PERMEABLE FRICTION COURSE MIXTURES ARE DIFFERENT

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ABSTRACT
Permeable friction course (PFC) mixtures are a special type of hot mix asphalt characterized by a high total air voids (AV) content, which confers special properties to this type of mix including high permeability and noise reduction capacity. Although substantial progress was achieved in the last decade in terms of developing a mix design procedure, recent research conducted at Texas A&M University assessed several aspects related to mixture evaluation, including volumetric properties, drainability, durability, and effects of densification to further enhance the design of this type of mixture. This paper summarizes corresponding relevant results and recommendations, which include improvement in the computation of the total AV content based on the application of dimensional analysis (to compute the bulk specific gravity of the compacted mixture (G_{mb})) and a calculation procedure to determine the theoretical maximum specific gravity of the mixture (G_{mm}). In addition, evaluation of field drainability can be conducted in terms of the water flow value (outflow time), and the expected value of permeability ($E[k]$) was recommended as an estimator to predict permeability. Furthermore, the Cantabro loss test was suggested for evaluating mixture durability. Verification of stone-on-stone contact during mix design, as well as density control during construction should also be specified to obtain a granular skeleton with adequate stability.

INTRODUCTION

Permeable friction courses (PFC), as defined by the Texas Department of Transportation (TxDOT), or new generation open-graded friction courses (OGFC), are asphalt mixtures designed with high total air voids (AV) content compared to dense-graded hot mix asphalt (HMA). Stone-on-stone contact of the coarse aggregate is also required to ensure adequate mixture stability. Thus, PFC mixtures serve as wearing courses that placed in thin thicknesses improve safety, especially in wet weather conditions due to water traveling through connected AV within the mixture instead of over the surface. In addition, compared to dense-graded HMA, PFC offers cleaner runoff and reduction of pavement noise [1-3].

The particular characteristics of PFC mixtures (e.g., high AV content, open gradation, and high drainability) lead to the necessity of specific approaches to conduct corresponding mix design and evaluation. Current TxDOT PFC mix design relies on volumetric properties to determine the optimum asphalt content (OAC). An evaluation of draindown and moisture susceptibility of the mixture are also conducted on specimens fabricated at the OAC defined by volumetric properties [4]. Recently, the National Center for Asphalt Technology (NCAT) [5-7] also proposed a mix design method that includes an assessment of both functionality and durability. Furthermore, ASTM D 7064-04 [8] contains a mix design procedure based on evaluating volumetric properties to establish the OAC. Although the consolidation of these methodologies have enhanced the design of PFC mixtures, additional research is still required to further improve specific aspects related to mixture characterization and evaluation.

This paper summarizes the main findings and recommendations reported in recent research conducted at Texas A&M University on the evaluation of PFC mixtures, including aspects related to: (*i*) volumetric properties, (*ii*) functionality-drainability, (*iii*) durability, and (*iv*) effects of densification. This research included PFC mixtures fabricated using both Performance Grade (PG) asphalts (PG 76-XX) and Asphalt Rubber (AR) asphalts and corresponding aggregate gradations as currently specified by TxDOT [9], which were evaluated using laboratory- and field-compacted (road cores) specimens.

The paper is organized in four main sections related to each mixture aspect evaluated. A summary and recommendations complete the paper.

VOLUMETRIC PROPERTIES

Total AV content (or corresponding density) is the main parameter used for selecting the OAC of PFC mixtures. The total AV content is determined as:

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

where G_{mb} is the bulk specific gravity of the compacted mixture and G_{mm} is the theoretical maximum specific gravity of the mixture. Although this AV calculation is simple, the characteristics of PFC mixtures, including the use of modified asphalts, high asphalt content, and high total AV content, pose difficulties in determining the required inputs.

