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Investigation on the low temperature property of asphalt fine aggregate matrix and asphalt mixture including the environmental factors

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HIGHLIGHTS

- The compaction level can be optimized by the BBR tests.
- The size of air voids in FAM and HMA results in the different moisture damage mechanism.
- FAM is the primary component to bear early aging caused by sunlight.
- The time-aging superposition principle is effective to highlight the effect of aging.

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ABSTRACT

Asphalt fine aggregate matrix (FAM) is an important component of hot-asphalt mix (HMA) pavements at the meso-scale, but the relationship between FAM and HMA is not clear with respect to thermal stress and relaxation capacity at low temperatures. Thus the bending beam rheometer (BBR) was adopted to investigate the low temperature property of FAM and HMA beams. The asphalt content in FAM was calculated by keeping the filler-bitumen (*FB*) ratio the same as it in the known HMA specimens. FAM and HMA beams were cut and trimmed to meet the geometry requirements. Virgin beams, beams subjected to four freeze-thaw cycles, and aging beams were tested by mean of a constant creep load using BBR. In this study, the time-aging superposition principle was developed to comprehensively interpret the data. Results show that the optimal compaction is a decisive factor to generate a strong asphalt pavement. The size of air voids in FAM and HMA beams contributes to different mechanisms of moisture damage caused by the freeze-thaw cycle. FAM is more sensitive to the sunlight aging, and the time-aging superposition principle is a useful tool to quantitative the effect of aging.

1. Introduction

The hot-mix asphalt (HMA) is generally divided into three phases at the mesoscale: coarse aggregate, asphalt fine aggregate matrix (FAM), and asphalt-aggregate interface. FAM consists of asphalt binder, fine aggregate, filler (sieve size smaller than 0.075 mm), and air voids. Results concluded from laboratory tests and numerical simulations show that most cracks occur and propagate within FAM [1]. Therefore, it indicates that FAM is sensitive to the characteristic scale of damage that occurs within asphalt pavements. Several studies have focused on investigating the mechanical properties of FAM related to moisture damage, fatigue, and cracking [2–4], as well as the effect of volumetric factors and the relationship to asphalt mixture [5]. DMA (dynamic mechanical analysis) and DSR (dynamic shear rheometer) were used to determine the properties of FAM at high and intermedium temperatures. Although the low temperature property of FAM can be obtained by adopting the same specimen size as it used in the asphalt mixture test [6], the sample fabrication and the testing protocol are complicated and time consuming. Therefore, it is necessary to develop a novel test preventing those complicated procedures.

Known as the standard test for binder at low temperature, BBR (bending beam rheometer) test is cost effective due to its simple operation. Research has proved that the creep behavior of small asphalt mixture beams can be investigated by using the BBR test described in binder specification [7,8]. In addition, the protocols, including method of sample preparation, the creep force, and the load duration, have been documented in the reference [9]. The

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reference also show that the results collected from thin asphalt mixture beams show good predictions with respect to the IDT (indirect tensile) test for large asphalt mixtures [10]. In one study, the effect of volumetric parameters and binder content on the creep behavior of asphalt mixtures was discussed based on the BBR test; the results indicate that the creep stiffness was dependent on those variables but the *m*-value was not affected [11]. In another study, the repeatability and reproducibility of BBR results on asphalt mixtures were verified using data collected from different laboratories. When conducting the data analysis, the maximum stiffness and minimum stiffness were removed for each group containing 10 beams. Final results showed that the coefficient of variation in the results was less than 10% in most cases [12].

Comparing to asphalt mixtures, FAM samples with smaller aggregate size are more likely to be treated as homogenous materials. Consequently, the BBR test must be suited to obtain the low temperature property of FAM because of excluding coarse aggregates. A former study adopted the BBR to determine the viscoelastic parameters of FAM used in discrete element models [13]. In cold regions, freeze-thaw cycle [14] and aging [15] are determining factors to deteriorate the low temperature performance of asphalt pavements. However, few studies focus on creep behavior characterization of FAM subjected to those experimental factors. Thus, it is effective to adopt the BBR test to investigate the low temperature property of FAM subjected to those environmental factors as well as the relationship to HMA. The main objective of this paper is to evaluate the effect of freeze-thaw cycle and aging on BBR test results for FAM and HMA beams. The second motivation aims at exploring the relationship between FAM and HMA based on the experimental differences. In this study, because the effect of aging is analogous to temperature, the time-aging superposition principle was developed to analyze the changes caused by aging.

