# EXPERIMENTAL CHARACTERIZATION OF TRANSPARENT SYNTHETIC BINDER MIXES REINFORCED WITH CELLULOSE FIBRES

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## ABSTRACT

The use of synthetic binders in wearing course mixes allows to integrate road pavements into urban surroundings. In fact, the mixes prepared with this binder mitigate the visual impact that common asphalt materials produce, allowing a pavement coloration depending on the aggregate dyes to be obtained. In this paper, the characterization of open graded mixes prepared with a synthetic binder, reinforced or not with cellulose fibres, was performed. In particular, nine mixes, with different binder and cellulose fibre contents, were investigated through several laboratory tests to find the 'optimum' mix in terms of both mechanical performance and durability. The study of all mixes was performed in two steps. In the first step, traditional tests were carried out: Marshall, Indirect Tensile and Cantabro tests. Moreover, to investigate the water effect on these open graded mixes, the traditional tests were also performed on specimens immersed in water for 15 days, and the results were compared. In the second step, the same nine mixes were investigated in terms of rutting behaviour by using Wheel Tracker Machine, and stiffness modulus and fatigue strength through Nottingham Asphalt Tester (NAT). Finally, the comparison with a traditional open graded mix (with SBS hard bitumen) was performed showing higher laboratory performance for the synthetic binder mix. This paper shows that specific synthetic binder and cellulose fibre contents provide an 'optimum' open graded mix.
*Keywords: synthetic binder, cellulose fibres, mechanical characterization, open graded mix*

# 1. INTRODUCTION

Pavement painting or, alternatively, transparent synthetic binders are used in urban roads in order to mitigate the visual impact of the dark colour of traditional asphalt binders. Since synthetic binders provide good performance in road construction and assure longer durability than pavement painting, Road Management Authorities are interested in extending their use to open graded mixes also. This high air void content (≈15%) of the material, on the one hand, makes water flow easier from the pavement and ensures an adequate level of traffic noise absorption. On the other hand, it produces three significant disadvantages in the pavement: a shorter service life than traditional wearing course owing to pore obstruction caused by dust and dirt, structural weakening because of restricted inter-granular contact areas and a loss of adhesion between aggregates and bitumen due to the action of water in the thickness of the entire layer. In fact, it is well known that water damage produces rapid deterioration of the pavement. In particular, Kringos et al. (2005) showed, through a finite elements analysis simulating the gradual development of damage due to water permeation, that water damage is mainly dependent on the adsorption characteristics of the aggregate-mastic system and on the diffusion and dispersion characteristics of the mastic.

In order to obtain porous asphalt mixes that provide adequate performance, a correct choice of the gradation curve (mainly characterized by mono-granular material) has to be matched with the use of modified binders and, if necessary, of additives. Several investigations have been performed in order to study the influence of modified binders and fibres on open graded asphalts.

Patrick et al. (2003), through Cantabro tests, showed that specimens prepared with modified bitumens improved their resistance characteristics (that means lower weight loss) with the increase in the amount of polymers in the binder.

As far as traditional binders reinforced with fibres are concerned, several authors (Montepara 1993, Santagata E. 1993, Santagata E. 1997) have shown that the fibres, if used in a correct amount and with proper characteristics of diameter and length, are able to control diffusion and propagation, in the mastic, of micro-fractures that cause many cracks in asphalt concrete pavements. In particular, in correspondence to a defined binder and fibres content, an improvement in deformation behaviour in creep conditions has been achieved and in a range of temperatures between 0°C and 40°C, a reduction in viscous and viscous-plastic components of the binder has been shown, thanks to the so called ‘grid effect’. Moreover, the tenacity and hardness of the fibres seem to increase the absorption of the deformation energy and thus the ductility and durability of the pavement structure.

More recently, Mallick et al. (2000) showed that the addition of fibres in open-graded asphalt mixes provides an improvement in their performance in terms of resistance to abrasion and thus a decrease in water damage. In fact, in these mainly mono-granular mixes, the fibres guarantee higher consistency to the mastic preventing segregation and providing higher thickness of aggregate coating that increases pavement durability in terms of both water damage and dislodging of aggregates due to traffic action.

As far as the kind of fibres to reinforce the open graded mixes is concerned, Cooley et al. (2000), through laboratory and in situ tests, showed that cellulose and mineral fibres provide comparable performance. Moreover, they showed that trial sections prepared with non-modified binders but reinforced with cellulose fibres, provided higher permeability values than SBS hard bitumen mixes, positively highlighting that fibres do not absorb rainwater.

