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Effect of volumetric factors on the mechanical behavior of asphalt fine aggregate matrix and the relationship to asphalt mixture properties

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HIGHLIGHTS

- The properties of FAM are evaluated with respect to asphalt and air void content changes.
- Quantitative comparisons between FAM and AC properties with compositional changes are made.
- A micromechanical model is used to study the linkages between the FAM and AC moduli.
- An empirical correlation is used to study the linkages between the FAM and AC fatigue properties.
- FAM can be useful for both practical and modeling tasks with proper material design and testing.

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ABSTRACT

The multiscale study of asphalt concrete using fine aggregate matrix (FAM) has become widespread in recent years. Different laboratory fabrication procedures have been proposed, and since FAM's sensitivity to compositional effects is unknown this literature cannot be coherently interpreted. In this paper, the mechanical responses of FAM at different volumetric compositions are systematically studied. The viscoelastic and tensile properties are found to be sensitive to volumetric composition. It is concluded that the use of FAM for modeling purposes requires accurate replication of FAM as it exists in the mixture. However, such strict requirements are not necessary for simpler, comparative evaluations.

1. Introduction

Asphalt fine aggregate matrix (FAM) consists of asphalt binder, filler-sized particles, fine aggregate particles, and air and it exists in the interstitial spaces between the coarse aggregate particles within an asphalt concrete (AC) mixture. FAM is important because it is a single characteristic length scale smaller than the AC and is therefore closer in characteristic size of the damage that occurs within the AC [1]. Experiments with FAM have been used to study fatigue damage, moisture damage and healing in AC mixtures, with the argument that the phenomena occur largely between the coarsest aggregate particles and so tests with FAM should provide direct indications of how they will affect AC mixture [1–4]. FAM materials are characteristically similar to AC mixtures with the primary difference being that the maximum aggregate size is generally smaller than 2.36 mm and so test samples can be created at smaller geometries and still meet representative volume element, RVE, requirements [5]. Maintaining the RVE requirements ensures that measured properties are not functions of the test geometry and that they represent the fundamental characteristics of the material. Being able to fabricate and test small geometries means that mechanistically viable experiments can be carried out using less costly equipment and in less time than would be required for larger geometries [6,7].

The question remains whether the benefits of FAM experiments outweigh the limitations of needing to utilize upscaling models to predict the properties of the AC. It is the contention of this paper that the benefits do outweigh these limitations, but that appropriate care must be taken in both the experimental phase, and the upscaling process. Both computational [8–12] and analytical [13–22] based upscaling approaches have been attempted with varying levels of success. The primary limitation with these approaches thus far has been the lack of an experimentally verified, functional based microstructural hypothesis for supporting the numerical discretization. These works primarily focus on applications to the case

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of non-damaged composites, but some have been expanded to explore the effects of localized disturbances on macromechanical responses [23–25]. The overall conclusion from these modeling efforts is that in order to completely understand the macromechanical response of a heterogeneous composite, one must first understand the mechanical response of that same composite at different length scales.

One shortcoming in the available literature is the detailed understanding of the fundamental characteristics of FAM as a function of volumetric composition changes. This lack of understanding makes it difficult to view the literature as a coherent set of information since most researchers utilize their own techniques to define and create FAM. One pragmatic approach is to set the largest size of aggregate in FAM based on resolution limitations with digital image analysis (2.36–2 mm) [26,27]. Kim and Aragao [28] proposed that the FAM contained particles smaller than 1.18 mm and all of the non-absorbed asphalt cement. Recently, Sousa et al. [29] also suggested the 1.18 mm threshold, but determined the asphalt content by staged sieve analysis. The authors of this paper have also proposed a method based on a series of microstructural and gravimetric experiments [30]. This method theorizes that all aggregates in the mixture are coated with a film of asphalt mastic (filler particles and asphalt) and that the FAM exists between the coated coarse aggregate particles. The aggregate size in the FAM is defined according to the nominal maximum aggregate size of the mixture and the asphalt content is determined based on the film of mastic coating the FAM aggregates. The FAM is further estimated to contain 40–70% of the air within the AC mixture based on analysis of computed tomography images of AC mixture. [30]. Aside from volumetric composition, compaction of the FAM is also an issue and Izadi et al. found that gyratory compaction replicated the microstructure of FAM as it exists in the mixture [31]. Obviously, there is no firm consensus on how the FAM exists in the mixture and how to replicate this in the laboratory. The purpose of this paper is not to rank order the potential fabrication methods. Rather, the data presented in this paper provides insight into why it is important to identify a method to replicate the FAM, and under what specific applications a more or less accurate replication is needed.

