FIBRA

Fostering the implementation of fibre-reinforced asphalt mixtures by ensuring its safe, optimized and cost-efficient use

Deliverable 3.1

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Braunschweig University of Technology

Braunschweig Pavement Engineering Centre (ISBS)

Empa, Swiss Federal Laboratories for Materials Science and Technology

CEDR Call 2018: Mechanical response of fibre-reinforced AC mixture and rheological properties of fibre-reinforced PA mortar

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Fostering the implementation of fibre-reinforced asphalt mixtures by ensuring its safe, optimized and cost-efficient use

Deliverable 3.1 – Mechanical response of fibre-reinforced mixtures (AC and PA) and rheological properties of fibre-reinforced PA mortar

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Executive summary

This report presents the first part of the experimental results obtained from WP3 of the FIBRA project. The work consists of two parts: the preparation and evaluation of fibre reinforced AC mixture, and the rheological properties of fibre reinforced PA mortar and influence factors. This deliverable D3.1 evaluates the suitable fibre type for AC mixture and PA mortar/mixture, respectively.

This deliverable is divided into five chapters:

- CHAPTER 1 briefly presents the motivation and framework of the study;
- CHAPTER 2 expounds the fibre reinforced mixtures and fibre reinforced PA mortar preparation procedure;
- CHAPTER 3 explains the testing plan for the entire set of bituminous materials;
- CHAPTER 4 discusses and analyses the experimental results;
- CHAPTER 5 summarizes the most relevant conclusions.

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1 Introduction

Asphalt mixture is the most widely used construction material for pavement world widely. This is confirmed by the fact that 90% of the entire pavement system in Europe, the U.S., and China consists of asphalt pavements. In the past decades, continuously increased traffic volume, environmental and economic demands induced the enhanced durability and fatigue resistance requirement for asphalt pavements. Different technology and attempt, such as fibre-reinforced asphalt mixtures (FRAM), have been conducted to overcome these issues.

In previous researches, plenty of efforts of FRAM were conducted on the conventional dense asphalt mixture. Results indicate that the FRAM can benefit the strengthen the viscoelasticity of bitumen which ultimately resulting in improved thermal cracking, fatigue, and rutting resistance of asphalt pavements. Besides the conventional dense asphalt mixture, the research and application of PA are getting more and more attractive by pavement institutions and researches recently. It can be attributed to the peculiar characteristics of PA are strictly associated with the environmental benefits and the increased driving safety that can be achieved when using such a paving material in comparison with the conventional asphalt mixtures. Numerous studies demonstrated the remarkable capability of porous asphalt in reducing the tire-pavement noise. This is assuming more and more importance in dense-populated cities especially for the residential area close to the road network. In addition, porous asphalt presents superior skid resistance offering a much safer driving experience as the occurrence of hydroplaning is substantially reduced compared to traditional paving materials. However, only limited researchers focused on the combination of PA and FRAM to improve the performance properties of asphalt pavement.

The objective of the FIBRA project is to overcome the technical barriers for the safety and cost-efficient implementation of FRAM with which an increasement of the performance properties of asphalt pavements, especially on the durability capability. A comprehensive literature review was conducted on the previous researches on the FRAM, in order to select the most promising fibres in (deliverable D2.1). Two different fibres, Type A (aramid) and Type P (polyacrylonitrile), were selected in this step, more detailed information is available in Chapter 2. In this current study, a preliminary study was carried out in the purpose to evaluate the suitable type of fibre for the conventional AC mixture and PA mixtures. For the fibre reinforced AC mixture, four different mixtures were prepared with a different type of bitumen and with/without fibres; then, several experimental tests were performed to evaluate the mechanical response of the fibre reinforced AC mixture. In the case of fibre reinforced PA mixture, the overall performance of PA mixtures reinforced with fibres was compared with the performance of a reference PA mixture without fibres; and asphalt mortar was also used for the experimental purpose since it plays a key role in the material response in terms of mechanical behavior. In order to evaluate the effect of different factors, distinct samples of asphalt mortars were prepared under different conditions, bitumen type, fibre type, and aging condition. The corresponding rheological tests were then conducted for a set of asphalt mortars in a wide range of temperatures. Some asphalt mortar samples were also broken under indirect tensile at different conditions to assess their fracture energy. In the following chapters, detailed information about the materials preparation, experimental work, the most relevant results, and analysis are illustrated.