Considering the above-mentioned theoretical and experimental results and the finding that the rheological characteristics of a synthetic binder (Canestrari et al., 2003) approximate the properties of a traditional road bitumen, the reinforcement with fibres should be necessary to allow the use of synthetic binders in open graded asphalt mixes.

In order to investigate this aspect, the performance characterization of open graded asphalt mixes, prepared with a synthetic binder reinforced or not with cellulose fibres, has been carried out in this paper.

## 2. MATERIALS AND EXPERIMENTAL PROGRAM

Asphalt concrete specimens were prepared by using a transparent synthetic binder, rose granite aggregates and grey pure cellulose micro-fibres.

Binder characterization with traditional tests provided a penetration range between 75÷85 dmm and a softening point of 65°C. Since one of the main characteristics of this synthetic binder consists in its transparency so that the pavement coloration depends on the aggregate dye, a temperature not higher than 120°C must be used in order to preserve this peculiarity (Canestrari et al., 2003).

The rose granite aggregates are characterized by a density of 2.60 t/m$^3$ and a Los Angeles value of 25. The different gradation fractions are combined in order to obtain a highly porous mix that is compliant with the Italian Road Specification (CIRS, 2001) of the Ministry of Infrastructures and Transport. The gradation curve, shown in figure 1, was selected as the central curve between the two standard limits.

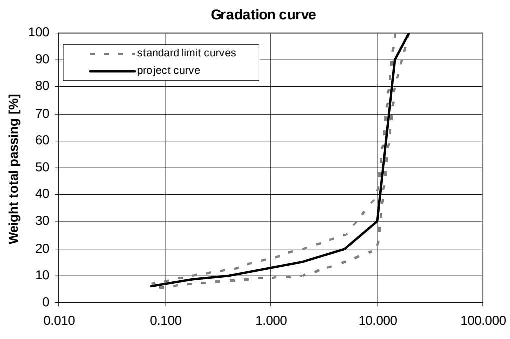



**Figure 1 Gradation curve**

The cellulose micro-fibres used have a density of 5 gr/cm$^3$ at 20°C and a length of 200-300 μm. They are usually available in capsules and are crushed in the mix plant during asphalt concrete production, thanks to the impact with the aggregates.

In this study, in order to obtain the right proportions of synthetic binder, aggregates and fibres, each single specimen was mixed in laboratory, so that it was necessary to crush the capsules of fibres in the Los Angeles Rattler and then sieve the obtained material with the 80 ASTM sieve.

Moreover, in order to assure the maximum dispersion of the fibres in the asphalt concrete mix, a preliminary investigation considering different procedures for mixing materials was necessary. In particular, it was observed that the preliminary combination of the fibres with the aggregates and the subsequent adding of binder is the most proper technique. As mentioned above, the chosen mixing temperature was 120°C in order to preserve the transparency of the synthetic binder.

In order to find the 'optimum' mix in terms of both mechanical performance and durability, three different binder contents (with respect to the weight of the aggregates) and three different fibres contents (with respect to the weight of the mix) were combined obtaining 9 different mixes. All of these mixes were subjected to the same tests according to the experimental program in table 1 in which the different compaction and test methods and the different influence parameters are shown.

**Table 1 Experimental program**

| | | | Traditional test investigation | | | | | | Performance test investigation | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Marshall Compactor (50+50 blows) | | | | Gyratory Comp. (50 gyr.) | | Roller Compactor | Gyratory Compactor (50 gyr.) | | | |
| Mix | Binder content [%] | Fibres content [%] | Marshall test | | Cantabro test | | Indirect Tensile | | Wheel Tracker (40°C) | Indirect Tensile Stiffness Modulus (20°C) | Indirect Tensile Fatigue Test (20°C) | | |
| | | | in air | 15 days in water | in air | 15 days in water | in air | 15 days in water | | | 150 kPa | 250 kPa | 350 kPa |
| 1 | 5.0 | 0.000 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 6 | 2 | 2 | 2 |
| 2 | | 0.063 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 6 | 2 | 2 | 2 |
| 3 | | 0.126 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 6 | 2 | 2 | 2 |
| 4 | 5.5 | 0.000 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 6 | 2 | 2 | 2 |
| 5 | | 0.063 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 6 | 2 | 2 | 2 |
| 6 | | 0.126 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 6 | 2 | 2 | 2 |
| 7 | 6.0 | 0.000 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 6 | 2 | 2 | 2 |
| 8 | | 0.063 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 6 | 2 | 2 | 2 |
| 9 | | 0.126 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 6 | 2 | 2 | 2 |

The whole experimental study was divided into two parts in which traditional and performance test investigations were carried out on all the above-mentioned 9 mixes. Both of these parts focused on the determination of the content of the binder and on the content of fibres that guarantee the best mechanical performance in terms both of resistance and durability as fixed by the Italian Road Specifications.

