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Influence of short and long term aging on chemical, microstructural and macro-mechanical properties of recycled asphalt mixtures

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HIGHLIGHTS

- ATR-FTIR showed the oxidation of the binders by the increase in the carbonyl and sulfoxide indexes.
- AFM images indicated a changes in the surface microstructure due to recycling.
- Fatigue and low temperature behavior as well as permanent deformation were investigated.
- A mixtures with 40% RAP in aged state performed as well as one with virgin materials.

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ABSTRACT

Recycled road materials produced with similar properties to virgin materials are a necessary means for environmentally friendly and sustainable asphalt pavements. In this project, a Swiss standard surface course and a high modulus base course were produced containing 0% or 40% reclaimed asphalt pavement (RAP), short and long term aged and, subsequently, investigated regarding their chemical, microstructural and mechanical properties. ATR-FTIR spectroscopy showed oxidation of the binder by the increase in the intensity of the spectral peaks attributed to carbonyl and sulfoxide groups. The microstructural characterization using AFM also showed changes in the bitumen surface microstructures in comparison to virgin binders. The addition of RAP did not significantly affect the stiffness modulus of surface course but increased the stiffness modulus of the high modulus base course at high temperatures. The addition of RAP had a negative effect on the fatigue performance of the base course and a positive effect on the binder course. The mixtures containing RAP had lower cumulative strain and strain rate than the mixtures without RAP. It was shown that in spite of the differences in chemical oxidation state and microstructural features, a well-designed mixture containing RAP can perform mechanically as well as that produced with virgin materials in laboratory experiments.

1. Introduction

Recycled asphalt concrete (RAC) is an important step in reducing construction and demolition waste and energy expenditure. It can be the product of mixing reclaimed asphalt pavement (RAP) with new aggregates, some new bituminous binder and/or recycling agent. RAP contains old asphalt binder and, therefore, has the added benefit of reducing the amount of new bitumen and/or recycling agent. However, in most cases the old binder has hardened considerably and a soft new binder or binder with recycling agent has to be added to achieve the expected mixture properties. Significant economic benefits derive from understanding the fundamental failure mechanisms of recycled asphalt concrete in order to prolong the service life of this important sustainable pavement material.

Asphalt concrete (AC) is a complex road material that consists of coarse and fine mineral aggregates, bitumen and air voids. The properties of asphalt concrete are a function of the size, amount, shape, composition and type of these ingredients. Furthermore, adding to the complexity is the viscoelastic behavior of the material due to the bituminous binder, making it highly time and temperature dependent. Hence, material aspects in recycled asphalt concrete are the topic of significant research efforts worldwide. Key parameters are types of fillers [1] and proportion of reclaimed asphalt pavement (RAP). Although long-term performance is a key to material selection, neither a complete fundamental base of knowledge nor a wide palette of experience are available to date. Some recent examples of research works in the public domain are mentioned in the following paragraphs.

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Hong et al. [2] reported on the Long-Term Pavement Performance (LTPP) of the Texas Specific Pavement Studies investigating the in situ performance of hot mix asphalt (HMA) with RAP based on about 16 years of data. The overall evaluation revealed that a well-designed mixture with 35% RAP could perform as satisfactorily as that produced with no recycled materials. Performance of up to 50% RAP containing surface mixtures showed that the high RAP mixtures were only slightly more susceptible to thermal cracking. An increase in RAP generally increases resistance to moisture damage. It was also shown by Doyle et al. [3] that high RAP content mixtures can be more susceptible to durability problems.

Sun et al. [4] have shown that using fine recycled concrete aggregate and coarse granite aggregate the moisture stability, high-temperature property, low-temperature property and fatigue property of asphalt mixtures were improved. Using different amounts of RAP, Arshad and Qiu [5] have shown that mixtures containing RAP showed significant variability and the variability increased with the increasing RAP content.

There are still many open questions regarding the use of RAC, especially when it contains high amounts of RAP. One concern is related to the contribution of RAP to the stiffness of the mixture. Furthermore, an important question is how the old binder from RAP mixtures blends with the new binder and how that translates into the macro-mechanical properties. Huang et al. [6] made a hypothesis that the binder in RAP forms a stiff layer around the RAP aggregates that in turn is coated with virgin binder resulting in a composite system that can enhance the performance of this composite material. Nahar et al. and Nazzal et al. [7,8] have studied the blending between RAP binder and virgin bitumen both by atomic force microscopy (AFM) and dynamic shear rheometer (DSR). Nahar et al. [7] studied the microstructures of the 'blending zone' with AFM. Using the averaged microstructural properties imaged by AFM, the fully blended binder properties were found to be in between those of the two individual binders. Also, the measurements obtained with the DSR showed that the complex modulus of the blended binder was situated in between the RAP binder and the virgin binder. In the study by Nazzal et al., it was reported that the blending occurs at the nano/microscale level in a fairly uniform manner and that the blended binder had significantly lower modulus than the RAP, but still larger than for the virgin bitumen. The authors have also reported that RAP binder brought adverse effects to the adhesion properties. A correlation between the nano/microstructural properties and the macro-mechanical properties is still missing.