2 Materials preparation

2.1 Types of fibres

In these empirical studies, two commercially available fibres, Type A and Type P, were selected to investigate the effect of their incorporation into conventional dense asphalt mixtures and porous asphalt mortar. Type A consists of a combination of aramid (A1) and polyolefins (A2) fibres of 19 mm length. The ratio of this blend of fibres is 1:7 (aramid: polyolefins). The other type is polyacrylonitrile fibres (type P) of 4 mm length and nominal diameter ca. 10 um. The basic properties includes thermal and chemical properties of these two fibres can be found in the deliverable D3.2. Figure 1 illustrates both types of fibres.

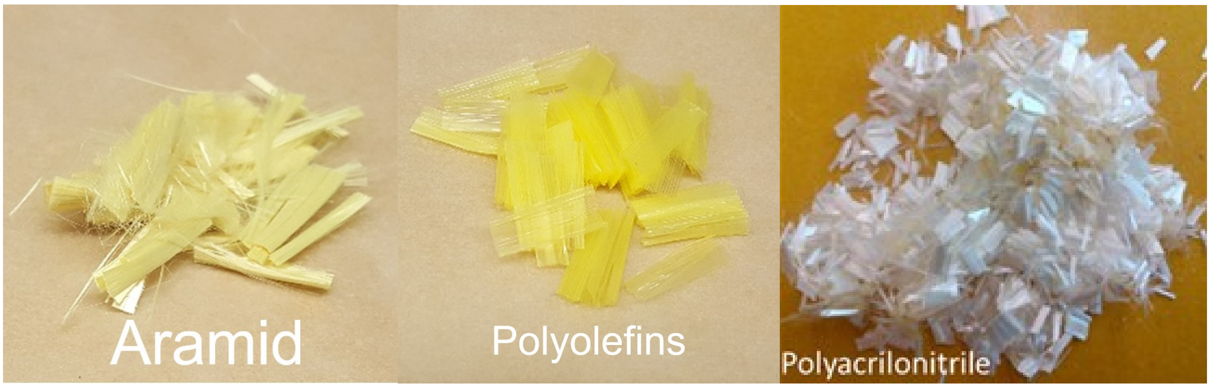


Figure 1. Different fibres used in this study: Type A (A1： left, A2: middle) and Type P (right).

2.2 Preparation of conventional mixtures

2.2.1 Asphalt Concrete (AC) mixture

As part of the experimental plan designed for the WP 3.1, four dense asphalt mixtures (AC B 22 H) were prepared and a number of specimens and slabs were compacted in order to evaluate their mechanical properties. Table 1 summarized the four different asphalt mixtures: one control mixture with polymer modified bitumen, one reference mixture with bitumen 50/70 and two fibre reinforced asphalt mixtures. Each fibre content was suggested by the manufacturers of the two fibres: fibre type A (0.05%) and type P (0.15%) by weight of the entire mixture.

Table 1. Dense asphalt mixtures (AC B 22 H) prepared for the WP3.

Name	Bitumen (4.2%)	Fibre
ACB22H - Control	PmB 45-80/65	-
ACB22H - Reference	50/70	-
ACB22H – Type P	50/70	P (0.15%)
ACB22H – Type A	50/70	A (0.05%)

Following the guidance of the fibres producers, the dry process was used to prepare the FRAMs, which means that no previous modification of the bitumen is done because the main content of the fibres is added directly with the aggregate fraction. Special protocol for mixing at lab scale was recommended for fibre Type A in order to improve the fibre distribution within the mixes. It was suggested that the aramid fibres (A1) were mixed previously with the pre-heated mineral aggregates whereas the polyoliefins fibres (A2) were added with the hot bitumen. The provider's protocol was later slightly adapted in order to ease the mixing procedure. First, the aramid fibre content was separated into two parts equally. Once the pre-heated (160°C) coarse aggregates were added to the mixer, one part of the aramid component (Figure 2a) was introduced. Afterwards, half of the content of fine aggregates plus the remaining content of aramid component (Figure 2b) were added to the mixer followed by the rest of fines on the top. Finally, the entire polyolefins component fibre were incorporated to the pre-heated bitumen (4.2%wt.) at 160ºC (Figure 2c) to immediately be poured into the mixer for a 2.5 minutes mixing process. Finally, a number of cylindrical specimens and slabs were compacted. In the case of Type P fibre, the entire fibre content was added to the preheated mineral aggregates before pouring the hot bitumen. For the reference and control asphalt mixtures which prepared without fibres, the conventional mixture procedures according to the European standards were followed. It should be noticed that, only fresh bitumen was used to prepare the AC mixture in this step.