In order to achieve this aim, in the first step, Marshall compacted specimens were subjected to Marshall and Cantabro tests, whereas Gyratory Compactor specimens were subjected to Indirect Tensile tests (table 1). Moreover, since open graded mixes were considered, a water-effect investigation was performed repeating the same traditional tests after 15 days of water immersion. Two repetitions were considered for each test configuration (table 1).

In the second step, the rutting test and the evaluation of stiffness modulus and fatigue strength were performed. In particular, the rutting tests were carried out at 40°C with the Wheel Tracker Machine on asphalt concrete slabs prepared with a roller compactor.

The stiffness modulus and the fatigue strength tests were performed at 20°C on Gyratory Compactor specimens. As far as the Indirect Tensile Stiffness Modulus is concerned, 6 repetitions for each test configuration were considered, whereas 3 different stress levels (150, 250, 350 kPa) were applied to study fatigue behaviour, and 2 repetitions for each level were performed (table 1).

Moreover, in each tested specimen the air void content was measured, according to EN 12697 – 6 (Sealed specimen method), in order to check if the requested air void content (≈16%) was reached.

Finally, the performance investigation results were compared with a traditional open graded mix prepared with SBS hard bitumen.

# 3. TEST EQUIPMENT AND TEST PARAMETERS

## 3.1 Marshall test and Cantabro test

Marshall compactor specimens were prepared with 50 blows for each specimen base according to EN 12697-30, and then subjected to Marshall tests according to EN 12697-34. This test provides three fundamental parameters: Marshall Stability, Flowing and Stiffness.

The Cantabro test is considered a good indicator of the bonding properties between binder and aggregates and is usually used to evaluate the water effect on the abrasion resistance of a pavement. A Marshall compacted specimen was weighed before testing ($P_1$), at 25°C, and then placed in the Los Angeles Rattler, without steel balls. After 300 revolutions, at a speed of 30 to 33 rpm, the specimen was removed and its weight was again determined ($P_2$). The percentage material loss ($\Delta P$) was calculated according to the following equation (1):

$$\Delta P = \frac{P_1 - P_2}{P_1} \cdot 100 \qquad \text{(Eq. 1)}$$

## 3.2 Gyratory Compactor and Indirect Tensile test

Gyratory Compactor (GC) specimens were produced according to EN 12697-31 considering a diameter of 100 mm and applying 50 gyrations.

Indirect Tensile tests were performed on GC specimens obtaining Indirect Tensile Strength (ITS) that represents the pavement ability to resist traffic loads. All test parameters were compliant with EN 12697-23.

## 3.3 Roller Compactor and Wheel Tracker Machine

Roller Compactor slabs (305×305 $mm^2$) were produced according to EN 12697-33, setting a slab thickness of 40 mm. In this study, the material amount was selected to reach the air void content obtained in the Marshall and in the GC specimens (16%).

The rutting tests were performed with the Wheel Tracker Machine on Roller Compactor slabs, choosing testing parameters compliant with BS 598-110 (1998).

During the test, in order to evaluate the rutting behaviour, rut depth was plotted as function of time.

All slabs were conditioned 12 hours at 40°C before testing.

## 3.4 Indirect Tensile Stiffness Modulus and Fatigue Test

Indirect Tensile Stiffness Modulus *ITSM* (EN 12697-26) and Indirect Tensile Fatigue *ITF* (EN 12697-24) behaviour of the open graded mixes were studied by using the Nottingham Asphalt Tester (NAT).

The Stiffness Modulus was determined on two perpendicular diameters of GC specimens. Since 2 repetitions for each diameter were considered, each stiffness modulus was obtained as the mean value of 4 evaluations.

The specimens fatigue behaviour was studied through a control stress test applying 3 different stress levels for each mixture. The number of cycles which caused the reaching of 10 mm of vertical displacement or the physical failure of the specimen was considered as cycles to failure. The bi-logarithmic plotting of the maximum tensile stress as a function of the cycles to failure provides the fatigue laws for the tested mixes. The period of the repeated load was 1.5 sec and 2 repetitions were considered for each stress value. All specimens were conditioned 24 hours at 20°C before testing.