Therefore, previous research [6, 7] examined both the vacuum method and dimensional analysis to compute G_{mb} for OGFC mixtures and recommended the vacuum method. However, minimum total AV content values for mix design of 16 and 18% were proposed when employing the vacuum method and dimensional analysis, respectively. More recent research [10] recommended determination of G_{mb} for PFC mixtures using dimensional analysis over the vacuum method [11] and did not support the use of both methods based on different minimum total AV content values. Dimensional analysis includes direct measurement of diameter and height to compute average values that define the total volume of the compacted specimen (V_{td}), expressed in cm^3, included in the G_{mb} calculation as follows:

$$G_{mb-\dim ensional} = \frac{\dfrac{W}{V_{td}}}{\rho_w} \quad (2)$$

where ρ_w is the density of water (g/cm^3) and W is the mass of the specimen in air (g). Computation of the total volume corresponds to the main difference between dimensional analysis and the vacuum method. Dimensional analysis assumes the compacted specimen as a regular cylinder with smooth faces. Therefore all surface AV are included as part of the specimen total volume. In the vacuum method, the surface AV are partially included depending on the shape of the bag in each surface AV. Ultimately, the fraction of AV included is a function of the particular stiffness of the bag required to use the vacuum method.

Alvarez et al. [10] also recommended using calculated-G_{mm} values over measured-G_{mm} values to compute the total AV content of PFC mixtures. The measured-G_{mm} value (also known as Rice Specific Gravity) for a specific asphalt content was determined according to the test procedure indicated in Tex 227-F [4]. The calculated-G_{mm} included computation of an average effective specific gravity of the aggregate (G_{se}) based on G_{mm} values measured at different lower asphalt contents (i.e., 3 to 5 %). Then, a calculated-G_{mm} value at the actual asphalt content used for mix design (i.e., 6 to 7% and 8 to 10%, for PG and AR asphalt, respectively) was determined as follows:

$$Calculated\ G_{mm} = \frac{100}{\dfrac{100 - P_b}{G_{se}} + \dfrac{P_b}{G_b}} \quad (3)$$

were P_b is the asphalt content and G_b is the asphalt specific gravity.

The use of calculated-G_{mm} values was recommended over measured-G_{mm} values based on: (*i*) reduced variability (evaluated in terms of the coefficient of variation), (*ii*) less error related to the loss of asphalt during the measurement of G_{mm}, and (*iii*) ease of production and handling of low asphalt content mixtures in the laboratory [10].

Although the total AV content (or corresponding density) is currently used for PFC mix design, preliminary evidence suggested that the connected AV content (i.e., water-accessible AV content) can have better correlation to mixture durability and functionality as compared to that obtained for the total AV content [12]. The proportion of the total volume of a compacted mixture that is accessible to water corresponds to the water-accessible AV content [13]. Assessment of both dimensional analysis and the vacuum method to compute the water-accessible AV content of PFC mixtures led to a recommendation of dimensional analysis [13]. The corresponding computation is conducted as follows:

$$Acces\,AV_{\dim\, no\, vacuum} = \frac{V_{td} - \dfrac{(W - W_s)}{\rho_w}}{V_{td}} \times 100 \qquad (4)$$

were W_s is the saturated mass in water measured by direct immersion of the specimen to allow access to water until a stable mass (W_s) is obtained. Although this dimensional analysis was originally defined based on W_s, the use of a more representative saturated mass measured after vacuum saturation of the compacted specimen (W_{sv}) was finally recommended.

The interconnected AV content, calculated by applying X-ray Computed Tomography (X-ray CT) and image analysis techniques, was 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 [13]. The interconnected AV content values were comparable to water-accessible AV contents computed using dimensional analysis with application of vacuum. X-ray CT and image analysis constitute a non-destructive technique that can be used to conduct additional research on the mixture internal structure (e.g., in terms of the interconnected AV distribution) to further analyze mixture functionality and durability.

DRAINABILITY

The drainability, conferred by an elevated connected AV content, that characterizes PFC mixtures contributes to improved safety under wet weather conditions and is the main reason to use these mixtures as surface courses in the United States. At present, measurement of drainability is not directly included as part of the PFC mix design since specifying a minimum total AV content (i.e., 18% on specimens compacted using the Superpave Gyratory Compactor (SGC)) is considered an indirect indication of adequate permeability [8, 9]. As an optional evaluation, ASTM International [8] and NCAT [5] suggested the measurement of permeability in the laboratory using SGC compacted specimens, and recommended a value of 100 m/day for minimum permeability.

