 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.



(a)



(b)

Figure 15. Concentric E-Cores (a) and E-Rings (b) Obtained from Thresholded Black and White Images to Analyze Horizontal Air Voids Variability.

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. In addition, 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).

4.6 RESULTS AND DISCUSSION

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

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

For each mixture studied, the analysis of e-cores computed for one road core and one SGC specimen is summarized in Figure 16. 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 16) in each data set obtained for SGC specimens and road cores.

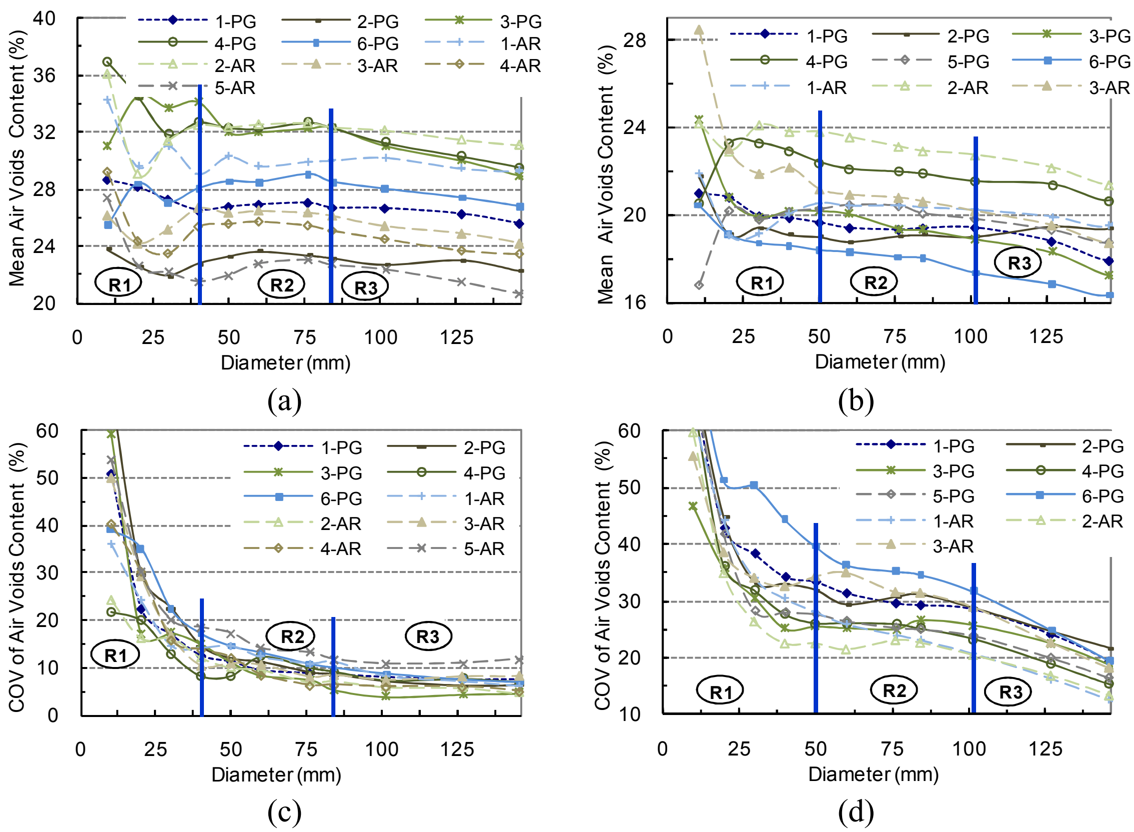


Figure 16. Mean Total Air Voids Content for E-Cores Obtained from Road Cores (a) and SGC Specimens (b), and COV of Total Air Voids Content for E-Cores Obtained from Road Cores (c) and SGC Specimens (d).

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 [46], 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 16b and Figure 16d 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 17. 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 18, which uses the same convention used in Figure 17 to identify the e-rings. These results are coincident with those shown in Figure 16b and Figure 16d, 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 [5, 7, 47] 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. [5] reported smaller values of total AV content in the outside region for short SGC specimens (i.e., 50 mm in height) of dense-graded HMA. The aforementioned discrepancies between PFC mixtures and dense-graded HMA can be related to differences in: (*i*) total compaction energy (i.e., number of gyrations applied, with dense-graded HMA receiving in most cases at least twice the energy applied to compact PFC mixtures), (*ii*) aggregate gradation, and (*iii*) asphalt content. However, additional research is required to determine the role of these factors in the internal structure of PFC mixtures compacted using the SGC.