# 4. RESULTS AND DISCUSSION

## 4.1 Traditional test investigation

### *4.1.1 Marshall test*

Stability and Stiffness, obtained performing Marshall tests, were analyzed in this study in order to find the optimum content of synthetic binder and cellulose fibres.

As far as the Marshall stability is concerned, figure 2 shows that, in each test configuration, in both air and water immersion, the stability value is higher than the minimum (= 5 kN) fixed by the Italian Road Specifications (CIRS, 2001). Moreover, it is possible to observe that the presence of the fibres, regardless of their amount, improves the mixes characteristics in all binder content conditions (except in one case for 5% binder content – figure 2a) and curing situations. In particular, figure 2 shows that better stability results can be obtained for 5.5% of binder content and 0.126% of fibre content for both air and water immersion curing.

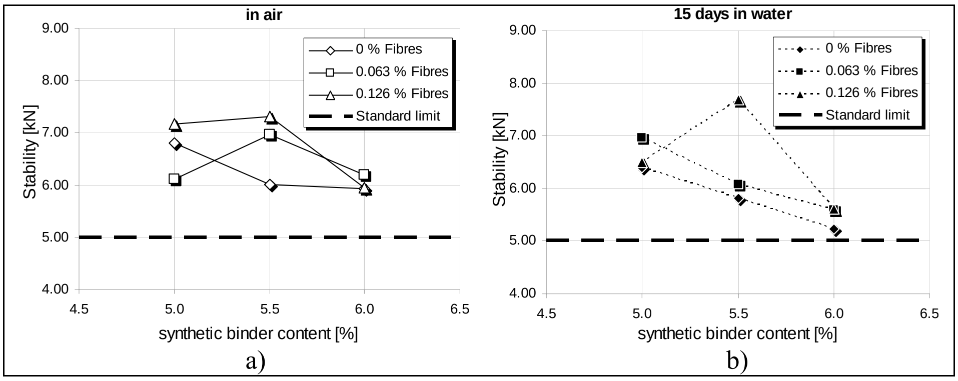



**Figure 2 Marshall Stability results**

As far as the Marshall stiffness is concerned, figure 3 shows that, after 15 days of water immersion, the stiffness values suffer a general decrease, for all synthetic binder and fibre contents. In particular, in both curing conditions, only 0.126% of fibres guarantees the overcoming of the minimum stiffness value (= 2 kN/mm, in dry conditions) fixed by the Italian Road Specifications (CIRS, 2001), except in one case. This behaviour can be explained considering the above-mentioned ‘grid effect’ performed by the fibres that control the micro-fracture propagation in the mastic, increasing stiffness of the mixes.

Highlighting that the Marshall test does not allow the evaluation of the contribution of the fibres in terms of performance behaviour, the combination of stability and stiffness results (figures 2-3) shows that open graded mixes with 5.5% of synthetic binder content and 0.126% of cellulose fibres content guarantee best results in terms of Marshall requirements.

