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Uniformity and mechanical properties of dense asphalt concrete with steel wool fibers

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HIGHLIGHTS

- ▶ We examine the distribution of steel wool fibers in dense asphalt concrete.
- ▶ The properties of the mixture are related to the length and diameter of the fibers.
- ▶ We recommend the use of certain geometries of fibers in dense asphalt concrete.

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ABSTRACT

Fibers in asphalt concrete are known for enhancing its strength and fatigue characteristics while increasing ductility. Additionally, fibers may increase the dynamic modulus, moisture resistance, creep compliance, rutting and freeze–thaw resistance of asphalt concrete, preventing the formation and propagation of cracks. The addition of fibers may influence the properties of the material, but it is not clear how is this influence, and which are the optimum amount, length and diameter of fibers needed for not having a negative impact on the mixture. For this reason, fibers (steel wool) distribution and their effect on the porosity and electrical conductivity of dense asphalt concrete have been studied. With that purpose, 25 different mixtures, with the same aggregates gradation and amount of bitumen, but with two different lengths of fibers, four different percentages, and four different diameters of steel wool have been built. Results show that long and thin fibers produce many clusters and a poor distribution, while short and thick fibers disperse very well in the mixture. It was also observed that fibers can be seriously damaged during the mixing and compaction processes. Finally, it has been found that steel wool fibers do not have a relevant influence on the particle loss resistance and flexural strength of dense asphalt concrete.

1. Introduction

Fibers in asphalt concrete are used to improve its properties, for example by enhancing the material strength and fatigue characteristics while increasing ductility [1,2]. Additionally, it has been found that fibers change the viscoelastic properties of a polymer modified asphalt binder [3]. They have the potential to increase the dynamic modulus [4], moisture resistance [5], creep compliance, rutting resistance [6] and freeze–thaw resistance [7] of asphalt concrete. Moreover, it is known that fibers may contribute to avoid the formation and propagation of cracks [8]. Especially, when the fibers have high tensile strength relative to asphalt mixtures, they may improve the cohesive and tensile strength of bituminous mixtures [9]. Besides, fiber-reinforced asphalt concrete may have a good resistance to ageing, moisture damage and reflection cracking [10]. Finally, fibers may also prevent drain down of binder in asphalt mixtures [11], as finely dispersed fibers provide a high surface area per unit weight and act like filler materials.

Fibers in asphalt concrete have other applications, such as improving its electrical conductivity. For this, carbon fibers [12–14] and steel wool fibers [15] have been used. It is known that the electrical resistivity of asphalt concrete decreases with the amount of fibers. If an increasing mass of fibers is added to the aggregates–bitumen mixture, there is a point where these percolate, creating an electrically conductive path thought the material [12,15]. Electrically conductive asphalt may be used for de-icing purposes. When an electrical current "meets" the resistance of the material, its temperature will increase, due to the Joule effect [12,13]. Another application for electrically conductive asphalt is asphalt monitoring, because changes in the internal structure of

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the material may cause changes in its electrical conductivity [14]. Additionally, conductive asphalt concrete has also been developed as solar collector for the heating and cooling of adjacent buildings, as well as to keep the pavement free of ice [16]: these fibers increase also the thermal conductivity of the material, transporting heat and helping the pavement to be at a constant temperature.

The final application for electrically conductive asphalt concrete is asphalt induction-heating [17,18], which may be used for asphalt crack healing applications. The first prerequisite of induction heating is that the heated material must be electrically conductive. If this material is placed in the vicinity of an alternating magnetic field, an alternating current is induced in the fibers which heat thanks to the Joule principle [19]. This concept has been used for closing cracks in asphalt concrete [20,21], as it is well known that asphalt induction-healing rates increase with temperature [21].

This paper has been prepared in the frame of a research about the effect of induction-heating of dense asphalt concrete. For this reason, electrically conductive steel wool fibers have been mixed into the asphalt concrete. The addition of such fibers may influence the mechanical properties of the pavement material. However, it is not clear which is the optimum amount, length and diameter of fibers needed for not having a negative impact in the mixture. For this reason, the dispersion of steel wool fibers has been studied. To reach this objective, 25 different asphalt concrete mixtures, with the same aggregate gradation and amount of bitumen, but with two different average lengths of fibers, four different fiber contents and four different diameters of steel wool have been investigated.

2. Experimental method

2.1. Materials

A dense asphalt concrete mixture was used in this research. The dense aggregate gradation is shown in Table 1. The aggregates consisted of crushed basaltic material (size between 2 and 11 mm and density 2770 kg/m^3), crushed sand (size between 0.063 and 2 mm and density 2688 kg/m^3) and filler (size < 0.09 mm and density 2638 kg/m^3). The virgin bitumen used was 70/100 pen, obtained from Kuwait Petroleum, with density 1032 kg/m^3.

