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ORIGINAL ARTICLE

A parametric study on the influence of steel wool fibers in dense asphalt concrete

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Abstract Environmental conditions combined with traffic loads contribute to premature deterioration of asphalt concrete pavements, reducing their strength and durability over time. To improve it, fibers can be incorporated in the mixture. Additionally, electrically conductive fibers can be used for self-healing purposes. In this context, this paper evaluates the influence of flexible steel fibers (steel wool) on the mechanical and physical properties of dense asphalt concrete. With these purposes, 25 different mixtures, with the same aggregate gradation and amount of bitumen, but with two different fibers lengths, four different percentages, and four different diameters of steel wool have been considered. Additionally, the influence of fibers on test specimens with three different types of damage: water damage, salt water damage and ageing have been evaluated through particle loss tests. Moreover, the influence of different temperatures on the flexural strength of dense asphalt concrete with steel wool fibers has been studied. It was found that steel wool fibers do not significantly improve the mechanical properties and damage resistance of dense asphalt concrete. On the other hand, steel wool fibers can change the air void distribution of a mixture, and therefore even reduce its particle loss resistance. As a recommendation, it is indicated that, for induction heating purposes, short fibers, with big diameters should be used, since they do not seem to alter the original properties of dense asphalt concrete.

Keywords Asphalt concrete · Fibers · Clusters · Damage resistance · Particle loss · Flexural strength

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1 Introduction

Wearing and environmental conditions, combined with traffic loads contribute to premature deterioration of dense asphalt concrete pavements, reducing their strength and durability over time. Three of the main factors affecting durability of asphalt concrete mixtures are ageing [1], water damage [2] and thermal cracking. These factors may have a negative influence on the stiffness of bitumen and on the particle loss of asphalt concrete pavements [3]. Ageing happens due to the loss of volatile components and to the oxidation of bitumen during asphalt concrete lifetime [1]. Water damage occurs generally as ravelling or stripping, caused by water infiltration through the pavement structure [4] and is characterized by the loss of bond between the aggregates and the binder [5]. Additionally, thermal cracking is a common phenomenon in cold regions, and through these cracks water can ingress to the pavement structure [6]. Thermal cracking is associated with the contraction that the pavement suffers at low temperature, and happens when the induced thermal stress is higher than the tensile strength of asphalt concrete at that temperature [7].

It is well known that fibers can be mixed in asphalt concrete to improve its strength and fatigue properties, while increasing its ductility [8]. Moreover, fibers can change the viscoelasticity [9], dynamic modulus [10], creep compliance, rutting [11] and freeze–thaw resistance [12] of asphalt concrete. Furthermore, when the fibers have high tensile strength relative to the binder, they may improve the cohesive and tensile strength of asphalt concrete [13]. Besides, in [14] it is shown that a bad distribution of steel wool fibers can lead to a higher porosity in the asphalt concrete, which may reduce its durability. Moreover, fibers in asphalt concrete may have other applications, such as improving its electrical conductivity [15]: If an increasing mass of fibers is added to the mixture, there is a point when these percolate, creating an electrically conductive path through the material.

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 [16]. Another application for electrically conductive asphalt is self-monitoring, because changes in the internal structure of the material will cause changes in its electrical conductivity [17]. Additionally, conductive asphalt concrete has also been developed as solar collector for the heating and cooling of adjacent buildings, as well as for de-icing applications [18]. However, the final use of electrically conductive asphalt concrete is with self-healing purposes via induction heating [19, 20]. If this material is placed in the vicinity of an alternating magnetic field, an alternating current will be induced in the fibers and these will heat thanks to the Joule principle [21]. This concept has been used for closing cracks in asphalt concrete [22], as it is well known that asphalt healing rates increase with temperature [23].

This paper has been prepared within the frame of research about the effect of induction-heating of dense asphalt concrete. For this reason, electrically conductive steel wool fibers have been added to the mixture. In [14] it was shown that the addition of such fibers influences the mechanical properties of the pavement material. However, it is not clear if these fibers offer an improvement against moisture damage, or different temperature conditions. Moreover, it is not clear if asphalt concrete with steel wool fibers would suffer damage in a saline environment. Although there is a study on that topic [24], the conclusions were only focused on the influence of a saline environment on porous asphalt with fibers. Therefore, the objective of this paper is to evaluate the influence of steel fibers (steel wool), with different diameters and lengths, on the particle loss properties of dense asphalt concrete with three different types of damage: water damage, salt water damage and ageing. Moreover, the influence of different temperatures on the flexural strength of dense asphalt concrete with steel wool fibers has also been investigated.

2 Experimental method

2.1 Materials

A dense asphalt concrete mixture was used in this research. The dense aggregate size gradation is shown in Table 1. The aggregates consisted of crushed basaltic material (grain size between 2 and 11 mm and specific density 2,770 kg/m^3), crushed sand (grain size between 0.063 and 2 mm and specific density 2,688 kg/m^3), and filler (size < 0.063 mm and density 2,638 kg/m^3). The virgin bitumen used was 70/100 pen, with a density of 1,032 kg/m^3.

Additionally, steel wool fibers were added to the mixture. The material used in the steel wool was low-carbon steel, with a density of 7,180 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 roughly 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). In total, 25 different types of mixtures were prepared: 24 with different original sizes, types and volumes of fibers and 1 without steel fibers (reference mixture), always maintaining the same mass of aggregates and bitumen, but changing the mass of fibers.