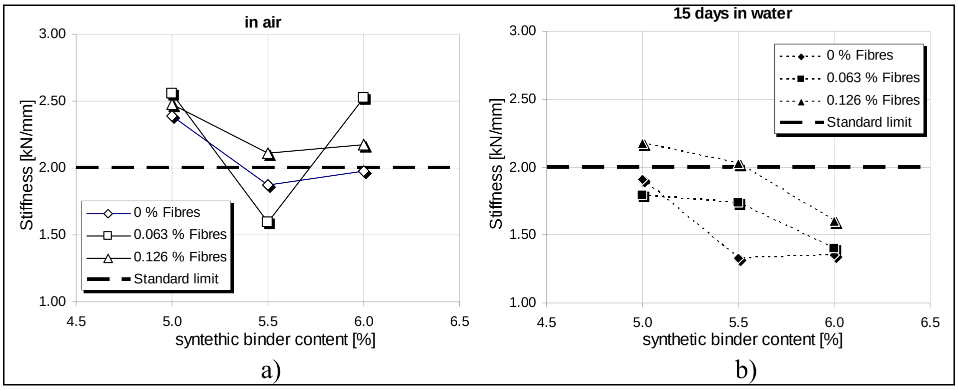



**Figure 3 Marshall stiffness results**

### *4.1.2 Indirect Tensile test*

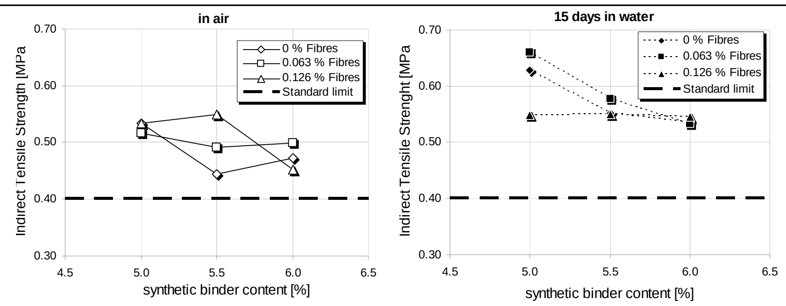
Indirect Tensile Strength ITS was considered to study the indirect tensile behaviour of the open graded mixes investigated.

Figure 4 shows that, in both air and water curing, Indirect Tensile Strength is higher than the minimum (= 0.4 MPa) fixed by the Italian Road Specification (CIRS, 2001). However, it is worth noting an apparently inconsistent behaviour because the indirect tensile strengths of specimens subjected to 15 days of water immersion are higher than those of non immersed specimens. This behaviour could be explained considering that, only in terms of indirect tensile test, the open graded mixes studied do not present moisture susceptibility, which makes it possible to assume that water immersion may provide improvements similar to those obtained with longer curing time.

As far as non immersed conditions are concerned, figure 4a shows that open graded mixes reinforced with 0.126% of fibres provide higher strengths when 5.5% of binder content is considered, whereas mixes with 0 e 0.063% of fibres provide higher strengths values when 5% of binder content is used. In fact, in this last condition, all mixes show analogous strengths for the three considered fibre contents.

After water immersion (figure 4b), a different behaviour for the mixes reinforced with the highest fibres amount (0.126%) with respect to the mixes with the other two amounts (0 and 0.063%) was observed. In particular, in the first case, when the binder content increases, an approximately constant ITS (close to the value achieved in the absence of immersion) was obtained, whereas for the two lower fibre contents (0 and the 0.063%), a decrease in indirect tensile strength was achieved. This different behaviour could be explained considering that water permeation has different effects in relation to the binder content. In fact, the combination of a low binder content (5%) and a high fibre amount (0.126%) could produce incomplete dispersion of the fibres in the mastic giving rise to water absorption effects. For higher binder contents (5.5 and 6%), the decrease in the strength, observed for low fibres amounts, was not suffered by the highest content (0.126%) probably thanks to the bigger dispersion of the fibres in the mastic, making the reinforcement action through the above-mentioned 'grid effect' easier.

As far as the Indirect Tensile investigation is concerned, open graded mixes with a synthetic binder content between 5÷5.5% and a cellulose fibre amount between 0.063÷0.126% guarantee maximum performance.



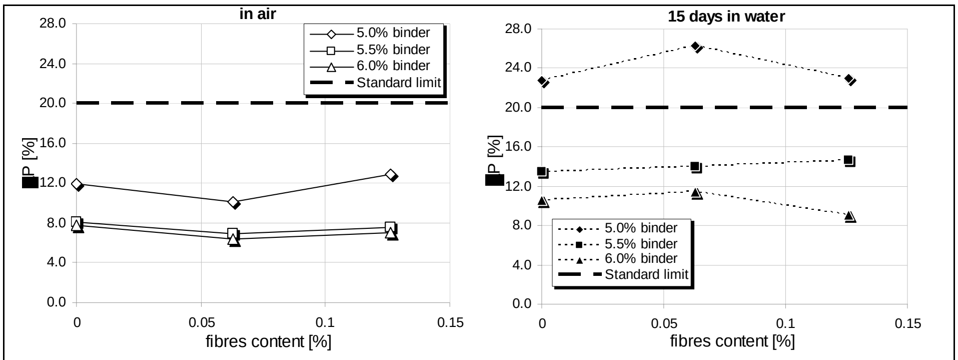

a) b)

**Figure 4 Indirect tensile Strength results**

*4.1.3 Cantabro test*

This test allows the study of the durability of the considered mixes in relation to binder and fibre contents, highlighting the effects of water immersion.