Figure 2. Mixing procedure for AC mixture with fibre Type A: a (left), b (middle) and c (right).

2.2.2 Porous Asphalt (PA) mixture

As previously mentioned, Porous Asphalt (PA) is an environmentally friendly material and can enhance traffic safety. The overall performance of PA mixtures reinforced with fibres was evaluated and compared it with the performance of a reference PA mixture without fibres.

A total of eight different experimental mixes were designed in order to evaluate their mechanical properties. Conventional 50/70 penetration graded binder was employed and ophite and limestone was used as coarse and fine aggregates respectively. Additionally, the filler applied was limestone. The fibre content was the same for each mixture. Since the objective was to evaluate the reinforcement effect of fibres for comparative purposes, without considering their anti-drainage capacity, the binder content was fixed in 4.3% w/w, and two different filler contents were used in the mix (high and low). The fibres, as in the case of the AC, were applying by dry method using a similar procedure. Table 2 summarizes the experimental plan carried out in this section.

Table 2. Porous asphalt mixture designs

Mixture Design	Bitumen		Fibres			Filler
	Type	Dosage1*	Type	Length	Dosage1*	Dosage2*
Ref H	50/70	4.3	-	-	-	4.9
Type A / H	50/70	4.3	Aramid + Polyolefin	19	0.05	4.9
Type P-12 / H	50/70	4.3	polyacrylonitrile	12	0.05	4.9
Type P-4 / H	50/70	4.3	polyacrylonitrile	4	0.05	4.9
Ref L	50/70	4.3	-	-	-	4.3
Type A / L	50/70	4.3	Aramid + Polyolefin	19	0.05	4.3
Type P-12 / L	50/70	4.3	polyacrylonitrile	12	0.05	4.3
Type P-4 / L	50/70	4.3	polyacrylonitrile	4	0.05	4.3

* Dosage1: (% b/w of mix); Dosage2: (%b/w of agg.)

2.3 Preparation of Porous Asphalt (PA) mortar

2.3.1 PA mortar for rheological tests

In this study, 18 different types of mortars have been prepared in order to carry out the tests. Concerning the rheological tests, PA 8, based on the active German standard, was selected as the reference material to re-construct the corresponding asphalt mortar. Firstly, the gradation of related asphalt mortar is computed based on the calculation method from Underwood and Kim; asphalt mortar is defined as asphalt bitumen and fine aggregate particles smaller than 0.15 mm. Next, the asphalt bitumen (56.74% wt.), fine aggregate (7.89% wt.) (between 0.075 mm and 0.15 mm) and filler (35.37% wt.) (smaller than 0.075 mm) were prepared. According to the German standard, only the PmB 40/100-65 pen-graded bitumen and one aggregate type, limestone, are used. Hence, the corresponding fine aggregates and filler were sieved and dried in the oven at 110 ºC for at least 24 h. After sharing the results with the project partners in May 2019, it was decided to use an extra straight asphalt bitumen, 50/70, to investigate the effect of bitumen type.

To prepare the asphalt mortar, three different mixing methods were used for mortar with and without different types of fibres. For the one without fibres, a pre-weighted amount of asphalt bitumen was heated to a temperature 160±5 ºC in the oven. Next, the weighted limestone fine aggregates and filler, pre-heated in the oven at 160 ºC for around 3 h, were added into the heated bitumen in batches continuously stirring the materials. Finally, after all the materials were blended, stirring was extended for an additional ten minutes. The temperature should be carefully controlled throughout the mixing process.