Table 1 Composition of the dense asphalt mixture

Sieve size (mm)	Aggregate mass% retained	Cumulative aggregate mass% retained	Mass (g)
11.2–8.0	15	15	2,325
8.0–5.6	15	30	2,325
5.6–4.0	10	40	1,550
4.0–2.8	10	50	1,550
2.8–2.0	10	60	1,550
2.0–1.4	7	67	1,085
1.4–1.0	6	73	930
1.0–0.5	9	82	1,395
0.5–0.25	6	88	930
0.25–0.09	5	93	775
<0.063	7	100	1,085
Bitumen 70/100 (% of mass of mixture)	5.6		868
Steel fibers (% volume of Bitumen)	**Length (mm)**	**Diameter (mm)**	**Mass (g)**
2 % fibers	2.5 and 7	0.02855 (Type 0000); 0.03642 (Type 00); 0.08389 (Type 1) and 0.15498 (Type 3)	132
4 % fibers			264
6 % fibers			396

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, the sand and finally, the filler. Thus, all the materials were mixed during approximately 5 min.

The first 16 kg batch was used to make Marshall specimens of 10 cm diameter, approximately 6 cm in height and exactly 1,190 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. Before the compaction started, the mixture 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 and with the order to have smooth surfaces of the slabs, both faces of the specimens were polished by using a polishing machine and until they reached a height of 5 cm. From this, slabs of 25 × 25 cm^2 were sawn.

Finally, Marshall specimens were preconditioned in four different ways before testing, according to the following configuration:

Dry test Specimens were conditioned in a temperature-controlled room at a temperature of 20 °C during 24 h.

Water Firstly, test specimens were vacuum-saturated. Secondly, they were submerged in a 40 °C water bath for 120 h.

Salt water Firstly, test specimens were vacuum-saturated. Secondly, they were submerged in a 40 °C salt–water bath for 120 h. The salt content (sodium chloride) was 30 % by weight of water.

Ageing Test specimens were placed in an oven for 240 h at 85 °C of temperature.

2.3 Air void content

The air void content was calculated in a geometrical way by measuring the height and mass of four

Marshall specimens for each mixture and calculating the bulk density. Additionally, as the 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:

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

where ρ_b is the bulk density of the mixture and ρ_t is the theoretical density without voids of the mixture.

2.4 Length of steel fibers before and after Marshall compaction

The average length of 50 fibers, before and after 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®). The reason why 50 fibers were measured is because this is a statistically representative number. Fibers were obtained by dissolving 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 Measurements of fiber clusters

Fiber clusters in the mixtures were measured by taking photographs of both faces from the 25 × 25 × 5 cm^3 slabs and by analysing the clusters with ImageJ®. 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 areas of clusters in the upper and the lower faces of the slab, respectively and A_{p1} and A_{p2} are the areas of the upper and the lower faces of the slab, respectively.

2.6 X-ray microtomography

In order to have an insight of the microstructure of the fibers in the asphalt concrete, X-ray microtomography on different specimens has been employed. Hence, representative beams of 10 × 2 × 2 mm^3 were extracted from test specimens with 2 % of long fibers type 3 (0.15498 mm diameter) and with 2 % of long fibers type 00 (0.03642 mm diameter). The X-ray microtomography scans were executed at the micro computed tomography facility at Empa. The reconstructions of the fibers were prepared by segmenting the materials found in a specific volume, based on simple algorithm of thresholding. With this simple method, aggregates, fibers, bitumen and air voids could be readily separated. The softwares used for this reconstruction were ImageJ®, DeVIDE® and Meshlab®.

2.7 Particle loss resistance

Among main purposes of fibers in dense asphalt mixture would be to prevent damage in road pavements, especially ravelling or potholes. For this reason, particle loss resistance tests, also known as Cantabro test, were chosen to assess the effect of steel wool fibers on the particle loss properties of the mixture. Marshall specimens were conditioned at a temperature of 20 °C during 24 h, in the same temperature-controlled room where the test setup was installed. In this way, each specimen was subjected to 300 revolutions at 30 rpm in the steel drum without steel balls. The mass of the specimen before and after the test was noted, and the particle loss was calculated using Eq. (3). Finally, measurements were taken from three Marshall specimens according to each mixture and damage configuration (see Sect. 2.2). In total more than 300 specimens were tested.

$$\text{Particle loss} = \left(\frac{w_1 - w_2}{w_1}\right) \times 100 \quad (3)$$

where w_1 is the initial specimen mass and w_2 is the final specimen mass.

2.8 Flexural strength

Flexural strength of dense asphalt concrete specimens was measured by means of semi-circular bending tests. Semi-circular test specimens with 10 cm of diameter and 2 cm of thickness were cut from Marshall test specimens. Additionally, a notch in the test specimens was cut with a thickness of about 2 mm and a depth of about 10 mm; the notch was cut at the mid-point in the direction of the loading from the central axis of the specimen.

All tests were performed inside a temperature-controlled chamber at four different temperatures:

−20, −7, 7 and 20 °C. Prior to testing, test specimens were kept in the temperature-controlled chamber at the test temperature for 2 h, to prevent any temperature gradient within the specimens. The test setup for the semi-circular tests specimens consisted of two support rollers at the straight (bottom) edge and one loading roller at the mid-point of the semi-circular arch. The spacing between the two support rollers was 8 cm. The equipment used for testing was a universal servo-hydraulic Dynasphalt machine with capacity of 10 kN. The load test was of 1 kN applied upon specimen at a loading rate of 0.5 mm/min. In total more than 300 semi-circular specimens were tested.