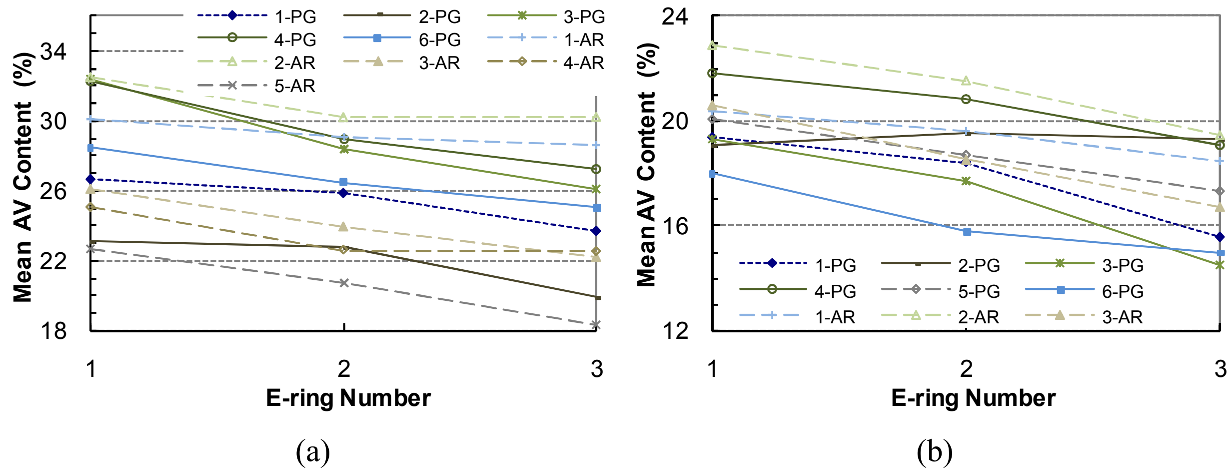


Figure 17. Mean Total Air Voids Content for E-Rings Obtained from Road Cores (a) and SGC Specimens (b).

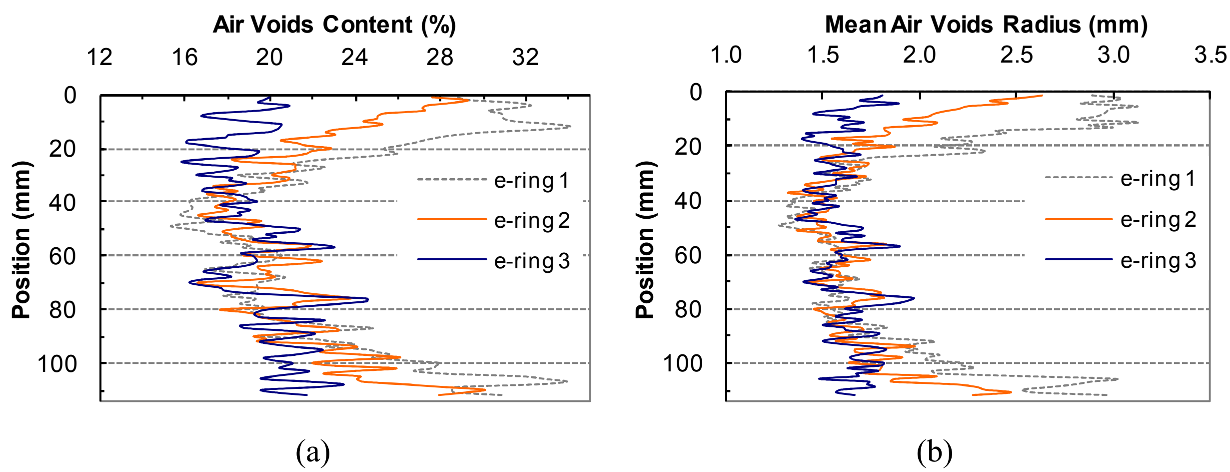


Figure 18. Typical Vertical Distribution of Total Air Voids Content (a) and Mean Radius of Air Voids (b) for E-Rings Obtained from SGC Specimens.

Plots of the quantiles of the distribution of total AV content values against the quantiles of the normal distribution (or 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. 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 10 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 10. Summary of Comparisons of Mean Total AV Content Values Computed for E-Rings.