The percentage material loss (ΔP) seems not to be dependent on the fibre content (figure 5a) and is inversely related to the binder content (a decrease in binder produces an increase in ΔP). This trend is emphasized for water immersed specimens (figure 5b). In particular, open graded mixes with a binder content of 5% provided a percentage of material loss higher than the minimum recommended by the test protocols (= 20%), suggesting that this binder content is not enough to guarantee an adequate resistance against water action.




a) b)

**Figure 5 Cantabro test results**

Moreover, the percentage of material loss obtained in this study for 5.5% and 6% of synthetic binder content was compared with ΔP obtained during other investigations in which modified binders were used in open graded mixes (Patrick et al. 2003, Gubler et al. 2005) and analogous results were achieved. The same is also true when plain bitumen porous mixes reinforced with fibres were considered (Mallick et al, 2000).

## 4.2 Performance test investigation

*4.2.1 Rutting test*

As far as the rutting development and maximum rut depth are concerned, figure 6 shows that the mixes with the highest fibre content (0.126%) provide best (that means lowest) results in terms of rut depth, for each binder content. This is due to the 'grid effect' that a higher amount of fibres produces, offering resistance to visco-plastic deformations that the repeated traffic loads generate. It is worth noting that, in the range of the studied cases, the mix with 6% of synthetic binder and 0.126% of fibres content provided the lowest rut depth (figure 6c).

Moreover, figure 6d shows that a standard open graded mix prepared with a content of 5% of SBS hard bitumen provides higher rut depth and thus lower rutting performance than a porous asphalt mix with 0.126% of fibre content for all the considered synthetic binder contents.

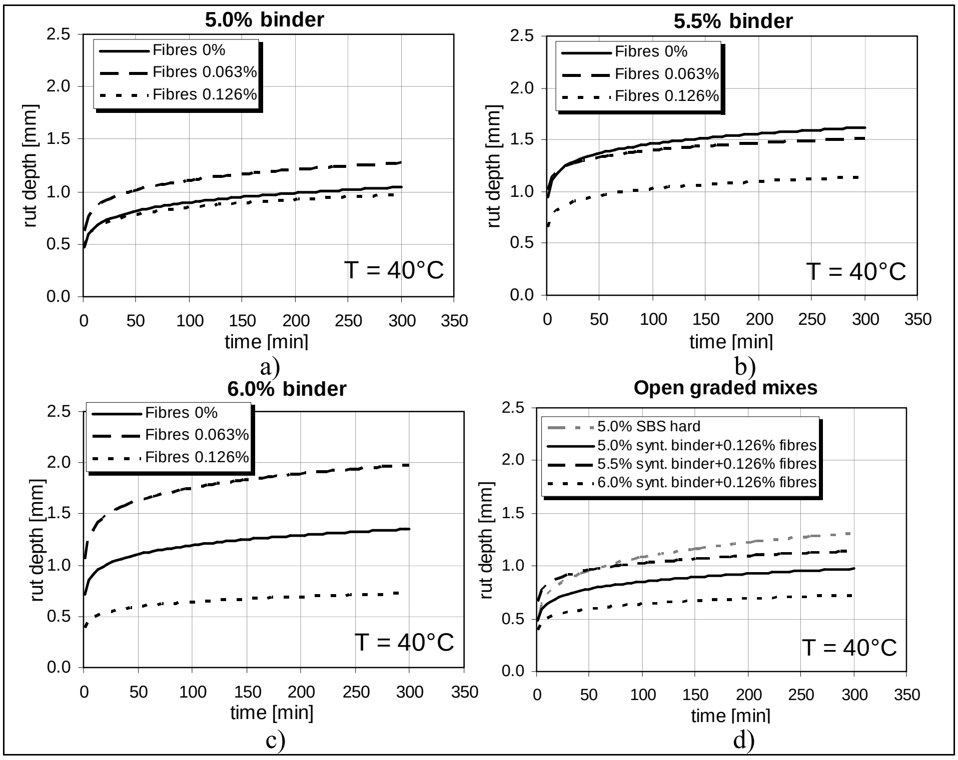



**Figure 6 Rutting test results**

*4.2.2 Indirect Tensile Stiffness Modulus test*

In figure 7, indirect tensile stiffness moduli, obtained as mean values of 6 repetitions, are represented for all test configurations. Figure 7 shows that the presence of fibres penalizes the mixes that have 5% of synthetic binder. In particular, the highest fibre content (0.126%) provides the lowest moduli for each binder content, whereas intermediate fibre amount (0.063%) guarantees the best performance for 5.5 and 6% of binder content. This behaviour could be explained considering that the lowest binder content is not able to ensure complete dispersion of the fibres in the mix and thus the improvement in the deformation characteristics of the mix through the above-mentioned 'grid effect' does not seem to be achieved. On the contrary, in terms of stiffness modulus, an excessive amount of synthetic binder (such as 6%) could produce, when mixed with fibres, a viscous mastic that is able to dissolve the beneficial effects of the fibres themselves.