Additionally, steel wool fibers were added to the mixture. The material used in the steel wool was low-carbon steel, with density 7180 kg/m^3. These fibers had four different diameters, 0.02855 mm (Type 0000), 0.03642 mm (Type 00), 0.08389 mm (Type 1) and 0.15498 mm (Type 3) and two different initial lengths: short fibers, with approximately 2.5 mm average length and long fibers, with around 7 mm average length). Finally, four different amounts of fibers were used: 0%, 2%, 4% and 6%, by total volume of bitumen in the mixture (see Table 1).

Table 1
Composition of the dense asphalt mixture.

Sieve size (mm)	Aggregate weight % retained	Cumulative aggregate weight % retained	Weight (g)
11.2–8.0	15	15	2325
8.0–5.6	15	30	2325
5.6–4.0	10	40	1550
4.0–2.8	10	50	1550
2.8–2.0	10	60	1550
2.0–1.4	7	67	1085
1.4–1.0	6	73	930
1.0–0.5	9	82	1395
0.5–0.25	6	88	930
0.25–0.09	5	93	775
<0.063	7	100	1085
Bitumen 70/100	(% of weight of mixture)	5.6	868
Steel fibers (% volume of bitumen)	Length (mm)	Diameter (mm)	
2% Fibers		0.02855 (Type 0000)	132
4% Fibers	2.5 and 7	0.03642 (Type 00)	264
6% Fibers		0.08389 (Type 1)	396
		0.15498 (Type 3)	

In total 25 different types of mixtures were prepared. 24 with different original sizes, types and volumes of fibers, always maintaining the same mass of aggregates and bitumen, but changing the mass of fibers and one without steel fibers (reference mixture).

2.2. Test specimens preparation

The materials were mixed in a laboratory planetary mixer at a mixing speed of 312 rpm. Two mixture batches were prepared for each of the 25 asphalt concrete mixtures studied. The amount of material in each mixture was something more than 16 kg. Materials were heated to 160 °C before mixing. The raw materials were added to the bowl in the following order: first the bitumen and the fibers, then the coarse aggregates, then the sand and finally, the filler. Materials were mixed during approximately 5 min.

The first 16 kg batch was used to make cylindrical Marshall specimens with 10 cm diameter, approximately 6 cm height and exactly 1190 g of mass. Immediately after placing the mixture into the mould, they were heated to 140 °C and compacted with a Marshall hammer, applying 50 blows on each face of the specimens.

The second 16 kg batch was used for preparing asphalt concrete slabs. These slabs were compacted by using a pneumatic laboratory wheel compactor [22]. Before the compaction started, the specimen was subjected to a pre-compaction with a low tire pressure (0.1 MPa) and a low maximum wheel load (1 kN). The effective compaction of the rolling-wheel specimen was performed at higher tire pressure (0.6 MPa) and a constant wheel load (5 kN). After the compaction, both faces of the samples were polished until they reached a height of 5 cm. From this, blocks of 25×25 cm^2 were sawn.

2.3. Air void content

The air void content was calculated in a geometrical way. For that, the exact height and diameter of four cylindrical test specimens for each mixture were measured in order to calculate the bulk density of each specimen. Additionally, as the exact percentage of materials and their density for each mixture were known, the theoretical density without voids for each mixture was found. From this, the air voids percentage was calculated as:

$$\text{Air void content} = \left(1 - \frac{\rho_b}{\rho_t}\right) \cdot 100 \quad (1)$$

where ρ_b is the bulk density of the mixture, measured in kg/m^3, and ρ_t is the theoretical density of the mixture, without voids, measured in kg/m^3.

2.4. Length and diameter of steel fibers before and after Marshall compaction

The average length of 50 fibers, before the mixing process and extracted from each mixture containing fibers, was measured by taking photographs under an optical microscope and by measuring the individual fibers length with an image processing program (ImageJ). Fibers were obtained by solving the bitumen in toluene and by extracting them with a magnet. Moreover, the average diameter of the fibers was calculated from 12 individual fibers for each type.

2.5. Morphology of steel wool fibers

The surface aspect of the fibers was studied by using an Environmental Scan Microscope (ESEM XL30, FEG) available at the Empa facilities. Each batch of fibers was examined before mixing and after mixing and compacting.

2.6. Individual fibers tensile strength

The tensile strength of individual fibers was measured by using a screw-driven universal testing machine with computer control and equipped with a 10 kN load cell. After measuring their diameter, each individual fiber was glued at each end into a paper form with approximately 50 mm diameter (Fig. 1) and tested until breakage. The force resisted by the fibers was defined as the average value obtained from 12 fibers samples.

2.7. Measurements of fiber clusters

Fiber clusters in the mixtures were measured by taking photographs of both faces from the $25 \times 25 \times 5$ cm^3 slabs and by analysing the clusters with ImageJ. An example of one of the analysed pictures is represented in Fig. 2. The percentage of clusters in the mixture was calculated as:

$$\text{Percentage of clusters} = \frac{1}{2}\left(\frac{A_{c1}}{A_{p1}} + \frac{A_{c2}}{A_{p2}}\right) \quad (2)$$

where A_{c1} and A_{c2} are the area of clusters in the upper and the lower faces of the slab, measured in m^2, respectively and A_{p1} and A_{p2} are the areas of the upper and the lower faces of the slab measured in m^2, respectively.