Recent research [14] concluded that obtaining a minimum value of total AV content or permeability on SGC compacted specimens does not ensure adequate drainability of field-compacted mixtures. The alternatives analyzed in the same research to improve the assessment of drainability of PFC mixtures included: (*i*) study of the relationship of water-accessible AV content (as a surrogate of the total AV content) and permeability data to indirectly assess permeability, (*ii*) evaluation of the relationship of laboratory permeability and field drainability, and (*iii*) analytical prediction of permeability.

The assessment of the relationship of water-accessible AV content and laboratory-measured permeability values (measured on SGC compacted specimens) suggested that this volumetric parameter can be used as a surrogate of the total AV content to evaluate permeability. However, additional data are required to evaluate if this conclusion is substantiated for road cores.

Field drainability was measured, according to the Tex-246-F test procedure [4], in terms of the water flow value (WFV). The WFV is the time (expressed in seconds) required for a given water volume to flow through a PFC mixture using an outflow meter 152 mm in diameter. Results reported by Alvarez et al. [14] provided evidence as to the practical possibility of specifying a minimum requirement of permeability (e.g., 100 m/day) based on the field assessment of WFV. Further research is required to better define upper and lower limits for WFV as well as its variability.

Based on a modified version of the Kozeny-Carman equation proposed by Masad et al. [15], the expected value of permeability ($E[k]$) was recommended [14] as an estimator to predict permeability for mix design and evaluation purposes. However, future research was suggested to improve the computation of permeability for field-compacted mixtures (e.g., based on the evaluation of road cores).

DURABILITY

Current TxDOT PFC mix design includes evaluating specimens produced at the OAC determined based on volumetric properties, for draindown (in accordance with Tex-235-F) and moisture susceptibility using the “boiling” test in accordance with Tex-530-C [4]. Thus, the current PFC design practice focuses on ensuring mixture functionality, based on a minimum total AV content, but there is a limited evaluation of durability in terms of the mixture resistance to disintegration (i.e., raveling) and susceptibility to moisture damage, which are still a concern for PFC performance.

In addition, phenomenological approaches used in the past for assessing durability of OGFC and European porous asphalt mixtures similar to PFC include the Cantabro Loss test (Cantabro test), the Hamburg Wheel-Tracking test (HWTT), and the retained tensile strength ratio [5, 6, 16]. Furthermore, the applicability of existing durability tests employed in dense-graded HMA and porous asphalt to design PFC mixtures was recently evaluated by Alvarez et al [17].

After evaluating the Cantabro test, the HWTT, and the Overlay test (OT); the Cantabro test (conducted using dry- and wet-conditioned specimens) was initially recommended to assess the suitability of the OAC established based on volumetric properties. The high variability of the HWTT- and OT-results, defined in terms of the coefficient of variation, was the main factor restricting their application for PFC mix design and evaluation. Although the Cantabro test results exhibit smaller variability as compared to those of the HWTT and the OT, the trends and variability of the Cantabro test results (observed as the asphalt content was modified) prevented recommendation of this test as a definitive tool for selecting the OAC. Ultimately, the Cantabro test could be used as a screening tool for identifying the best material combinations to include in more advanced testing towards determination of the OAC. Thus, future work should be directed toward the development of an analytical model that allows a more fundamental understanding of mixture durability [17].

The Cantabro test (as described in Tex-245-F [4]) is conducted by subjecting a SGC compacted specimen (115 ± 5 mm in height and 150 mm in diameter) to 300 revolutions in the Los Angeles abrasion machine without any abrasive load. The final mass (W_f) measured after subjecting the specimen to abrasion is compared to its initial mass (W_o) to compute the Cantabro loss according to Equation (5).