As far as the comparison between the studied open graded synthetic binder mixes and a porous mix prepared with 5% of SBS hard bitumen is concerned, figure 7 shows that, when a fibre reinforcement was considered analogous results were found, whereas, in the absence of fibres, higher modulus values were obtained.

From this part of the study it was possible to conclude that open graded mixes with a synthetic binder content of 5.5% and a cellulose fibre amount of 0.063% guarantees best performance. Moreover, the obtained values of stiffness modulus are comparable or even higher than those of open graded mixes prepared with modified bitumen.

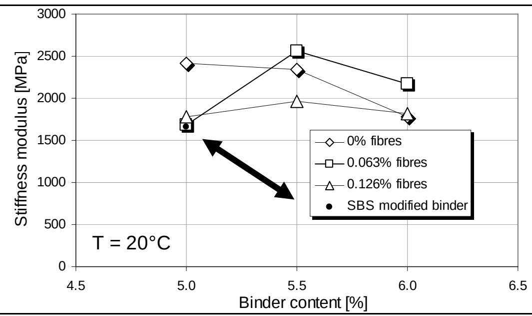



**Figure 7 Indirect Tensile Stiffness Modulus results**

*4.2.3 Indirect Tensile Fatigue test*

In order to study the fatigue behaviour of the investigated mixes, the fatigue curves were considered.

Figure 8a shows that different synthetic binder contents do not produce significant changes in indirect tensile fatigue strength.

As far as the fibre effect is concerned, figures 8b-c-d show that when the binder content increases, the presence of the fibres improves the mix fatigue characteristics. In particular, figure 8d shows that the mix with 6% of binder and 0.063% of fibres provides higher strength than the mix without fibre reinforcement, confirming the results obtained in the stiffness modulus investigation. Moreover, it is worth noting that with a 5.5% of synthetic binder (figure 8c), both mixes reinforced with fibres provide results very close to the mixes without fibres, highlighting that the fibres do not penalize the fatigue behaviour for this binder content. Moreover, figure 8d shows that the open graded mixes with 6% of synthetic binder provide strength not higher than 10% of a dense graded asphalt concrete for wearing courses in same experimental conditions. The reason for this behaviour could be found considering the theory of fracture mechanics according to which the presence of discontinuities and/or defects in the material, such as in open graded mixes, could produce stresses that are higher than the theoretical ones, computed considering the theory of the continuum. However, it is worth noting that the service life of a porous asphalt mainly depends on the loss of drainage characteristics rather than on fatigue cracking so that pore obstruction causes the end of pavement life.

Finally, figure 8e shows that the mix prepared with 6% of synthetic binder and 0.063% of cellulose fibres provides performance of one order of magnitude bigger than the above-mentioned open graded mix prepared with 5% of SBS hard bitumen.

