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# Improvement of asphalt mixture performance with glass macro-fibers

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## HIGHLIGHTS

- Use of macrofibers to reinforce asphalt concrete.
- Studied of rutting and fracture performance of mixtures.
- Macrofibers improves the rutting performance.
- Macrofibers improves the asphalt concrete fracture behavior.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Cracking is a common failure in concrete asphalt mixtures due to fatigue and low temperatures. For centuries fibers have been used to reinforce materials and short and long fibers have extensive use in Portland cement concrete to control cracking and provide residual capacity. In the field of flexural pavements, fibers are commonly used in mixtures like stone mastic asphalt to increase the asphalt content that this mixture requires without binder drain down. Although many works show the reinforcement of asphalt mixtures with short fibers, there is a lack of information about the design and performance of asphalt mixtures incorporating macrofibers. This work explores the use of glass macrofibers in asphalt concrete mixtures. Improvements in fracture behavior at low to medium temperatures were found and macrofibers increased the first peak fracture stress and gave higher residual stress capacity. Additionally, rutting behavior was significantly improved by the addition of fibers reaching up to 50% reduction in permanent deformation with respect to mixtures without fibers.



## 1. Introduction

Fibers have been used for centuries to reinforce brittle materials and influence the cracking process by increasing toughness, tensile strength and durability. As an example, Fiber Reinforced Concrete (FRC) has been developed. Although asphalt concrete has a viscous elastic behavior at medium to high pavement temperatures, it performs as a brittle material at low temperatures.

In the pavements field, fibers have not been extensively used to reinforce asphalt concretes. Cellulose fibers with a large specific area are commonly used in mixtures like stone mastic asphalt (SMA) or porous asphalts to add a major percentage of asphalt that these mixtures require without binder drain down during the mixing and placement process [1–3].

Mahrez et al. [4] studied an SMA with glass microfibers finding improvements in dynamic modulus and fatigue behavior; they also

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found improvements in the rutting behavior of the mixture. The benefits of fibers in rutting improvement can be due to increases in the consistency of the mastic and lock mechanism between aggregates [5].

An interesting phenomenon was observed by Kutey et al. [6] while performing the Accelerated Loading Facility test. Asphalt concretes with polyester microfibers showed the presence of microcracks, but they do not progress or increase to a level of alligator crack patterns. In this case, as well as in FRC, fibers act like a bridge transferring stresses and limiting the growth of cracks.

Many investigations have reported improvements in behavior of Fiber Reinforced Asphalt Concretes (FRAC) [7–17]. However, all mentioned works refer to short fibers (length <25 mm). To the author's knowledge, no studies incorporating macrofibers (length >35 mm) are available. Additionally, it was observed that no design method exists for this type of FRAC mixture. The fibers are normally used in mortars and Portland cement concretes to control cracking and obtain residual load capacity in cracked states. The action mechanism and improvements of macrofibers in the field of asphalt concrete mixtures are still very much unknown. This work analyses the effects of fiber incorporation on the performance of asphalt mixtures regarding fracture response at low temperatures and rutting at high pavement service temperatures. Results from asphalt mixtures incorporating both micro and macro glass fibers are compared with those obtained on control asphalt concretes without fibers.

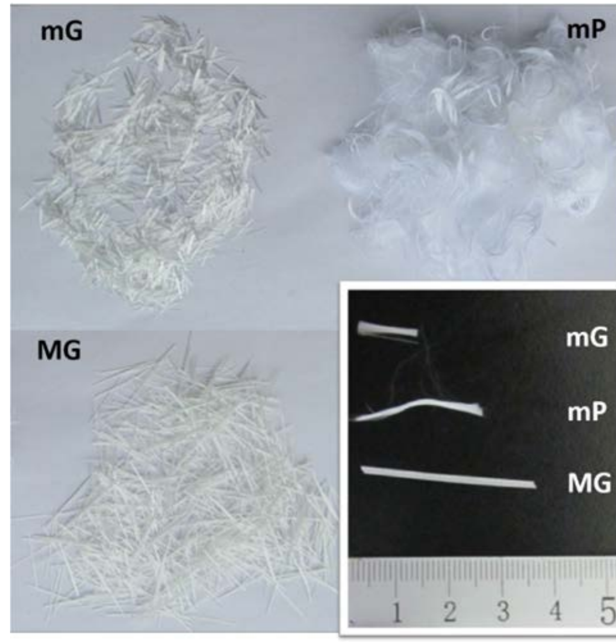


**Fig. 1.** Micro and macro fibers.

## 2. Experimental

Firstly, as a preliminary study, glass and polyester microfibers were incorporated into conventional asphalt concretes and their effect on the rutting (at 60 °C) and fracture performance (at temperatures <10 °C) was studied. With a novelty approach in a second phase, the same properties were analyzed on similar asphalt concretes where different dosages of glass macrofibers (54 mm in length) were incorporated; in addition, volumetric and mechanical properties of these FRACs were studied.