Like the asphalt mixtures, the dry process was selected to prepare the materials with different fibres, with a different order of incorporation of fibres. For fibre Type A, a small metal can was used to mix the fine aggregate, filler, and fibres. Firstly, the needed fine aggregate and filler were weighted and mixed and then divided into three equivalent parts. Since fibre Type A is provided in two sub-types (see Figure 1), the total amount of fibres is obtained with a combination of 13% from component aramid and 87% from component polyolefins by weight. It should be mentioned that the aramid fibre should be separated into two parts equally. Next, 1/3 filler was added, followed by half of fibre aramid, 1/3 filler, the remaining content of fibre aramid and the last 1/3 filler was added on the top. After that, the can with the material was put into the oven at 160ºC for 3 h, and then, the entire fibre polyolefin was incorporated. Next, the can was carefully placed on a scale and the heated and pre-weighted bitumen is poured, at 160 ºC, to the mixed materials. Finally, the can was covered and subjected to high speed mixing for blending purposes, for a duration of two minutes at 2500 rpm. Such a method was used to ease the homogenization of fibres in the mortar. For asphalt mortar prepared with fibre Type P, the entire amount of fibres was added directly to fine aggregate and filler. The same mixing procedure was applied as in the case of blending fibres Type A. Single fibre content was used by following the suggestion from the provider, respectively. For fibre Type A, 0.07 % wt. was applied; in the case of fibre Type P, the fibre content of 0.15 % is conducted to the original porous asphalt mixture was adopted, and then, the corresponding portion, 1.31%, was calculated for the related mortar.

In the purpose of investigating the effect of aging conditions. The standard Rolling Thin Film Oven Test (RTFOT) and Pressure Aging Vessel (PAV) procedure based on the European standards were applied for the fresh asphalt mortars to simulate the short-term, long-term and double long-term aging conditions in the laboratory environment. In total, 18 different asphalt mortars with different bitumen type, aging conditions, and fibre content were prepared in this study. Information on the entire set of asphalt mortar is reported in Table 3.

Table 3. Basic properties of asphalt bitumen and prepared PA mortar.

Classification / Aging condition	asphalt mortar					
	40/100-65			50/70		
	No fibre	fibre A	fibre P	No fibre	fibre A	fibre P
Fresh	√	√	√	√	√	√
RTFOT	√	√	√	-	-	-
RTFOT+PAV	√	√	√	√	√	√
RTFOT+2PAV	√	√	√	-	-	-

* Pen: Penetration (0.1 mm), Soft: Softening point (ºC),
√: prepared material, -: not prepared material

2.3.2 PA mortar for fracture energy tests

Regarding the fracture parameters of fibre reinforced asphalt mortar, cylindrical specimens with a diameter of 100 mm were manufactured with gyratory compactor (Figure 3). All mixtures were prepared with a target air voids of 2.50% in order to avoid the variability that can be generated by the porosity of the mixtures. 50/70 penetration grade bitumen was also employed as binder, and limestone was used as filler and fine aggregate fraction (in this case, below 2 mm). The particle size distribution, as in the case of rheological tests, is the same than conventional PA mixture. The binder content used in the mortar mix was adjusted as a consequence of the increase of the surface area of the aggregates, the binder quantity of full PA reference mixture was geometrically adapted, so 9.3% by weight of mixture was finally employed. The same criteria were employed with the fibres. It was considered that fibres was homogenously distributed in the asphalt of the full mixture, so the rate of fibres recommended by the provider (between 0.05% and 0.15% above mixture), was converted using the rate of fibres above binder as reference. Finally, three percentages were used: 0.1%, 0.2% and 0.3% above weight of mortar.