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

Performing the test under controlled temperature conditions (i.e., 25°C is recommended) is an important aspect to reduce the variability of the Cantabro loss. Previous research indicated that the mixture resistance to disintegration of porous asphalt mixtures can be evaluated using the Cantabro loss [3], although Nielsen [18] indicated poor correlation for the same variables. In addition, the analysis of Cantabro loss values suggested that the aggregate properties have a larger effect on the mixture resistance to disintegration as compared to the asphalt properties. Furthermore, the Cantabro loss and the water-accessible AV content showed a direct relationship, indicating the importance of controlling the volumetric properties to ensure adequate durability [17].

DENSIFICATION EFFECTS

Current construction specifications for PFC mixtures do not include a minimum density requirement. Construction control is now based on verification of gradation and asphalt content as well as visual inspection to qualitatively assess mixture density, variability, and segregation. However, proper compaction is required because low density PFC mixtures are prone to raveling [19]. In addition, the design and construction of a PFC mixture should produce a compacted mixture with an equilibrium density that ensures both durability (in terms of resistance to raveling and permanent deformation) and functionality (in terms to drainability and noise reduction capacity) requirements. Furthermore, since the design of PFC mixtures (i.e., selection of the OAC) is based on a target density, the field density should be included as a control parameter.

Recent research [20] provided evidence of the differences in total AV content for field-compacted PFC mixtures, produced according to the current construction specifications, and laboratory-compacted mixtures produced as part of the corresponding mix design using the SGC. Whereas the total AV content of the laboratory-compacted mixtures was in the range of 18 to 22%, this AV content was in the range of 23 to 34% for field-compacted mixtures. The same research also included an evaluation of the densification effects on PFC mixtures based on the study of the internal structure, conducted using X-ray CT and image analysis, and a comparison of performance based on macroscopic response. Results of this evaluation suggested that the changes in densification after obtaining stone-on-stone contact (computed as suggested by NCAT [5]) led to modifications of the mixture properties and performance. The magnitude of these modifications suggested the convenience of verifying stone-on-stone contact, as part of the mix design, and the necessity of controlling the density during construction.

In addition, the analysis of the internal structure of field-compacted and laboratory-compacted mixtures provided evidence of important differences in the corresponding distribution and size of AV, which suggest that SGC compacted specimens are not entirely representative of the characteristics exhibited by field-compacted mixtures.

SUMMARY AND RECOMMENDATIONS

This paper presents a summary of recent research conducted at Texas A&M University on PFC mix design and evaluation including volumetric properties, drainability, durability, and the effects of densification. Primary findings and recommendations are summarized as follows:

- Dimensional analysis to compute G_{mb} and a procedure for calculating G_{mm} were proposed to improve determination of the total AV content (or corresponding density) and thus selection of the OAC.
- Computation of the water-accessible AV content, considered as a surrogate of the total AV content for mix design and evaluation, by using dimensional analysis with application of vacuum was recommended. In addition, the water-accessible AV content values were comparable to interconnected AV content values computed using X-ray CT and image analysis. This non-destructive technique can provide information related not only to the mean AV content, but also to the internal distribution and size of connected AV.

- The study of drainability suggested that: (*i*) field drainability can be evaluated in terms of the WFV (outflow time) and (*ii*) an indirect assessment of drainability can be conducted based on the relationship of permeability and the water-accessible AV content (as a surrogate of the total AV content). Analytical prediction of permeability was recommended by using the expected value of permeability, determined using a modified version of the Kozeny-Carman equation.
- The analysis of different durability tests (including the HWTT, OT, and Cantabro test) led to recommendation of the Cantabro test, conducted on dry- and wet-conditioned specimens, to evaluate mixture durability. However, additional research is still required to develop a more fundamental approach for evaluating mixture durability and performance.
- Verification of stone-on-stone contact during the mix design as well as density control during construction were recommended to obtain a coarse-aggregate skeleton required to ensure adequate mixture durability.
- Preliminary comparisons of the internal structure of field- and laboratory (SGC)-compacted mixtures suggested the necessity of future research to recommend a modified protocol to produce laboratory specimens that ensures better reproduction of field-compacted mixture characteristics.

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