### 2.1. Materials and mixtures

The Fiber Reinforced Asphalt Concrete (FRAC) used in this study was developed from a common dense grade asphalt concrete. The base asphalt mixture was made using two fractions of coarse aggregates (6–20 mm and 6–12 mm), crushed sand (0–6 mm) and a conventional asphalt binder (CA30 Argentinian standard IRAM 6835; PG 64-16). Table 1 shows the mixture proportions and the asphalt binder characteristics. Fig. 1 shows the different fibers used in this work, and Table 2, their main properties.

The difference between micro and macro fibers is related to the maximum aggregate size and the interaction inside the asphalt mixture. Glass microfibers have a length shorter than the maximum aggregate size of the asphalt mixture. Its main influence is to modify mastic behavior. However, the glass macrofibers have a length that is longer than maximum aggregate size and is expected to influence the fracture behavior and crack propagation. The fibers act as a bridge in the cracks and transfer the stress. The polyester microfibers have a length similar to the maximum aggregate size, but because of its shape and rigidity, it is expected to affect the mastic behavior without improving the fracture behavior. In addition, these nomenclatures are the way manufacturers classify the fibers.

In the preliminary study, micro glass and polyester fibers (mG and mP) were incorporated at 0.4% of the weight of the mixture. For the main program, macro glass fibers (MG) were incorporated at different dosages (0.2, 0.4 and 0.6% of the weight of the mixture).

In all cases, the fibers were mixed with the hot aggregates for a minimum of 30 s to enhance fiber dispersion and then the asphalt binder was added while continuing to mix for nearly 2 additional minutes. For instance, Fig. 2 shows the distribution of the macrofibers (MG) during the mixing process.

A control mixture (C) was prepared to compare the performance of the different FRACs studied. The FRACs were labeled according to the type of fiber (mG, mP or MG) and the dosage of fiber (02, 04 or 06).

Asphalt concrete slabs (300 × 300 × 50 mm) were cast in each case to perform wheel tracking and notched beam bending tests as described in the next section. They were compacted with a roller compactor in accordance with the EN 12697-33. Marshall specimens were also produced for FRACs with macrofibers to compare

**Table 1**
Base asphalt concrete characteristics.

| | Coarse aggregate 16–20 mm | Coarse aggregate 26–12 mm | Crushed sand 0–6 mm | Asphalt binder |
|---|---|---|---|---|
| *Mixture proportions* | | | | |
| Weight % | 23.8 | 10.5 | 60.9 | 4.8 |

| | Viscosity at 60 °C [Pa.s] | Penetration [dmm] | Softening point [°C] |
|---|---|---|---|
| *Binder properties* | | | |
| CA-30 | 335 | 47 | 54.8 |

**Table 2**
Fiber properties.

| Fiber | | Microglass mG | Micropolyester mP | Macroglass MG |
|---|---|---|---|---|
| Length | [mm] | 12 | 25 | 36 |
| Aspect ratio | (l/ø) | 58 | 1250 | 67 |
| Density | [g/cm$^3$] | 2.68 | 1.34 | 2.68 |
| Tensile Strength | [MPa] | 1700 | 300–500 | 1700 |
| Modulus of elasticity | [GPa] | 72 | 10 | 72 |
| Softening point | [°C] | 860 | 250 | 860 |


**Fig. 2.** FRAC mixing. Fiber incorporation and mixture aspect.

volumetric and mechanical properties with those of the control mixture.

## 2.2. Test procedures

### 2.2.1. Marshall test

Marshall Samples were produced according to ASTM D6926 from C, MG02, MG04 and MG06, to analyze the effect of macrofibers in the volumetric and mechanical properties. The density (D), air voids (V), Stability (S) and Flow (F) were measured (ASTM D2726, ASTM D3203, ASTM D6927).

### 2.2.2. Wheel tracking test

The rutting performance was evaluated in the laboratory with the Wheel Tracking Test (WTT). The device is held in a chamber, Fig. 3, to maintain the sample at the required test temperature which represents a high pavement temperature. In this work, the temperature was 60 °C and at least two samples were tested for each asphalt concrete.

The test procedure was configured according to EN 12697-22 "small size device" standard. The rut depth was measured on the sample at one minute intervals through a LVDT. Each rut data point was the average of the 25 measurements taken on the central 100 mm of the sample wheel path. The collected data were used to obtain the curve of permanent deformation versus cycles and fitted with a potential model, Eq. (1).

$$Dn = a \cdot n^b \tag{1}$$

where Dn: permanent deformation, n: wheel cycles, and a and b: model constants.

Wheel tracking slope (WTS) and proportional rut depth (PRD), Eqs. (2) and (3) respectively, were calculated with the WTT results. WTS is calculated over a period of time that represents the shear resistance behavior of the mixture against rutting. This parameter is considered a better tool for characterization of the rutting performance of mixtures. The PRD was used as a comparative parameter.

$$WTS = \frac{D_{10000} - D_{5000}}{5} \left[\frac{mm}{10^3\ cycles}\right] \tag{2}$$

$$PRD = \frac{D_{10000}}{sample\,height}\ [\%] \tag{3}$$

where $D_{5000}$ y $D_{10000}$: permanent deformation at 5000 and 10000 cycles, respectively.