While some of the previous research has evaluated FAM characteristics for select conditions, none have carried out systematic evaluations of the material properties with respect to sensitivity to volumetric changes. Such an evaluation can benefit analytical/computational modeling efforts, but can also be useful for evaluating the effectiveness of FAM-based experiments in practical engineering applications like; performance based mix design, selecting amongst material alternatives for a given application, and/or rapid forensic studies [32–33]. The objectives of this paper are to demonstrate and quantify;

- How changes in asphalt and air void content affect the dynamic shear modulus, $|G^*|$, and tensile properties (strength and strain at failure) of FAM, and
- How FAM and AC mixture behaviors are related through analytical micromechanical modeling for $|G^*|$ and through correlation for damaged properties.

The unique contribution of this research is in the systematic evaluation of these effects and in the quantification of compositional effects on modulus and tensile properties. These findings have implications in both engineering practice and multiscale modeling applications and will be useful in reviewing and compiling conclusions from the existing literature.

2. Materials and test method

2.1. Materials

Two granite-based AC mixtures with highly angular, cubical, low deleterious content, and well graded aggregate are used for this study. The first mixture has a nominal maximum size of aggregate (NMSA) of 9.5 mm and the second has a NMSA of 19.0 mm. These materials are respectively referred to as the 9.5 mm and 19.0 mm mixtures throughout this paper, and were chosen to provide different sized representative FAM as discussed below. The FAM materials are labeled as either coarse FAM (C-FAM) or very fine FAM (VF-FAM), depending on the maximum aggregate size. The C-FAM consists of aggregates passing the 2.36 mm sieve. The maximum aggregate size for the VF-FAM is based on the experimental findings from the authors that the maximum aggregate size in the FAM is equal to the fine aggregate initial break sieve used in the Bailey method of mix design [30,34]; 0.6 mm for the 9.5 mm mixture and 1.18 mm for the 19 mm mixture. Different FAM materials have been created at different asphalt binder and air void contents within these maximum aggregate sizes as shown in Table 1 and Fig. 1.

With respect to the materials listed in Table 1, the asphalt content was controlled by carefully weighing in a target mass of asphalt binder during fabrication. Although the mean air void contents are shown in Table 1 it is noted that all of the

Table 1
Test conditions and designations for the primary mixtures.

Mix	FAM Size	Name	Asphalt content by mass (%)	Air void (%)	Direct tension[a]
9.5 mm	C-FAM	CFL-9	8.27	9.1	
		CFM-9	9.70	9.1	
		CFM-7	9.70	6.5	
		CFM-5	9.70	4.5	
		CFH-9	11.2	9.1	
		CFH-7	11.2	6.5	
	VF-FAM	VFAS-4	16.5	3.3	X
		VFBS-4	15.2	3.9	X
		VFBS-8	15.2	7.8	X
		VFCS-4	13.2	4.5	X
		VFCS-8	13.2	8.0	X
		VFDH-12	11.6	12.4	X
		VFDH-19	11.6	19.4	X
		VFDL-21	8.5	21.0	
		VFEH-4	15.6	4.4	X
		VFEL-10	12.2	9.5	
		VFFS-2	16.3	1.7	
		VFFS-5	16.3	4.6	
19.0 mm	VF-FAM	VF19AS-2	13.1	1.9	
		VF19AS-4	13.1	3.7	
		VF19BS-5	11.7	5.0	X
		VF19BS-8	11.7	8.2	X

[a] X indicates that direct tension testing was performed.