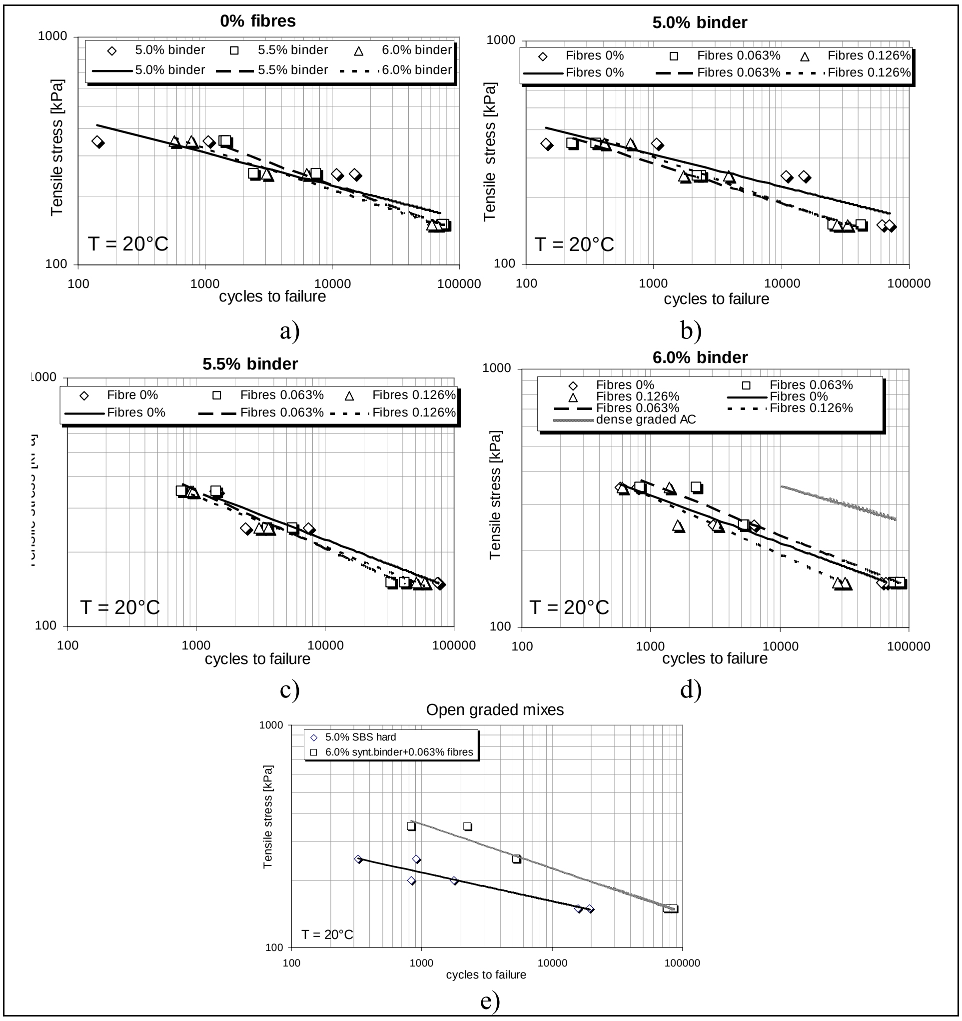



**Figure 8 Indirect Tensile Fatigue test results**

## 5. CONCLUSIONS

The interest to use the transparent synthetic binder to produce open graded mixes needs the study of the mechanical performance of these materials, considering different parameters.

In this experimental investigation, characterized by traditional and performance tests, 9 mixes, different in synthetic binder and fibre contents, were studied. It has been shown that there are valid grounds to use synthetic binders reinforced with fibres, in open graded mixes.

The main results, for different performed tests, can be summarized as follows:

- Marshall tests showed that the porous mix with 5.5% of synthetic binder reinforced with 0.126% of cellulose fibres assures the best behaviour in terms of both Marshall stability and Marshall stiffness. In particular, it was found that the highest fibre content (0.126%) is necessary in water immersion conditions;
- mixes with 5÷5.5% of binder content and 0.063÷0.126% of fibre amount provided the best results in terms of indirect tensile strength;
- Cantabro test showed that synthetic binder contents higher than 5% provide results analogous to those obtained for mixes with modified bitumen. On the contrary, a 5% synthetic binder content provides the highest percentage material loss;
- the best behaviour in terms of both rate of rut depth increase and absolute value of rut depth, at 40°C, is assured by the mix reinforced with 0.126% of fibres;
- the stiffness modulus investigation, performed at 20°C, showed that the presence of fibres needs high synthetic binder content (≥ 5,5%). Moreover, an excessive amount of fibres reduces the mix stiffness;
- indirect tensile fatigue test, performed at 20°C, showed that open graded mixes with synthetic binder provide strengths of one order of magnitude lower than traditional dense graded mixes. Moreover, also for fatigue tests, the presence of fibres needs high binder content (≥ 5,5%).

Following these results, it is clear that the best behaviour in terms of both traditional and performance tests is provided by the open graded mix with 5.5% (with respect to the weight of the aggregates) of synthetic binder reinforced with 0.126% (with respect to the weight of the mix) of cellulose fibres. The only exception to this finding is represented by the indirect tensile stiffness modulus results. However, the ‘optimum’ binder and fibre contents (5.5% and 0.126%, respectively) can not be considered completely adverse when the stiffness modulus is considered. In fact, the stiffness moduli obtained with 0.126% of fibres, for all binder contents, are comparable with those achieved with the other fibre amounts. Moreover, the highest fibre content provides the lowest range of variation of the stiffness moduli.

Finally, this experimental investigation shows that open graded mixes produced with synthetic binder and reinforced with fibres provide better performance than a porous mix prepared with an SBS hard bitumen.

Since this study showed a dependence of the performed tests on the analysed parameters (binder and fibre contents), it is worth noting that an in situ investigation is necessary. In particular, a trial section should be laid with different binder and fibre contents, in order to determine the most suitable test methods for the mix design of open graded mixes with synthetic binders.

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