### 2.2.3. Notched beam bending test

Bending tests of notched beams are usually adopted to evaluate the fracture behavior of different mixtures. In these experiments, beams of 50 × 75 × 300 mm were cut from slabs of 50 × 300 × 300 mm. The beams were notched at the center; the depth of the notch (15 mm) was long enough to ensure adequate stress intensity at the notch tip to initiate a crack, but short enough to prevent crack initiation under self-weight [18]. A three point bending load configuration was used and the test was controlled with a clip gage that registered the crack mouth opening displacement (CMOD). A constant CMOD rate of 0.9 mm/min was used. Tests were performed at 0 and 10 °C in at least three samples for each temperature and mixture type. Fig. 4 shows the beams and a scheme of the test setup.


**Fig. 3.** Wheel Tracking device.

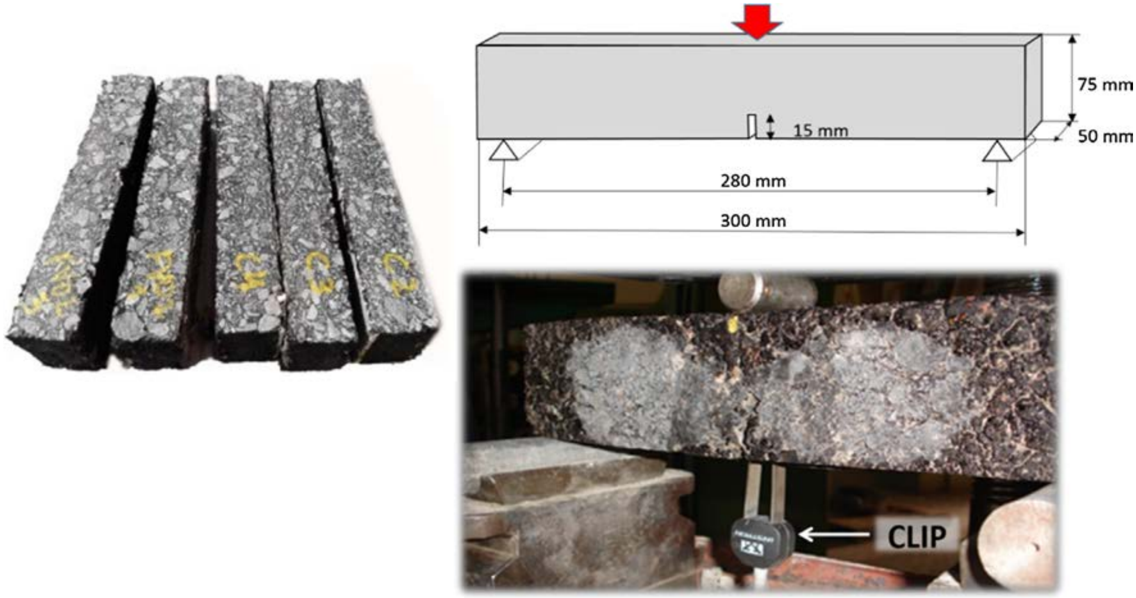


**Fig. 4.** Bending test of notched beam.

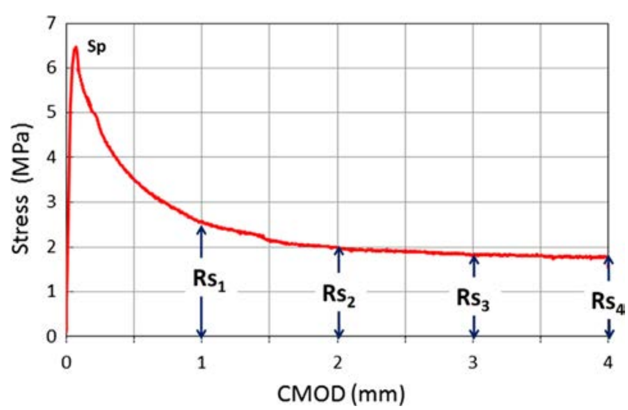


**Fig. 5.** Typical curve result of bending test.

A typical stress versus CMOD curve of a test can be seen in Fig. 5. As results, the peak stress (Sp) and four residual stresses (Rs) for CMOD of 1, 2, 3 and 4 mm ($Rs_1$, $Rs_2$, $Rs_3$ and $Rs_4$) were obtained. Residual stress is defined as the post peak tension that supports the material at a specific CMOD. It is related to the capacity to resist fracture of the material and still support loads. In addition, two toughness parameters ($T_1$, $T_3$) were calculated as the area under the stress-CMOD curve up to CMOD limits of 1 and 3 mm, respectively.