2.9 Abbreviations and statistical analysis

In Table 2, abbreviations for the variables included in this study have been represented. In total, nine variables have been analysed. Three concerning the characteristics of the fibers: diameter, initial length and final length of the fibers. Three related to the volumetric properties of the mixtures: percentage of fibers in the mixture, air voids content and percentage of clusters. And three in relation to the mechanical properties of the mixtures: particle loss resistance, semi-circular flexural strength and maximum deformation. Moreover, in Table 3, data for all the mixtures analysed have been indicated and in Table 4 the Pearson's correlation coefficients between all the variables studied have been represented. This correlation coefficient has values between 0 and 1; 0 being no correlation at all and 1 a perfect correlation. As an indication, it can be said that when the Pearson's correlation coefficient ranges from 0 to 0.4 there is a low or very low correlation; from 0.4 to 0.7, there is a moderate correlation and from 0.7 to 1 there is a high or very high correlation. This table shows the relationships between all the variables studied in this paper. Finally, probability–probability plots (*P*–*P* plots) have been used to understand the statistical distribution of some particular cases.

3 Discussion and results

3.1 Physical properties of the mixtures

In Table 3, the average length of the fibers before and after mixing is shown. It can be observed that in the case of the long fibers, there is a reduction of more than six times in their original length. This is especially remarkable for fibers with 0.15498 mm, diameter in the cases where the average original length was 7.753 and 2.437 mm, respectively. However after mixing and Marshall compaction, the average length of the fibers was 1.981 mm for the long fibers and 1.894 mm for the short fibers. Additionally, it can be observed that the final length of the fibers after mixing and compacting increases with their diameter. For example, in the case of fibers which are initially short, the final length of those with 0.02855 mm diameter is 1.129 mm, while the final length of fibers with 0.15498 mm diameter is 1.894 mm. The reason for this is the higher tensile resistance of the larger diameter fibers. Moreover, in Table 4 it is statistically confirmed that the final length of the fibers is mostly influenced by their diameter.

During this study, it was observed that clusters of fibers appear during the mixing process. In Table 3, the percentage of clusters of fibers in the mixtures, after mixing and compacting is shown. When the fibers are initially long, the final amount of clusters is slightly higher than when fibers are initially short. The average percentage of clusters in the mixture for short fibers is 0.35 %, while the average percentage of clusters for long fibers is 0.41 %. Additionally, the amount of clusters grows with the percentage of fibers. It is remarkable that the highest amount of clusters appeared for fibers with 0.02855 mm diameter, while the minimum was for fibers with 0.15498 mm diameter. This was influenced by the total number of fibers in the mixture and was higher for the fibers with short diameter. Finally, it can be observed that the air void content in dense asphalt concrete increases with the number of clusters and that the percentage of clusters is highly dependent of the percentage of fibers in the mixture (see Table 4). Fibers can act to absorb bitumen and thus decrease the amount of effective binder in the mixture [14].

Furthermore, in Table 3 it can be seen that the lowest air voids content is obtained for the reference mixture, without fibers (1.51 % air void content). Additionally, mixtures with 2 % long fibers, with 0.15498 mm diameter have a much lower air void content than the rest of the mixtures with 2 % long fibers. This happened because, in the specific case when 2 % of fibers were used, there were more clusters of fibers in mixtures with long fibers than in

Table 2 Variables included in the parametric study

Variable used		Abbreviation	Unit
Classification	Name		
Characteristics of the fibers	Diameter of fibers	DF	mm
	Initial length of the fibers	IL	mm
	Final length of the fibers	FL	mm
Volumetric properties of the mixtures	Percentage of fibers	PF	%
	Air void content	AVC	%
	Percentage of clusters	PC	%
Mechanical properties of the mixtures	Particle loss	PL	%
	Semi-circular flexural strength	FS	kN
	Semi-circular max. deformation	MD	mm

Table 3 Characteristics of the fibers and properties of the mixtures studied

Fibers type	Characteristics of the fiber			Volumetric properties of the mixture			Mechanical properties of the mixture		
	DF (mm)	IL (mm)	FL (mm)	PF (%)	AVC (%)	PC (%)	PL (%)	FS (kN)	MD (mm)
Short	0.02855	2.777	1.129	2	2.010	0.000	3.049	1.394	1.462
				4	5.213	0.398	4.061	1.747	1.071
				6	8.120	0.862	8.659	2.101	0.769
	0.03642	1.999	1.155	2	1.881	0.112	4.830	2.192	2.147
				4	4.758	0.629	3.929	1.782	1.116
				6	7.212	0.668	4.432	2.083	0.819
	0.08389	2.275	1.679	2	2.347	0.081	3.416	1.705	1.279
				4	4.345	0.461	3.565	1.264	1.135
				6	5.665	0.471	3.427	1.926	1.256
	0.15498	2.435	1.894	2	1.980	0.050	4.209	2.139	1.660
				4	4.174	0.237	3.998	2.412	1.263
				6	5.685	0.282	3.129	1.631	1.352
Long	0.02855	6.211	1.001	2	5.866	0.243	8.966	2.672	0.738
				4	6.594	0.500	8.492	0.786	1.424
				6	8.003	0.700	10.327	3.008	0.596
	0.03642	6.146	1.198	2	5.818	0.250	9.868	2.908	0.642
				4	6.146	0.480	7.213	1.022	2.110
				6	6.519	0.472	5.289	2.136	1.261
	0.08389	7.233	1.456	2	3.386	0.186	4.161	1.007	1.959
				4	5.083	0.479	3.493	0.718	2.062
				6	6.110	0.543	3.023	1.950	1.431
	0.15498	7.753	1.981	2	2.287	0.178	3.499	1.804	1.533
				4	4.168	0.412	2.993	2.322	1.189
				6	5.883	0.467	2.302	1.319	2.166
Reference mixture				–	1.511	–	3.221	2.032	1.656

mixtures with short fibers. Additionally, in the cases where 4 % long fibers with 0.02855 mm diameter and 0.03642 mm diameter are used, the air void content is very similar to the corresponding cases where 2 % of fibers were applied. Besides, the air void content in all the mixtures with 6 % fibers was much higher than the