The goal of this paper is to gain an understanding of chemical, microstructural and macro-mechanical characteristics of RAC containing RAP, particularly as a consequence of short and long term aging in the laboratory. To this end, results of various laboratory experiments are presented employing mixtures with 0% or 40% RAP focusing on long term durability. Currently, for hot mix asphalt, Swiss standards allow no recycled materials in high trafficked surface courses on the other hand, 30% and 60% RAP by mass are allowed for binder course and base courses respectively [9]. In this paper, partial chemical characterization of the bituminous binders was made to establish aging stemming from oxidation of binder molecular components using Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) spectroscopy. Atomic force microscopy (AFM) was used to characterize the surface microstructural features of the binder films, which, at least in part, reflect the chemical composition, intermolecular and colloidal interactions in the bitumen (both at surface and in bulk). For macro-mechanical characterization, various test procedures were explored in order to characterize the material's resistance to fatigue, permanent deformation and low temperature cracking. Furthermore, of fundamental interest was the behavior of the material in the linear viscoelastic (LVE) domain characterized by the stiffness modulus. Table 1 summarizes the experiments performed and the resulting characterizations.

2. Experimental

2.1. Materials

2.1.1. Mixtures

Two types of pavements, a Swiss standard surface course with 11 mm maximum aggregate size (AC 11 S) and a high modulus base course with 22 mm maximum aggregate size (AC EME 22) have been investigated following the Swiss standards [9] as well as additional test methods. The mixture designations used were Mx05, Mx07 for AC 11 S containing 0% and 40% RAP and Mx30 and Mx32 for AC EME 22 respectively as listed in Table 2. The standard mixture properties such as aggregate gradation, binder content, air void content and type of RAP and the binder properties such as penetration and softening point are also listed in Table 2. Two types of RAP fractions were used: RAP 1 refers to the finer fractions 0/11 mm and RAP 2 to the coarser fraction 11/22 mm as shown in the gradation in Table 2. For the mixture, the virgin asphalt binder used were penetration grade 70/100 (here annotated V70/100; V stands for virgin) for Mx05, a combination of 70/100 and 160/220 (V160/220) for Mx07 and 10/20 (V10/20) for Mx30 and Mx32. The lower case letters after the mix designation (*a*, *b*, *c*, *d*) in the figures and tables refer to the different batches.

2.1.2. Binders

Binders were chosen and characterized as to their relevance for the mixtures listed above: Virgin binders (V160/220, V70/100 and V10/20), recovered binders of soluble bitumen from the bituminous mixtures listed in Table 2 [10], and a 50:50 by weight mixture of extracted binder from RAP (BitRAP) and V70/100; annotated Blend(50/50). In order to ensure mixing of the blend; the latter was prepared by weighing both BitRAP and V70/100 in the same container and placing it in the oven at 134 °C for 10 min, stirring the mixture by hand for 1 min and placing it back in the oven for another 10 min, before removing it from the oven and stirring by hand for another minute.

2.2. Sample preparation

2.2.1. Macro-scale mix design and sample preparation procedure

The mixtures were produced using the Marshall design procedure, as this is the standard method in Switzerland. The mixtures with recycled materials were designed to the target aggregate gradation and binder content and penetration of the virgin materials (with 0% RAP) which were used as reference mixtures. For the AC mixtures containing 40% RAP, the binder V70/100 was blended with the softer binder V160/220. AC EME mixtures need a hard bitumen similar to the old binder in the RAP itself. Hence, no soft binder was necessary and the same bitumen V10/20 as for the reference mixture without RAP was used. The following procedure was used to prepare the mixtures: RAP material, if used, was heated in an oven at 130 °C and 135 °C for AC 11 S and AC EME 22 respectively for 3 h. The virgin minerals were distributed in pans and heated at the appropriate mix temperatures for 36 h in an oven. For 0% RAP for the two types of mixtures the mix temperature was 165 °C and 180 °C. For the 40% RAP mixtures, the minerals were heated to higher temperatures (185 °C and 200 °C for Mx07 and Mx32 respectively) than RAP (130 °C and 135 °C respectively) in order to ensure the target mixing temperatures. The binder was heated to the mixing temperature (130 °C and 170 °C) and the mixer was heated to 180 °C. First, the heated minerals were added to the mixer, followed by the heated RAP material. These components were allowed to mix for 2 min before the heated new binder was added. Each mixture was prepared in 150 kg batches and distributed in 25 kg carton boxes to be used later for compacted sample preparation. For the preparation of 100 mm in diameter and 65 mm high cylindrical samples standard Marshall hammer compaction was used with 2×50 blows to each side of the sample.

2.2.2. Binder films for AFM measurements

The binder films were prepared as follows: ca. 150 mg of the bitumen were removed from the supplier's bucket using a spatula, avoiding the material at the surface, and, subsequently, spread by buttering action over a ca. 20×20 mm^2 area on a 25×25 mm^2 glass slide. For the heat treatment (annealing), these samples were placed in the oven at 110 ± 2 °C for 18–20 min, subsequently removed from the oven, covered with a glass cap to prevent dust deposition and allowed to cool down and stand at room temperature for 24 h prior to any measurements. The annealing temperature was kept below the mixing temperature in order to minimize the aging effects on the binders. The final bitumen film thickness was roughly 375 µm, calculated considering the bitumen density equal to 1 g/cm^3.