## 3. Results and discussion

The use of macrofibers for asphalt concrete reinforcement is a non-developed field. The main objective of this work was to explore the rutting and fracture performance of Fiber Reinforced Asphalt Concrete (FRAC), mainly incorporating macro glass fibers. Additionally, the use of microfibers and their possible improvements on mixture properties are studied and compared. It must be mentioned that the selected micro (glass or polyester) and macro fibers (glass) used in these exploratory experiments are designed for use in mortars and Portland cement concrete. Because of this, it is important to note that the fiber was developed to optimize its geometry (length, diameter), material (strength, modulus, elongation capacity) and adherence (shape, texture) to maximum its efficiency in both the fresh (incorporation in the mix process) and hardened (material performance) states. As a consequence, the results showed herein are promising and could possibly improve if fibers could be specifically developed for use in asphalt concrete mixtures. In the following section, the main results are shown and discussed.

### 3.1. Preliminary studies on FRACs incorporating microfibers

Rutting and fracture performance of FRACs with 0.4% glass (mG) and polyester (mP) micro fibers were studied. A control mixture (C) was also included as a reference.

Fig. 6 and Table 3 show the results of the wheel tracking tests. It can be seen that the incorporation of mG and mP improves the rutting behavior. In Table 3, a reduction in final deformation ($D_{10000}$) of 25 and 54% is observed for mG04 and mP04, respectively, when compared to C. The WTS and PRD parameters, normally used in the specifications to characterize the rutting requirements, also reflect this improvement. For example, in the Argentinian specifications [19], the limits of WTS and PRD are given and depend on the traffic

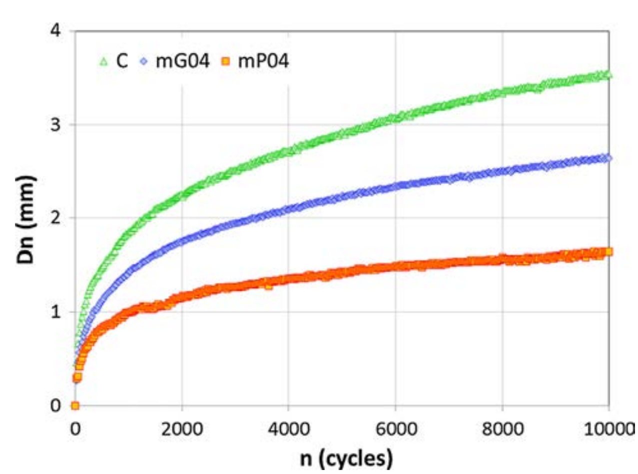


**Fig. 6.** Permanent deformation versus cycles for FRACs with microfibers.

**Table 3**
WTT result for FRAC with microfibers.

| | WTS (mm/$10^3$ ciclos) | PRD (%) | $D_{10000}$ (mm) |
|---|---|---|---|
| C | 0.132 | 7.0 | 3.58 |
| mG04 | 0.098 | 5.2 | 2.70 |
| mP04 | 0.050 | 3.2 | 1.66 |

**Table 4**
Wheel tracking limits for asphalt mixtures in Argentinian specification.

| Argentinian specification for Wheel Tracking Test (EN 12697-22 – B procedure)* | | | | |
|---|---|---|---|---|
| Position in pavement | Traffic level | | | |
| | T1 | T2 | T3 | T4 |
| Surface | WTS ≤ 0.08<br>PRD ≤ 5% | WTS ≤ 0.10<br>PRD ≤ 8% | WTS ≤ 0.12<br>PRD ≤ 7% | WTS ≤ 0.15<br>PRD ≤ 10% |
| Base | WTS ≤ 0.10<br>PRD ≤ 8% | WTS ≤ 0.12<br>PRD ≤ 10% | WTS ≤ 0.15<br>PRD ≤ 10% | WTS ≤ 0.15<br>PRD ≤ 10% |

T1 ≥ 1500, T2: 800–1499, T3: 200–799, T4 ≤ 199 (vehicles/day).
* Table taken from Ref. [19].

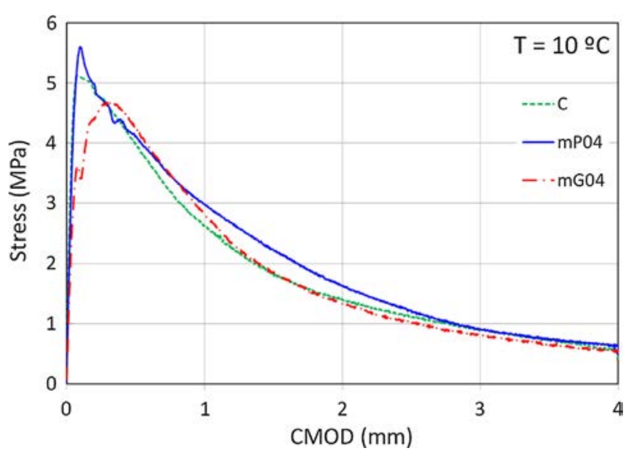


**Fig. 7.** Stress – CMOD curves of FRAC incorporating microfibers.

level (T1–T4) and the position of the mixture in the pavement (surface, base), see Table 4. According to these limits, C is a mixture which applies as a surface mixture for T4 traffic or as a base mixture for T3 traffic. The mG04 and mP04 mixtures can be used in more extreme conditions (higher traffic), such as surface mixtures for T2 and T1 traffic, respectively.