Table 4 Pearson coefficients for the relationship between the variables studied on dense asphalt concrete

	Characteristics of the fibers			Volumetric properties of the mixtures			Mechanical properties of the mixtures		
	DF	IL	FL	PF	AVC	PC	PL	FS	MD
Characteristics of the fibers									
DF	–								
IL	0.14	–							
FL	0.97	0.07	–						
Volumetric properties of the mixtures									
PF	0.00	0.00	0.00	–					
AVC	0.38	0.20	0.42	0.77	–				
PC	0.33	0.09	0.33	0.79	0.86	–			
Mechanical properties of the mixtures									
PL	0.59	0.17	0.66	0.03	0.54	0.30	–		
FS	0.07	0.11	0.10	0.03	0.16	0.03	0.41	–	
MD	0.34	0.23	0.33	0.19	0.46	0.35	0.49	0.67	–

air void content in the rest of the mixtures. This happened because the number of fibers in the mixture was very high. As a result, the specific surface of the fibers was also quite high (see Fig. 1a, b). In Table 4, it can also be seen that the air void content in case of 6 % fibers remained the same regardless of the length of fibers and did not change for fibers with maximum diameter above 0.08389 mm. As a conclusion, in Table 4, it can be observed that the air void content in the mixture depends mainly on the percentage of clusters of fibers in the mixture.

3.2 Mechanical properties of the mixtures in dry conditions and at 20 °C

In Table 3, the particle loss values of dense asphalt concrete are shown. Furthermore, in Fig. 3a, the relationship between the particle loss resistance of dense asphalt concrete with short and long fibers and the air void content of the mixtures has been represented. It can be observed that the particle loss percentage increases exponentially with the increase of the air void content in the mixture. Additionally, it has been found that dense asphalt concrete with 2 % of steel wool fibers shows higher particle loss than mixtures with 4 and 6 % of steel wool fibers. In short, steel wool fibers improve the particle loss resistance of dense asphalt concrete, but as the air void content increases with the volume of fibers, its beneficial effects are lost. The reason for the increase of the air void content is the growth of fiber clusters that happens with the increase in the number of fibers (see Table 3).

Besides, in Table 4, it can be observed that the factors that most affect the particle loss resistance in dense asphalt concrete are the fibers length and the fibers diameter. In Table 3, it can be observed that when the diameter of the fibers increases, the particle loss of dense asphalt concrete approaches to that of the reference mixture. Moreover, in Table 4 it can be seen that the air void content is a critical parameter influencing the particle loss of dense asphalt concrete. As it has been explained above, the air void content depends mainly on the percentage of fiber clusters in the mixture, which is also related to the fibers length, to the number of fibers in the mixture and to their diameter.

Moreover in Table 3, the ultimate flexural load resisted by dense asphalt concrete with different types of steel wool fibers, obtained by means of semi-circular specimen's tests and tested at 20 °C is shown. In this table, it can be observed that the diameter or the percentage of fibers in the mixture does not have a clear influence on the maximum flexural load resisted by the dense asphalt concrete. These points are confirmed by the data in Table 4. To support these conclusions, in Fig. 2a, the *P–P* plot of the specimen's flexural strength, using a normal distribution function, for all the mixtures studied has been represented. Moreover, in Fig. 2b the *P–P* plot of the specimen's flexural deformation, using a normal distribution function, for all the mixtures studied has been

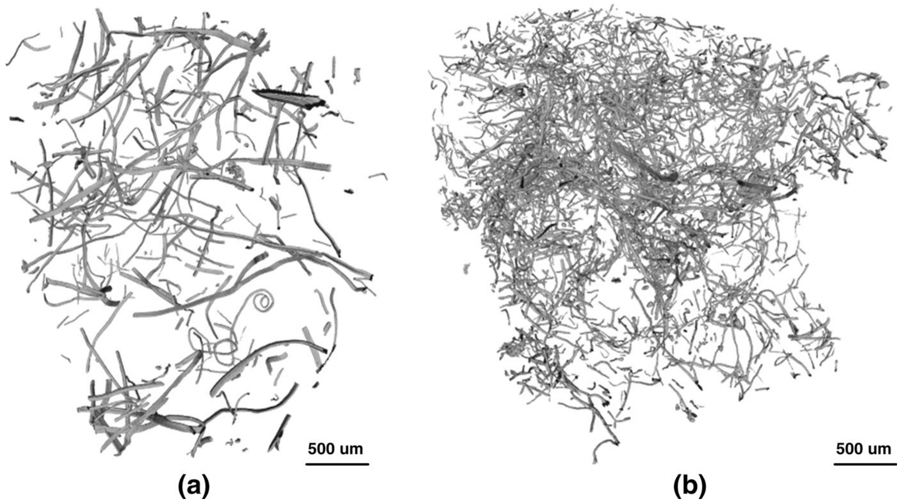

Fig. 1 CT-scan reconstructions of fibers distribution into the dense asphalt concrete with **a** 2 % of long fibers type 3 (0. 15498 mm diameter) and **b** 2 % of long fibers type 00 (0.03642 mm diameter)