E-rings with statistically equivalent means, α=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 mixture 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 10 suggest that this phenomenon affected 70% of the road cores analyzed. 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, led to the conclusion that this heterogeneous distribution of AV is exhibited by both AR- and PG-mixtures produced with different aggregate gradations (Table 9). Therefore, this is not a mixture dependent phenomenon.

Previous research [4, 5, 7] 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 [47]. An irregular temperature profile can also be a factor generating heterogeneity in PFC mixtures. Even though research on dense-graded HMA [6] 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 10 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 16b and Figure 16d) and e-rings (Figure 17b) 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 [30] 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 mixture design and evaluation.

4.6.2 Analysis of the Vertical Distribution of Total Air Voids Content

The patterns of vertical distribution 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 19b. The distributions are similar to those reported by Thyagarajan et al. [47] 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 19a): (*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 (e.g., 4-PG mixture) obtained for SGC compacted specimens. 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.

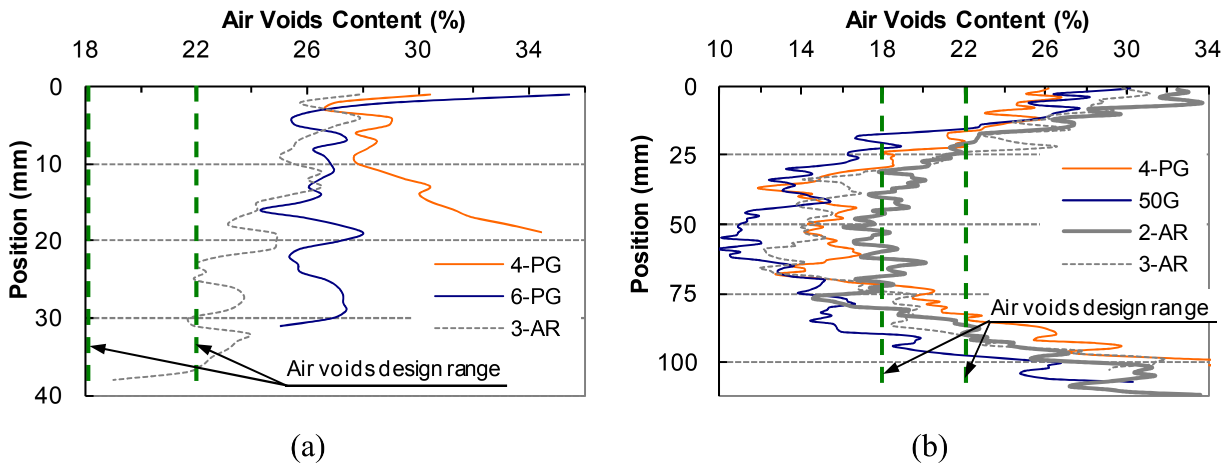


Figure 19. Vertical Distribution of Total Air Voids Content for Road Cores (a) and SGC Specimens (b).

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 [48] and the open gradation that allows a faster loss of heat, specially at the pavement surface. In addition, even though previous research [5] 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 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 mixture design. A similar conclusion was obtained in a previous study that addressed the effects of compaction in PFC mixtures [24].

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 19a. 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 mixture 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 [24]. In addition, research conducted on Danish porous asphalt [49], 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 19 allows for the conclusion that restrictions in the validity of laboratory tests conducted for mixture 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 [11, 43] 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 [50] 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 AV 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 20 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. Discrepancies in the compactibility of PG- and AR- mixtures [24], mostly related to differences in the rheological properties of AR and PG asphalts [51], explain the different effect obtained for these mixtures after modifying the compaction energy. 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 [31] 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 [30], 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.