Fig. 7 shows examples of typical fracture test results obtained for C, mG04 and mP04 asphalt concretes tested at 10 °C. In general terms, the incorporation of microfibers does not change the fracture behavior at this temperature, with the toughness being similar for the three mixtures. Some reduction in the peak load appears in the case of these FRACs, which can be associated with a slight decrease in compactability. Although this behavior can be different at lower temperatures, and perhaps some effect of the presence of microfibers can appear, it can be inferred that the contribution of microfibers in the fracture performance is not very significant.

### *3.2. Study of glass macrofiber asphalt concrete*

With the purpose of observing the effect of macrofibers on asphalt concrete performance, Marshall, rutting and fracture tests were performed on mixtures MG02, MG04, MG06 and C (control).

Table 5 shows the mean values of density (D), Air Voids (V), Stability (S) and Flow (F) measured during the Marshall tests. It can be

**Table 5**
Volumetric and mechanical parameter of mixtures with macro fibers.

| | D [g/cm$^3$] | V [%] | S [kN] | F [mm] |
|---|---|---|---|---|
| C | 2.428 | 4.4 | 17.9 | 4.2 |
| MG02 | 2.411 | 4.5 | 19.4 | 5.0 |
| MG04 | 2.407 | 4.4 | 18.1 | 5.2 |
| MG06 | 2.390 | 5.6 | 19.3 | 5.9 |

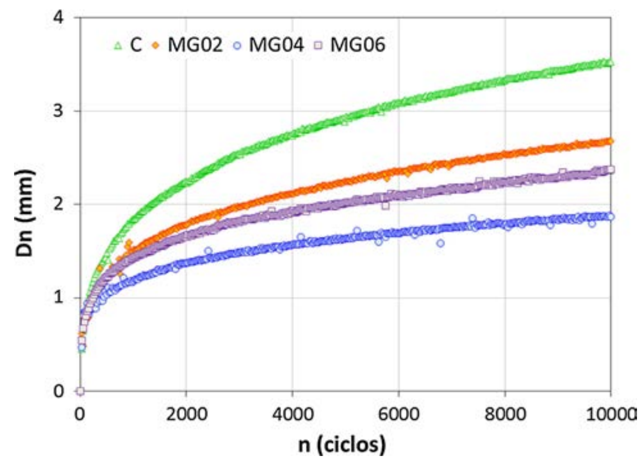


**Fig. 8.** Permanent deformation versus cycles for FRAC with glass macrofibers.

observed that the density of FRACs were lower than C and decreased as the dosage of fibers increased. This was expected because the design asphalt content of mixture C (4.8%) was kept constant. The long shape of the fibers affects the compactability of the mixtures since the asphalt content was not adjusted to account for their incorporation. Besides, the Marshall compaction method (with blows) affects the compactability of samples with fibers. Gyratory compaction would be a better method. It can be concluded that the FRAC design must include a definition of

**Table 6**
WTT result for FRAC with macro fibers.

| | WTS (mm/$10^3$ cycles) | PRD (%) | $D_{10000}$ (mm) |
|---|---|---|---|
| C | 0.132 | 7.0 | 3.58 |
| MG02 | 0.090 | 5.2 | 2.70 |
| MG04 | 0.047 | 3.7 | 1.87 |
| MG06 | 0.069 | 4.2 | 2.14 |

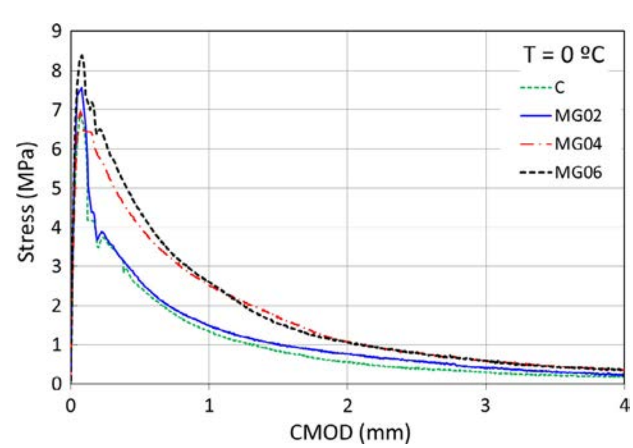


**Fig. 9.** Fracture test results for some samples of the studied mixtures at 0 °C.

optimum asphalt content; however this was not the main objective of this work. A proper design method for FRAC mixtures is not defined at the moment and represents a future challenge. From Table 5, it can also be observed that stability of the FRACs were in the same order as C, despite the lower densities. The flow values for the FRACs were a little higher than in C.