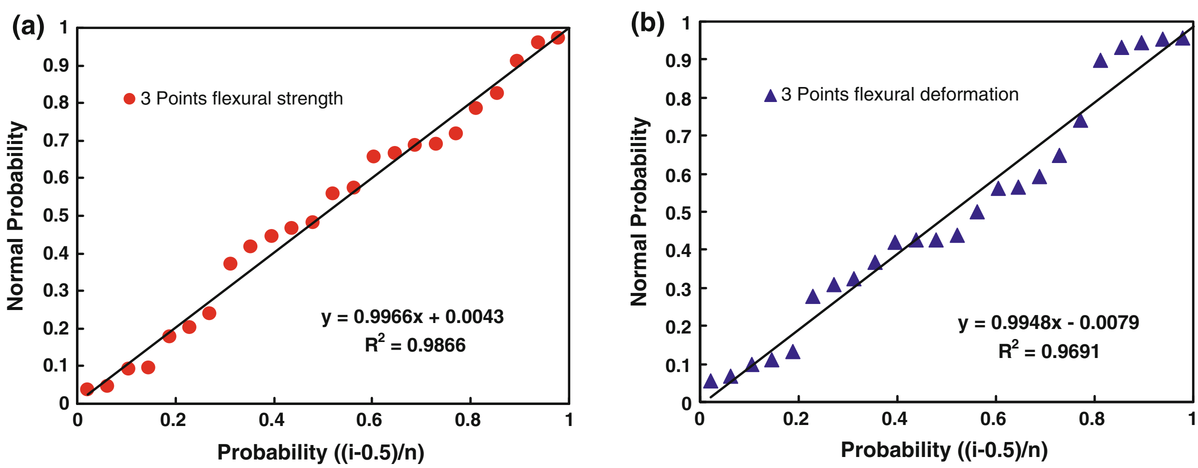

Fig. 2 *P–P* plot of **a** semi-circular flexural strength and **b** semi-circular maximum deformation of dense asphalt concrete

represented. In these figures, it can be observed that all the results align in a 1:1 straight line, which indicates that the fiber amount or diameter does not have a significant effect on the semi-circular flexural strength of dense asphalt concrete. Finally, the air void content or the amount of fiber clusters in the mixture have a low influence in the semi-circular flexural strength of dense asphalt concrete (see Table 4).

3.3 Influence of environmental conditions on dense asphalt concrete particle loss

In Fig. 3, the relationship between the particle loss resistance of dense asphalt concrete with short and long fibers and the air void content of the asphalt concrete mixtures after different preconditioned: water damage (Fig. 3b), salt water damage (Fig. 3c) and ageing (Fig. 3d) is presented. From Fig. 3 it can be concluded that the particle loss behaviour of dense asphalt concrete tested with fibers will change depending on the type of environmental damage that the material has suffered. In Fig. 3a, test specimens under dry conditions show a relatively higher particle loss resistance than the rest of the test specimens, preconditioned under different aggressive environments simulated in laboratory. For example, dense asphalt concrete, with 2 % fibers and 2 % air void content, under dry conditions, shows 3 % particle loss, while the particle loss is approximately 5.5, 3 and 3.5 % for water damage, salt water damage and ageing preconditions, respectively. Moreover, dense asphalt concrete, with 2 % fibers and 6 % air void content,