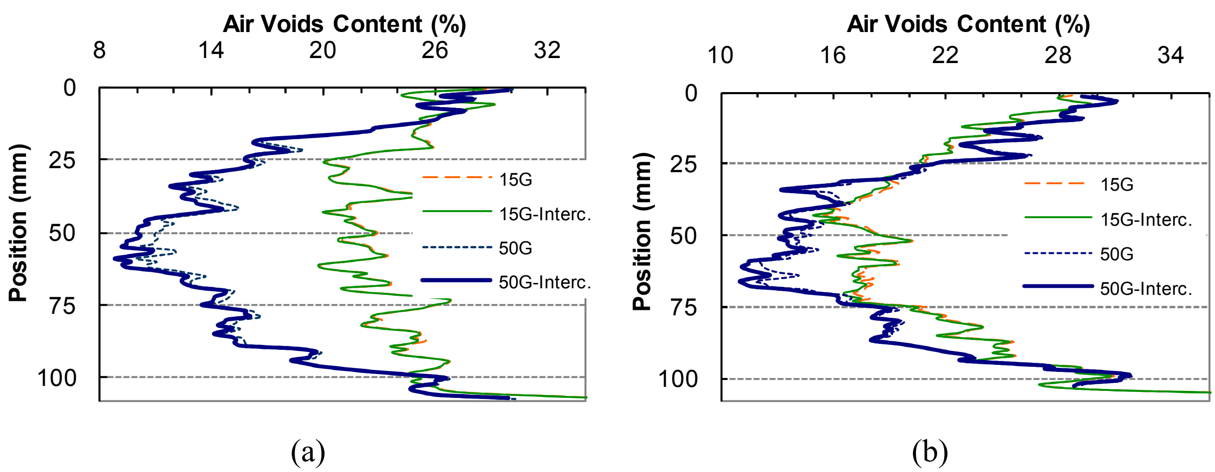


Figure 20. Vertical Distribution of Total Air Voids Content for SGC Specimens of the 6-PG (a) and 3-AR (b) Mixture.

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 19). 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 [5, 44], is mostly related to the distribution of the compaction energy in the SGC specimen as discussed in detail by Thyagarajan et al. [47].

4.7 CONCLUSIONS AND RECOMMENDATIONS

This paper presents a study of the internal structure of PFC mixtures, assessed in terms of air voids (AV) characteristics, computed for both field-compacted mixture specimens (road cores 152 mm in diameter) and specimens prepared 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. Further research is recommended to determine the effect of both the compaction pattern and temperature profile on the patterns of vertical AV distribution obtained for field-compacted mixtures. The differences in mean values of total AV content probably relate 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 of the internal structure of mixtures fabricated by applying compaction control as well as the effect of other mixture and operational variables (e.g., aggregate gradation, AV size, AV connectivity, asphalt aging, and traffic speed) 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.

5 CONCLUSIONS AND RECOMMENDATIONS

This report summarizes the main activities conducted, analysis performed, and corresponding findings and recommendations proposed to improve the assessment of drainability and stone-on-stone contact and to enhance the comparison of the internal structure of laboratory- and field-compacted PFC mixtures. Based on the specific conclusions and recommendations provided in each of the three previous chapters, general conclusions are subsequently provided.

The assessment of drainability led to recommendation of the expected value of permeability (based on a modified Kozeny-Carman equation) for analytical prediction of permeability during mix design and evaluation. However, additional research is still required to improve the prediction of permeability for road cores. The water-accessible AV content was also proposed as a surrogate of the total AV content for indirect assessment of permeability. In addition, field drainability of PFC mixtures can be evaluated in terms of the water flow value (outflow time).

Enhancements for the quantitative determination of stone-on-stone contact were proposed based on an analysis conducted using the Discrete Element Method and image analysis techniques. This analysis led to recommendation of the criterion based on the slope of the gradation curve to determine the breaking-sieve size of PFC mixtures. According to this criterion, the breaking-sieve size corresponds to the sieve size at which the slope of the gradation curve below this size begins to flatten out. In addition, verification of stone-on-stone contact using a maximum *VCA* ratio of 0.9 over the current criterion (VCA=1.0) was recommended to ensure construction of PFC mixtures with fully developed stone-on-stone contact.

The analysis of mixture internal structure led to recommendation of a reduction of the horizontal heterogeneity of total AV content by using road cores with a minimum 152.4 mm diameter and coring SGC specimens from 152.4 to 101.6 mm in diameter. In addition, the limitations to compare the vertical distribution of AV of field- and laboratory-compacted mixtures supported recommendation of field-compaction control and future analysis of mixtures produced accordingly. This future analysis will allow identification of the pattern of AV distribution that should be reproduced in SGC specimens.

These recommendations can be integrated in the current PFC mix design method to improve the assessment of PFC mixtures. However, complete implementation and validation of the improved mix design method requires future evaluation of performance (including functionality and durability) of mixtures fabricated as recommended in the improved method.

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