Fig. 8 shows the results of wheel tracking tests for FRAC with glass macrofibers in different dosages (MG02, MG04 and MG06). It can be observed that the incorporation of macrofibers had a positive effect in the reduction of rutting with respect to the control mixture (C). It can be seen that MG04 shows a better response to rutting than MG06. In this case, 0.4% of MG seems to be a more optimum fiber dosage for rutting improvement.

The parameters WTS, PRD and $D_{10000}$ calculated for the FRACs are given in Table 6. When comparing these results with the limits indicated in Table 4, it can be seen that all FRACs (MG02, MG04 and MG06) meet the specification for a surface mixture exposed to T1 traffic (the highest requirement), mainly MG04 and MG06. As said

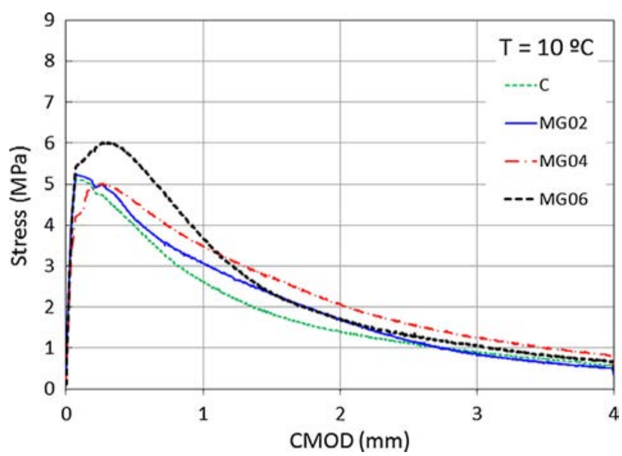


**Fig. 10.** Fracture test results for some samples of the studied mixtures at 10 °C.

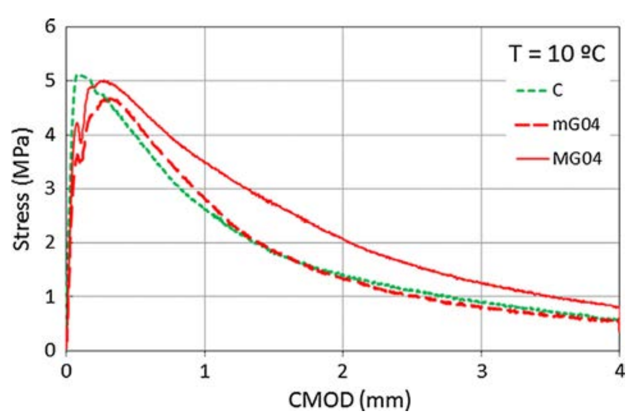


**Fig. 11.** Comparison of stress – CMOD curves of reference mixture without fibers (C), FRAC with micro glass fiber (mG04) and FRAC with macro glass fiber (MG04).