Figure 3. An illustration of the fibre reinforced asphalt mortar (smaller than 2 mm) specimen

3 Testing characterization

3.1 Testing for the conventional asphalt mixtures

3.1.1 Asphalt Concrete (AC) mixture

3.1.1.1 Water sensitivity test

The water sensitivity test was performed according to the European standard EN 12697-12

Method A. Hence, a set of 8 specimens (D=100 mm, h=60 mm) was divided into two equally sized subsets and conditioned. One subset was maintained dry in a climate chamber at 22 °C while the other subset was saturated and stored in water at elevated conditioning temperature (40°C) for 68 to 72h. After conditioning, the indirect tensile strength of each of the two subsets was determined in accordance with EN 12697-23 at the specified test temperature of 22°C (Equation 1). The ratio of the indirect tensile strength of the water conditioned subset compared to that of the dry subset is determined in accordance with Equation 2 and expressed in percentage (%). The parameter of *ITS* was selected to compare the difference between the wet and dry process while *ITSR* was applied to evaluate the effect of fibres.

$$ITS = \frac{2F}{\pi D h} \tag{1}$$

$$ITSR = 100 \cdot \frac{ITS_w}{ITS_d} \tag{2}$$

where,

ITS	indirect tensile strength (MPa),
F	force (N),
D and *h*	diameter and the height in mm, respectively.
ITSR	the indirect tensile strength ratio, in percent (%);
ITS_w	the average indirect tensile strength of the wet group in;
ITS_d	the average indirect tensile strength of the dry group.

3.1.1.2 Rutting resistance

Rutting resistance (permanent deformation) test was assessed by using the large device wheel tracking test according to the European Standard EN 12697-22. The entire set of asphalt mixtures listed in Table 1 were tested. The testing device and the related sample are illustrated in Figure 4. In this test, the susceptibility of asphalt mixture to deform was conducted by the rut formed by repeated passes of a loaded wheel at a constant temperature of 60 ºC. The wheel tracking tests are conducted on two laboratory compacted slabs (two per asphalt mixture) with (500 mm × 180 mm × 100 mm). After a zero measurement the relative rut depth, e.g., the absolute rut depth as a percentage of the specimen height, was determined at different time intervals. For mixture AC B 22 H according to the Swiss standard, the rut depth after 30,000 passings (one passing includes one forth and back) is relevant.

Figure 4. Rutting resistance test according to EN 12697-22.

3.1.1.3 Resistance of fatigue

The fatigue resistance was investigated based on the adapted German standard AL-Sp-Asphalt 09, which has been included in the European Standard EN 12697-24. The Marshall specimen was conducted to perform the Indirect Tensile Test (IDT), while a continuous sinusoidal load was applied instead of the haversine impulse with rest periods. The testing setup is illustrated in Figure 5. The loading frequency of 10 Hz and a constant temperature of 20 ºC were used in this study. Through the vertical load, a state of stress is produced in the middle of the specimen that leads to its eventual failure. According to the standards, three loading amplitudes, 0.05‰ to 0.3‰, are implemented allowing the loading cycles to reach the fatigue criterion (Equation 4). The smallest loading amplitude is chosen in that way that the specimen fails after 10^6 cycles and the largest amplitude so that the specimen withstands at least 10^3 cycles. The entire set of asphalt mixture listed in Table 1 was tested. A total of nine specimens were tested, three at each of three strain levels.

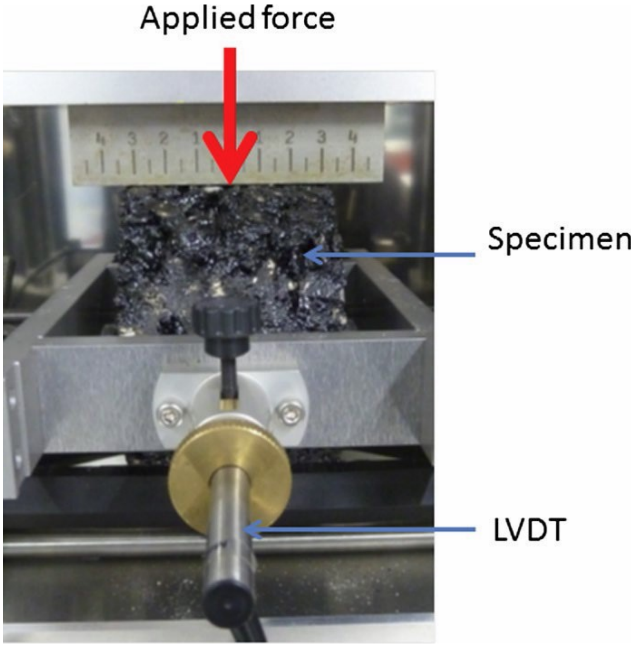


Figure 5. Test set-up for the indirect tensile test.