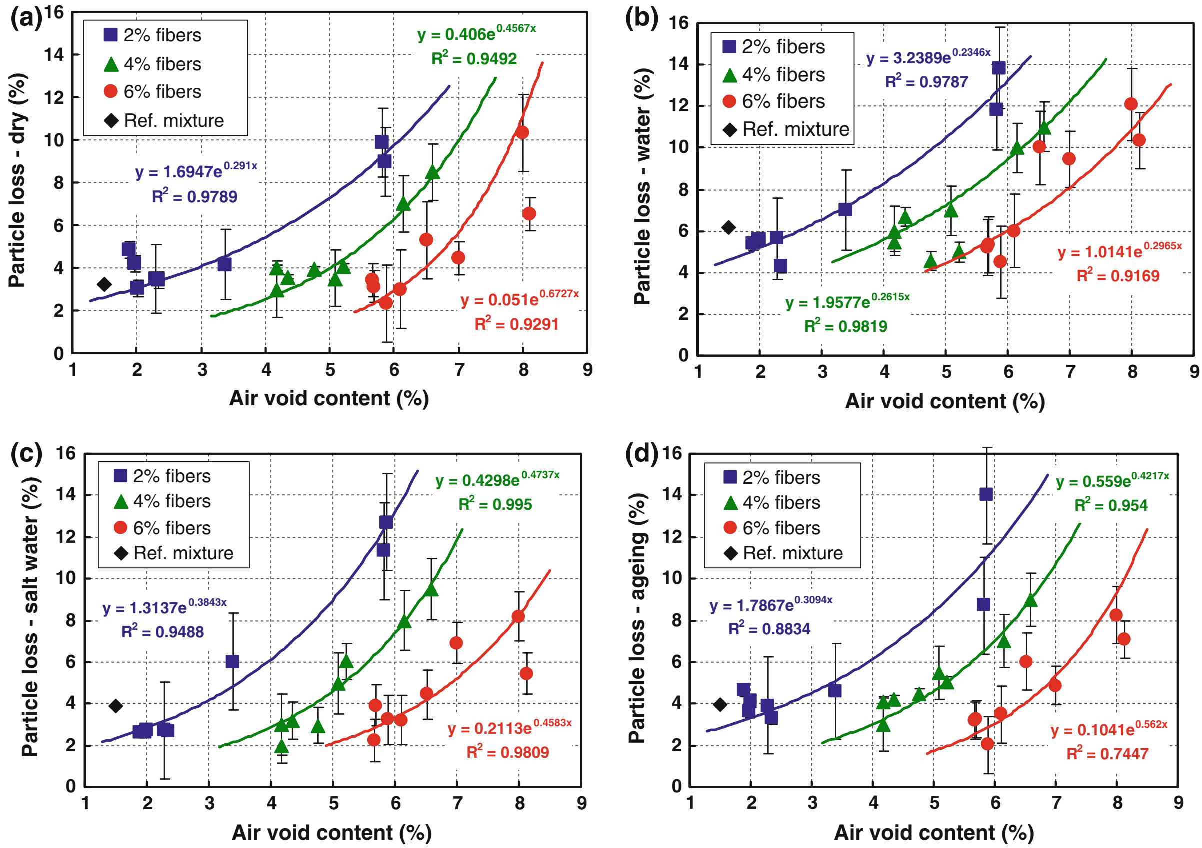

Fig. 3 Particle loss percentage of dense asphalt concrete test specimens versus their air void content for laboratory conditions: **a** dry, **b** water damage, **c** salt water damage, **d** ageing

Table 5 Average relationship DIF between particle loss of conditioned specimens and non-conditioned specimens

Damage type ratio	Short fibers	Long fibers	Average DFI (short + long fibers)
Water damage	1.508	1.647	1.578
Salt water damage	1.167	1.131	1.149
Ageing	1.074	1.105	1.090

shows 10 % particle loss, while the particle loss is approximately 11.5, 13 and 11.5 %, for water damage, salt water damage and ageing pre-conditions, respectively. Finally, as from these results it is unclear which type of pre-condition affects more particle loss resistance of dense asphalt concrete, a damage increase factor (DIF) has been calculated by making the relationships between the particle loss of pre-conditioned ($PL(\%)_{conditioned}$) and non-pre-conditioned ($PL(\%)_{non\text{-}conditioned}$) specimens with equivalent air void content:

$$DIF = \frac{PL(\%)_{conditioned}}{PL(\%)_{non-conditioned}}. \tag{4}$$

Moreover, to evaluate the damage increase caused by the pre-treatments, an average of the DIF values for all the mixtures has been calculated. The values obtained can be observed in Table 5. In this table, the data represent the DIF factor after the different pre-conditions. From these values it can be seen that damage is higher in mixtures with long fibers than in mixtures with short fibers. This happens because mixtures with long fibers presented a higher porosity: as it is well known, particle loss resistance increases with the air void content in the mixtures. Additionally, water damages asphalt concrete more than ageing or salt water (Average DIF 1.578). This happens because the contact angle between water and bitumen is

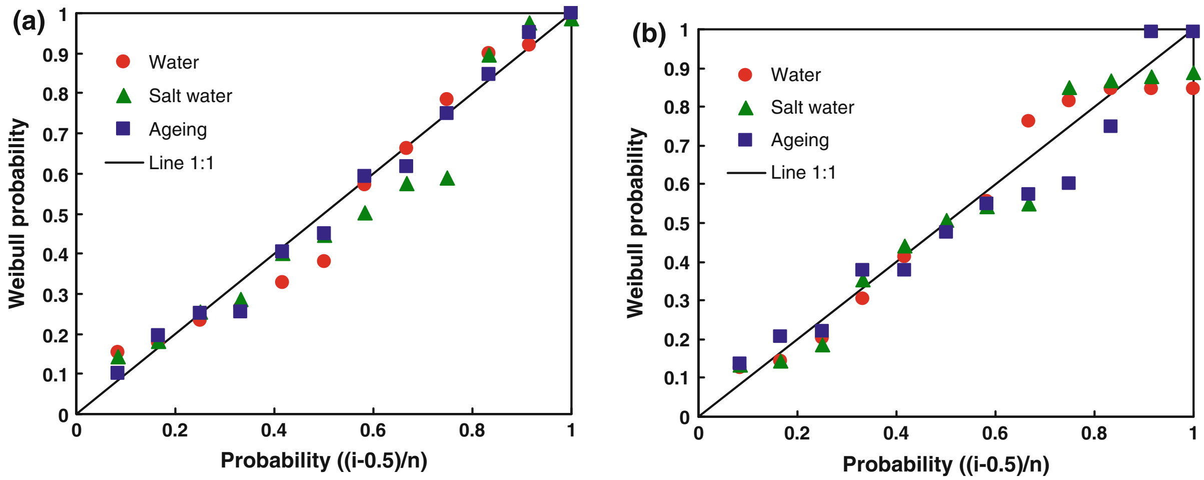

Fig. 4 *P–P* plot of the relationship between the particle loss of conditioned specimens and non-conditioned specimens for **a** mixtures with short fibers **b** mixtures with long fibers