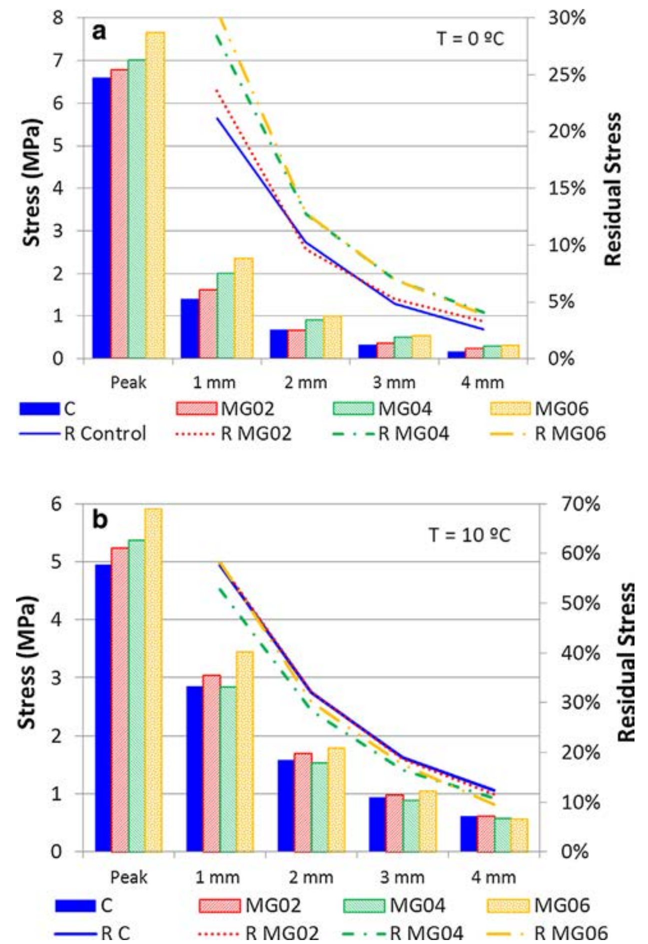


**Fig. 13.** Peak stress and residual stresses at different CMOD; a: T = 0 °C, b: T = 10 °C.

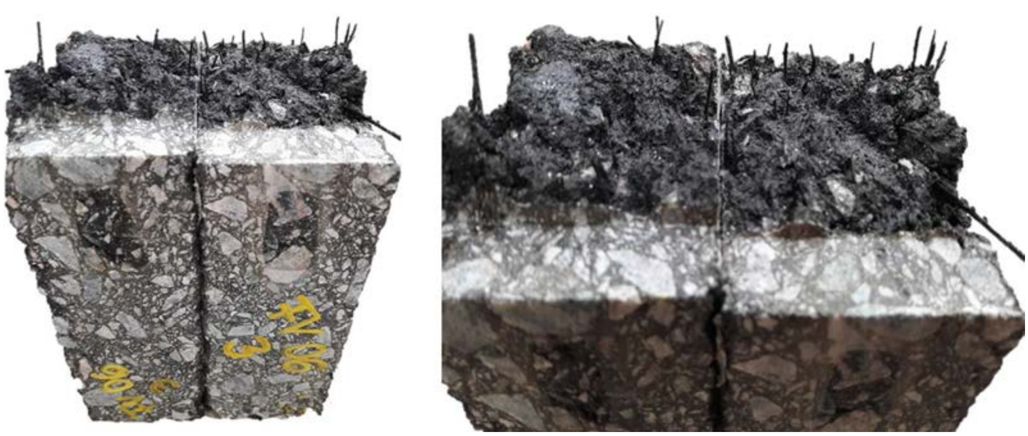

**Fig. 12.** View of fracture surface after bending tests.

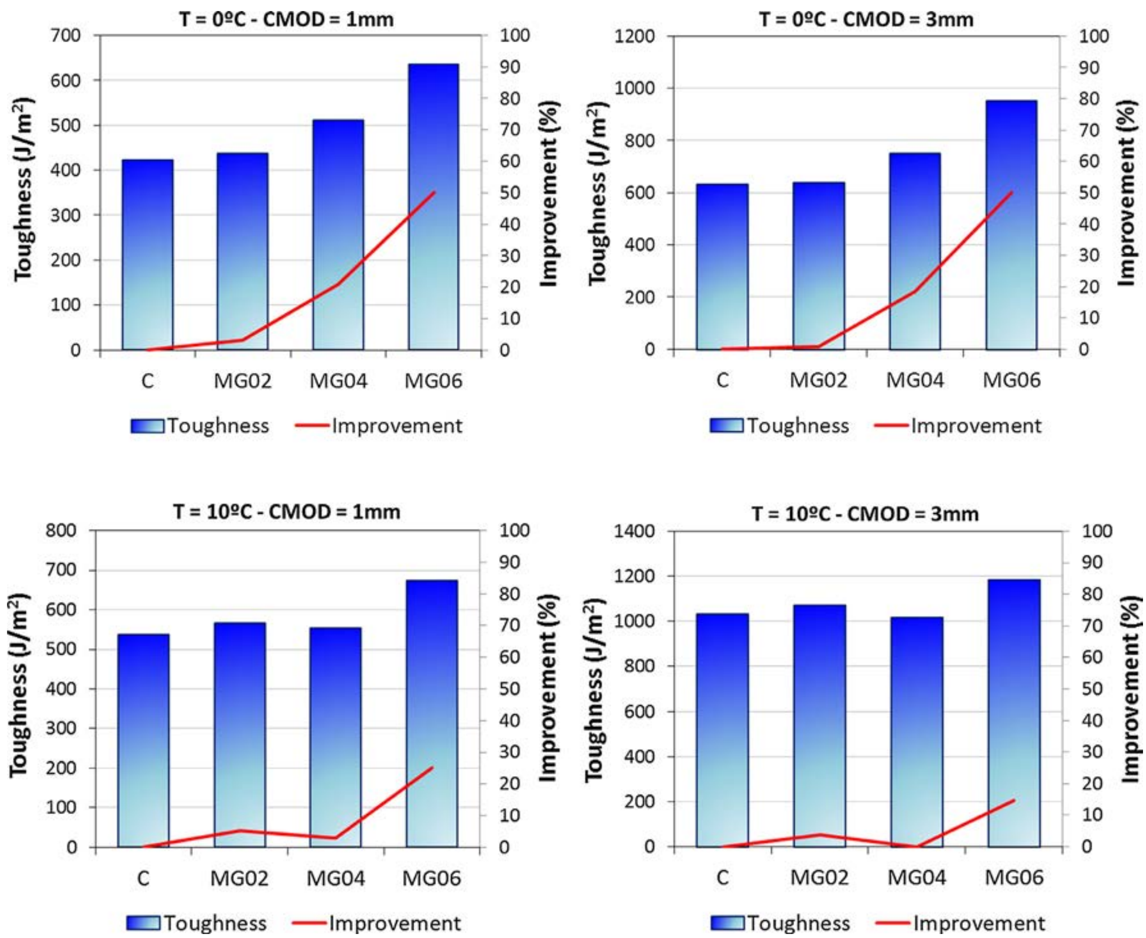


**Fig. 14.** Comparison of toughness of asphalt concretes obtained from bending tests.

before, C meets the criterion of a surface mixture with T4 traffic or a base mixture with T3 traffic. By comparing micro and macro glass fibers (compare Tables 3 and 6), it can be seen that mG04 had a similar response that MG02; however, it must be noted that the rutting performance of the FRAC incorporating 0.4% of polyester microfibers was better, and similar to those for MG04.