According to the standard, two parameters were selected to evaluate the fatigue resistance: the numbers of loading cycles, N_{macro}, when energy ratio (*ER*) (Figure 6a) reached its peak, as the product of the number of cycles and stiffness modulus (Equation 3):

$$ER(N) = |E(N)| N \tag{3}$$

where *E*(N) is the stiffness modulus at the particular cycle *N.*

Conventionally, the Wöhler line (Equation 4) can be used to express the material's fatigue function as shown in Figure 6b. Hence, a minimum of three different strain amplitudes is required for each testing condition.

$$N_{Macro} = C_1 \cdot \varepsilon_{el}^{C_2} \tag{4}$$

where,

ε_{el} horizontal elastic initial strain;

C_1, C_2 fitting constants.

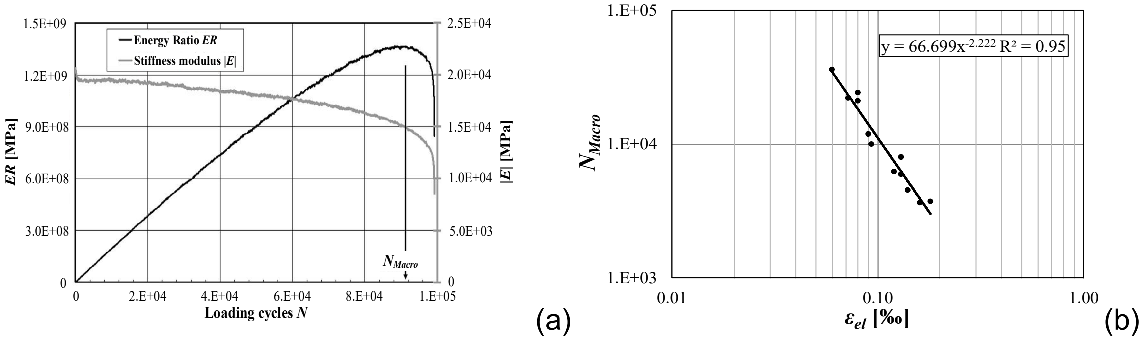


Figure 6. (a) Schematic to obtain the N_{macro} based on the maximum value of *ER* at *f*=10Hz; (b) an example of fatigue function (Wöhler line) at *T*=20 °C and *f*=10 Hz.

Furthermore, from the fatigue line the classical parameter ε_6 defined as strain to reach one million cycles was also calculated.

3.1.2 Porous Asphalt (PA) mixture

3.1.2.1 Volumetric properties and permeability

Mixture volumetric properties were focused on the macroscopic evaluation including bulk specific gravity (EN 12697 – 6) of the compacted mixture, total air voids (AV) (EN 12697 – 8), and interconnected air voids (IAV) (ASTM D7063 – 05). Closed air voids were also calculated like the difference between AV and IAV.

The permeability (*k*) of the specimens was also measured with the radial flow falling head permeameter. Based on Darcy’s law, the permeability of the mixture can be calculated according to Equation 5.

$$k = \frac{aL}{At}\ln\left(\frac{h_1}{h_2}\right) \tag{5}$$

where,

a and *A* the cross sections of the standpipe and the specimen in mm^2 ;

L the height of the specimen in mm;

t the time required for the water to fall from an initial height of 300 mm above the sample (h_1) to a height of 100 mm above the sample (h_2).

3.1.2.2 Cantabro test

Cantabro loss particle test (EN 12697 – 17) was carried out to assess the raveling of the porous asphalt mixtures. This test measures the percentage of particle loss that occurs when the specimen is subjected to abrasion in the Los Angeles machine. The Cantabro test was also performed in wet conditions according to the NLT 362/92 Spanish standard. In this case, the specimens were submerged in water at 60 °C for 24 hours. Then the samples were kept at 25 °C for another 24 hours before performing the test. In both cases, the loss in mass is expressed as the percentage after 300 turns and is calculated according to Equation 6**.**

$$Particle\ loss(\%) = \frac{m_i - m_f}{m_i} \times 100 \tag{6}$$

where, m_i and m_f correspond to the initial and final mass of the specimens.