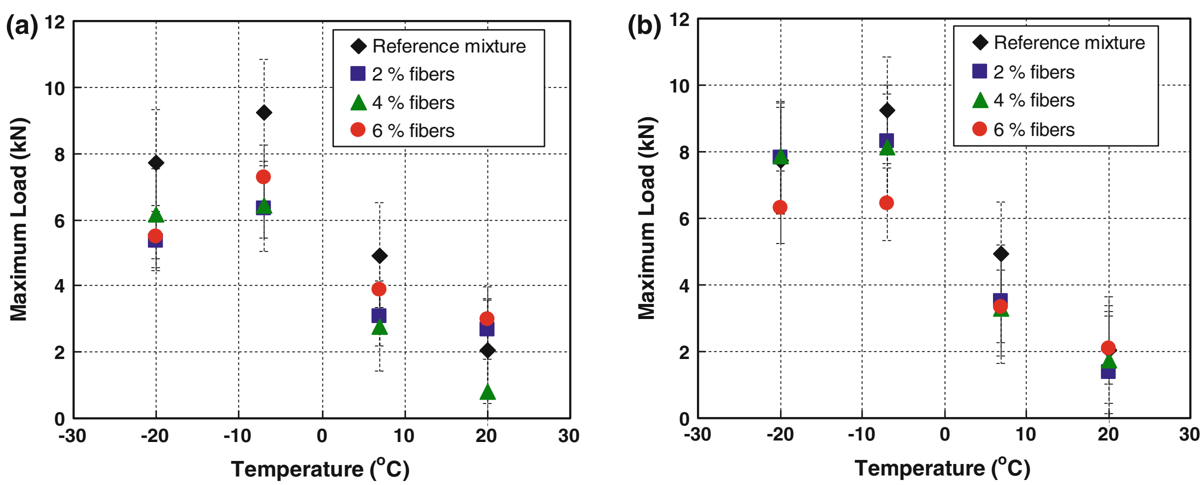

Fig. 5 Maximum flexural load resisted by semi-circular specimens of dense asphalt concrete at different temperatures in **a** mixtures with short fibers and **b** mixtures with long fibers

relatively small and water can penetrate in the interface between the binder and the aggregates, reducing the cohesion of asphalt concrete [25]. Moreover, in the case of the salt water pre-condition, the final damage levels were lower than in the case of water pre-condition (Average DIF 1.149). Although it is known that salt in water can decrease the contact angle between bitumen and aggregates [26], increasing the damage levels, in this case the high concentration of salt (30 %) served to decrease the oil–water viscosity ratio reducing damage penetration [27]. Finally, ageing is the pre-condition that shows a lower DIF (Average DIF 1.090). During the ageing process, the stiffness of dense asphalt concrete increased due to the oxidation and loss of volatiles of bitumen [28] and the binder became more prone to brittle fracture.

From these data it is still unclear if steel wool fibers in dense asphalt concrete can reduce the particle loss levels caused by environmental damage. For this reason, in Fig. 4, the Weibull probability of all the calculated DIFs has been calculated and presented against the data percentiles. The Weibull distribution function was chosen because the particle loss in dense asphalt concrete occurs due to the many small cracks that happen during each loading cycle. When impacts are repeated during the tests and due to the

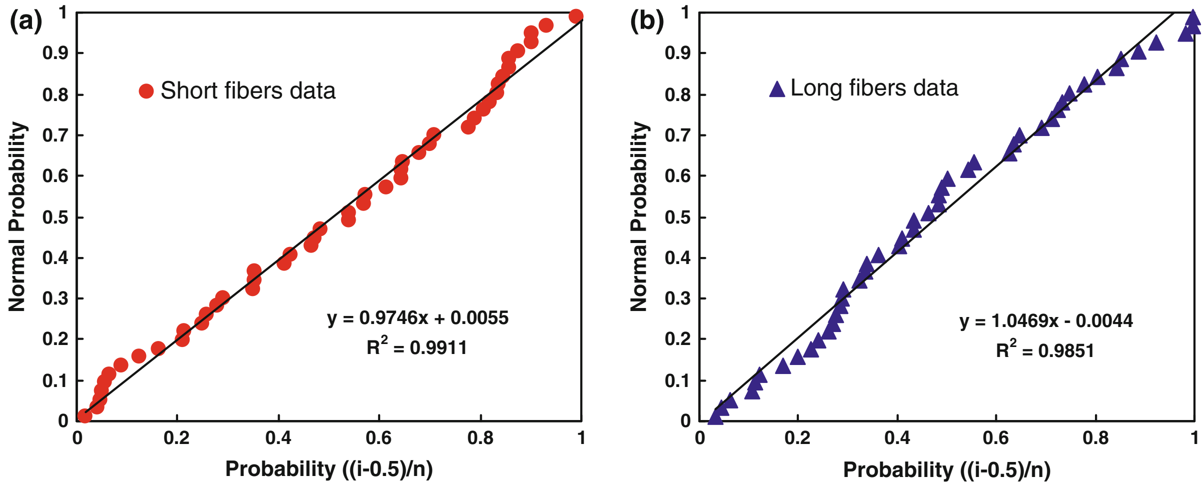

Fig. 6 *P–P* plot of the ratio between the flexural strength of the test specimens with steel wool fibers and the flexural strength of the reference mixture, at different temperatures, for **a** mixtures with short fibers and **b** mixtures with long fibers

accumulated damage, big cracks that separate the aggregates from the matrix can appear. In Fig. 4a, the *P–P* plot for short fibers is presented, while in Fig. 4b, the *P–P* plot for long fibers can be seen. In both figures, it can be observed that the relationship between the Weibull probability and the data percentiles is linear, for every pre-treatment applied. This means that the DIFs for each pre-treatment can be represented by a single Weibull distribution Function, and that the variability of this function happens due to the scatter, not to the amount or type of fibers in the mixture. For this reason, it can be affirmed that steel wool fibers do not contribute to improve the damage resistance of dense asphalt concrete to water, salt water or ageing of dense asphalt concrete.