2. Materials and fundamental properties

An asphalt mixture with a nominal maximum aggregate size (NMAS) of 12.5 mm and the corresponding FAM with a NMAS of 2.36 mm were included in this paper, and the gradations are shown in Table 1. The gradation of FAM were obtained by excluding the coarse aggregates greater than 4.75 mm from the gradation of HMA. A PG (Performance Grade) 64–28 binder was used for all HMA and FAM specimens. The optimal asphalt content for HMA was determined based on the volumetric results of mixture cylinders. These specimens were compacted to 50 gyrations using the Superpave gyratory compactor (SGC). It can be summarized that the optimal binder content for HMA is 4.15% and the air voids content is 4.5%. Some of the asphalt in the mixture is adsorbed by the aggregate; the rest is called effective asphalt. In this study, the asphalt content of FAM was obtained by controlling the *FB* (filler-bitumen) ratio in FAM to be the same value in HMA. *FB* is defined as the ratio of filler to effective asphalt by weight [16]; it has been shown to have a significant impact on the performances of asphalt mastic as well as asphalt mixture [17–19]. The asphalt content of FAM specimens can be calculated according to the method described in several related specifications [20–22] and a former study [23]. The *FB* ratio for HMA was found to be 1.25, and then the asphalt content of the corresponding FAM within HMA was calculated to be 6.92%. Three kinds of HAMs (HAM-A, HMA-B, and HMA-C) and FAMs (FAM-A, FAM-B, and FAM-C) were set to be contrasting groups. The specimens in groups named A, B, and C were compacted to 30 gyrations, 50 gyrations, and 70 gyrations, respectively. Therefore, the air void and the compaction level were included into the investigation on the relationship between HMA and FAM.

To explore the internal air voids within FAM beams and HMA beams, industrial computerized tomography (ICT) was utilized to obtain the size distribution of air voids. The scanning voltage is 190 kV, the scanning electric current is 100 μA, and the voxel resolution is 69.09 μm. The percent of the count for five volume groups can be seen in Fig. 1(a). Small air void occupies the predominant status for FAM, and large air void are the main size type for HMA. Fig. 1(b) depicts that small and closed air voids can be found in FAM beams. On the contrary, large and open air voids are obviously seen in HMA beams. The size difference of internal air voids for FAM and HMA could provide an insight into explaining the experimental results shown as below.

3. Experiments

HMA and FAM specimens were cut from cylinders compacted to three gyration levels. Six cylinders were cut into small beams by excluding the top and bottom layer of the cylinders. The size of HMA and FAM beams is set to be 127 × 12.7 × 6.35 mm with a dimensional tolerance of ±0.25 mm. Each experimental group has five beams. The definition of the freeze-thaw cycle was illustrated in Fig. 2(a). First, the beams were dried in a sealed container for 24 h, and then the dry mass was determined immediately. Second, the beams were saturated, in a water environmental cabinet, for 24 h at 25 ± 0.5 °C. Third, the beams in a saturated surface dry (SSD) condition were frozen, in an air environmental cabinet, for 24 h at −20 ± 0.5 °C. Finally, the beams were thawed, in water, for 24 h at 25 ± 0.5 °C, and then the SSD mass was determined immediately. Additionally, the balance must be sensitive to 0.01 g. In this study, 4, 8, 16, and 32 cycles were included to explore the influence of freeze-thaw cycle on the creep behavior of FAM and HMA beams.

Generally, older pavements suffer many distresses caused by aging. For asphalt binders, the rolling thin film oven (RTFO) and pressure aging vessel (PAV) are used to simulate short- and long-term in-service aging [24–27]. The temperature and pressure are the main factors in RTFO and PAV without accounting for any effect of ultraviolet light. However, these tests are not suited to FMA and HMA beams which can be destroyed by high temperatures. Thus, the beams were placed on the roof and directly exposed to the natural environment for two months starting from February of 2015. The location is on the roof of department of civil and environmental engineering at the University of Utah, Salt Lake City. Fig. 2(b) shows that the outdoor climate is not too extreme to destroy the shape of beam. On the other hand, it assures that the sunlight is a predominant factor to simulate ultraviolet aging within asphalt pavements in-service.

As previously mentioned, the BBR tests were conducted based on the same requirements described in the asphalt binders specification except a greater loading value. Because the mixture beam

Table 1
Passing rate of aggregate for HMA and FAM.

Sieve (mm)	19.0	12.5	9.5	4.8	2.36	1.18	0.6	0.3	0.15	0.075
	Percent passing (%)									
HMA	100.0	92.0	81.0	55.0	37.0	24.0	14.0	10.0	8.0	5.0
FAM	–	–	–	100.0	67.3	43.6	25.5	18.2	14.5	9.1