Figs. 9 and 10 show the results of fracture tests performed at 0 and 10 °C, respectively. In tests at 0 °C (Fig. 9), MG02 presents a behavior similar to that of C. However, MG04 and MG06 show a better fracture behavior with higher residual capacities after the peak stress. A higher residual capacity was observed for small CMOD (<1 mm) and then a very low residual stress for greater crack openings. It is not clear at the moment if this reduction is only due to adherence failure between the fibers and asphalt mastic, or if there are fiber breaks. A similar behavior was observed in tests performed at 10 °C (Fig. 10). The FRACs had a higher residual capacity than the C concrete, but on a smaller scale.

A comparison between micro and macro glass fibers at the same dosage can be seen in Fig. 11; MG04 improves the fracture behavior while mG04 does not.

After the bending tests, the beams were completely opened in order to analyze the fracture surfaces and the distribution of fibers. Fig. 12 shows the aspect of one sample of MG06.

Other positive aspects can be observed in Fig. 13; the residual stresses are expressed in absolute values and also as a percentage of the first peak. The incorporation of macrofibers increased the peak stress of asphalt concrete, for both temperatures, but the increases in residual stresses are more evident at lower temperatures. The C mixture had a more brittle behavior at the lower temperature with a drastic decrease in the post peak stress, while the FRACs showed higher stress values. For example, for a CMOD of 1 mm, the residual stresses of MG04 and MG06 almost doubled that of C.

From Fig. 13a (tests at 0 °C), it can be seen that the higher percentages in residual capacities correspond to MG04 and MG06. As expected, the differences are less significant in the tests performed at 10 °C.

Fig. 14 shows the calculated toughness parameters at 0 and 10 °C. Toughness was calculated as the area under the stress-CMOD curve up to CMOD limits of 1 and 3 mm. It was confirmed that the incorporation of macrofibers improves the fracture behavior; as the fiber dosage increases higher improvements of toughness appear. The improvements are greater at 0 °C, when the concrete asphalt has a more brittle behavior, and therefore, the fibers develop a more important role acting as a bridge once the crack occurs transferring the stress. As fiber dosage increased, the density of the fibers in the fracture section increased, and thus more fibers were working. The main failure mechanism that generated the reduction in residual stress for CMOD higher than 1 mm was related to fiber pull out because of a lack of adherence with the mastic.

## 4. Conclusions

The main objective of this work was to explore the possible improvements in asphalt concrete performance due to the incorporation of macrofibers. Fiber Reinforced Asphalt Concretes (FRACs) were produced, incorporating different dosages (0.2, 0.4 and 0.6% in weight) of glass macrofibers without optimizing the asphalt content. Additionally, two microfiber (glass and polyester) mixtures (in a single dosage of 0.4%) and a control mixture without fibers (C) were studied. The main conclusions are as follows.

The densities of FRACs with macrofibers were lower than those of mixture C. This is attributed to the fact that the asphalt content was not adjusted to account for the incorporation of the fibers. The behavior of FRACs could be improved by optimizing the asphalt content in the mixture design. The stabilities of the FRACs were along the same order as those for C despite the lower densities, whereas the flow values were a little higher than those for C. A proper design method for these types of mixtures should be developed.

The rutting behavior of the asphalt concretes was clearly improved by the addition of micro and macro fibers. Specification parameters such as Wheel Tracking Slope and Proportional Rut Depth, calculated from the wheel tracking test, showed important improvements in the FRACs with respect to the control mixture.

Glass macrofibers improved the fracture resistance of the asphalt concretes. In bending tests, fibers increased the maximum stress and gave residual stress capacity, especially for fiber dosages greater than of 0.4%. Greater improvements were found at the lower of the two temperatures studied (0 °C).

From the results obtained in this work, and in particular for these aggregates, asphalt binder and gradation, a glass macrofibers dosage of 0.4% in mixture weight seems to be an optimum dosage since this mixture obtained the maximum improvement when compared to the other glass macrofiber mixtures. It should be noted here again that the asphalt content was not optimized for these FRACs.

It is also important to note that the fibers used in these exploratory experiments are designed and employed for Portland cement mortars and concretes. Considering that fibers are optimized in their geometry, material properties and bond, in accordance to the matrix for maximum efficiency, the obtained results are promising and could possibly be improved by using macrofibers that are optimized for use in asphalt concrete.

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