3.4 Influence of steel wool on the temperature behaviour of dense asphalt concrete

Figure 5 shown the maximum flexural load resisted by semi-circular test specimens, with different percentages of fibers, initial lengths of the fibers and at different temperatures, from −20 to 20 °C. From these it is difficult to observe a clear difference between asphalt concrete materials with various percentages of fibers. Moreover, it can be seen that the maximum load resisted by dense asphalt concrete reduced with the increase of the temperature. The reason for this is the loss of viscosity that bitumen suffers when the temperature is increased, which results in a decrease in the cohesion of asphalt concrete. Moreover, it can be observed that there is a reduction in the maximum load resisted by the pavement when the temperature is lower than −7 °C. In previous researches [29], it has been found that the toughness of asphalt concrete increases from −5 to −15 °C and then decreases down to −30 °C. This is explained as the effect of internal damage due to differential thermal contraction, which is consequence of the large difference in the coefficients of thermal contraction between aggregate and the binder.

Moreover, to prove that the amount or type of fibers does not have an influence on the flexural strength of the mixture, independently of the test temperature, a ratio between the flexural strength of all the test specimens with steel wool fibers and the flexural strength of the reference mixture, tested at the same temperature as the materials with fibers, has been calculated (see Fig. 5). For reasons of clarity, these data have not been presented in the paper. To prove that the difference between them is due to the scatter, the normal probability of these values has been calculated and presented against the data percentiles in Fig. 6. Data from mixtures with short and long fibers have been separated because, as it has been explained above, they have different air void distribution. Results show that the data align in a straight line, with a 1:1 slope. This means that the differences in the flexural strength between test specimens with fibers and test specimens without fibers is due to statistical variations, and that, as it has been shown in Table 4, the diameter, the amount of fibers in the mixture or the temperature does not have a significant influence on the flexural strength of the mixture.

4 Conclusions

This research has served to quantify the effect of steel wool fibers on the volumetric and mechanical properties of dense asphalt concrete. For that, mixtures with different amounts of fibers, diameters and original lengths have been analysed. The properties that have been measured have been classified in three main groups: characteristics of the fibers, i.e., diameter, initial and final length; volumetric properties of the mixtures, i.e., the air void content or the percentage of clusters and, mechanical properties of the mixtures, which include the particle loss and the semi-circular load and deformation at 20 °C. Additionally, the particle loss resistance of dense asphalt concrete with steel wool fibers has been analysed after subjecting the material to three different types of environmental damage simulated under laboratory conditions: water, salt water and ageing. Finally, the semi-circular strength of dense asphalt concrete with steel wool fibers has been tested at different temperatures, from −20 to 20 °C.

During this research it has been found that the characteristics of the steel wool fibers change after mixing and compacting: their final length is reduced and it is independent of their original length. This suggest to the hypothesis that fibers suffer damage during the mixing process and as result they degrade and are break into pieces. The final length of the fibers in the mixture after mixing and compacting is proportional to their diameter.

Moreover, steel wool fibers have a strong impact on the volumetric characteristics of dense asphalt concrete; for example, the air voids content. The reason for this is that many clusters of fibers may appear during the first moments mixing. Clusters have a very high specific surface and work as “sponges” for bitumen, reducing the effective amount of bitumen in the mixture for coating the aggregates. In this paper, it can be observed that the percentage of clusters grows with the amount of fibers in the mixture, when the diameter of fibers is reduced and with the length of the fibers before mixing.

Furthermore, it has been found that the particle loss of dense asphalt concrete increases exponentially with the increase of the air void content in the mixture and that the percentage of steel wool fibers improve the particle loss resistance of dense asphalt concrete, but as the air void content increases with the volume of fibers in the mixture, its beneficial effects are lost. Additionally, it has been found that at 20 °C, the amount, diameter or length of fibers do not have any influence on the semi-circular flexural strength of dense asphalt concrete. Also, it has been observed that the air void content or the amount of clusters in the mixture have a relatively low influence on the semi-circular flexural strength.

In addition, in this research it could be observed that different pre-conditions, such as submerging the test specimens in water, in salt water or ageing them, cause different types of damage on dense asphalt mixture with steel wool fibers. It has been found that water is the factor that damages most dense asphalt concrete, followed by salt water and ageing. Besides, it has been concluded that steel wool fibers do not improve or worsen particle loss resistance of dense asphalt concrete to water, water with salt or ageing.

Moreover, it has been seen that dense asphalt concrete with steel wool fibers increases its flexural strength when the temperature is reduced, until it reaches a point between −7 and −20 °C, where the flexural strength starts decreasing. Moreover, it has been found that the amount or type of fibers do not have an influence on the flexural strength of the mixture, independently of the test temperature.

As a final conclusion, it can be said that the mechanical properties of asphalt concrete studied in this research are not improved by the use of steel wool fibers. Additionally, steel wool fibers can change the air void distribution of the mixture, and this may even harm its particle loss resistance. If steel wool fibers are to be used in asphalt mixtures, then shorter, larger diameter fibers should be used because they have less effect on the volumetric properties of the mixture.

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