3.1.2.3 Indirect tensile test and energetic parameters of fracture

The specimens were tested both in dry and wet conditions (ITS_{dry} and ITS_{wet}). The ITS (EN 12697 – 23) was measured by loading diametrically the samples across the circular cross section (Equation 1) and the moisture sensitivity was also evaluated based on the indirect tensile strength ratio (Equation 2), so the same method as asphalt concrete was applied. From this test, toughness can also be determined by analyzing the area under the stress-strain curve as shown in Figure 7. The toughness consists of two parameters, the Fracture Energy (FE) and the Post-cracking Energy (PE). The former corresponds to the area under the stress-strain curve until the strain at the maximum stress is reached, ε_p. The PE is calculated as the area under the stress-strain curve from ε_p to $2\varepsilon_p$.

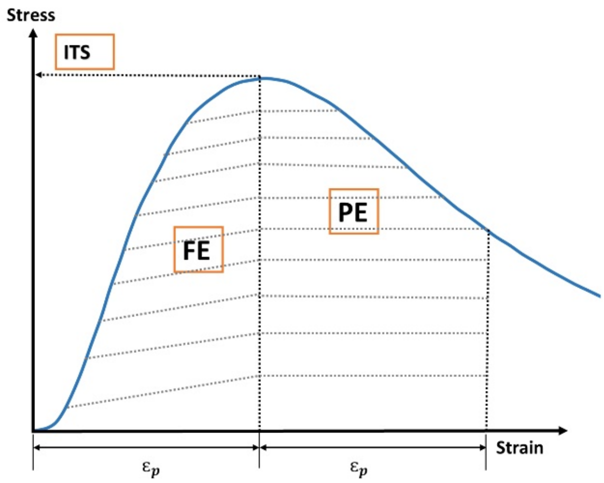


Figure 7. Scheme of toughness calculation.

3.2 Testing for the Porous Asphalt (PA) mortar

3.2.1 Rheological tests of PA mortar

3.2.1.1 Multiple Stress Creep and Recovery Test (MSCRT)

The response of the mortar to permanent deformation was addressed based on the Multiple Stress Creep and Recovery test (MSCRT) with an available DSR (Figure 6a) based on the active AASHTO standard T350. For this purpose, the 25 mm parallel plate was used with a 2 mm gap (Figure 6b). Because the maximum particle of asphalt mortar was 0.15 mm; hence, this measurement gap was adopted based on the following equation:

$$d \leq \left(\frac{a}{10} \right) \tag{7}$$

where, *d* is the maximum particle size of mortar and *a* is the measurement gap.

The conventional MSCRT procedure consists of 1 s creep loading followed by 9 s recovery at the two conventional stress levels of 0.1 and 3.2 kPa for 10 cycles. In this study, additional stress levels, 6.4 kPa, 12.8 kPa, and 25.6 kPa were imposed as a higher stiffness was expected to be exhibited by mortar compared to the bitumen. The entire set of asphalt mortar listed in Table 2 were tested. It should be noticed that only standard stress levels were applied for the mortar prepared with 50/70 bitumen; however, extra tress levels were used for the one prepared with 40/100-65 bitumen. A fixed temperature of 60 °C was set for the entire testing campaign. For each testing condition, at least three samples are prepared and performed. Two parameters were calculated as the output of MSCRT: the non-recoverable compliance, J_{nr}, which can be considered as a rutting potential index, and the percent recovery, *R*, (%) which reflects the elastic property of the material. Jnr and percent recovery can be expressed as follows:

$$J_{nr} = \frac{Nonrecoverable\,strain}{Maximum\,Strain} \tag{8}$$

$$\%R = \frac{Recovered\,strain}{Maximum\,Strain} \tag{9}$$

3.2.1.2 Linear Amplitude Sweep (LAS)

In this study, the Linear Amplitude Sweep (LAS) test was used to evaluate the fatigue resistance capability of the asphalt mortar based on the active AASHTO standard TP101. The principle of this test is using an oscillatory strain sweep test that generates damage to the bituminous material by applying linearly increasing load amplitudes. The LAS test consists of two steps: Step one: a frequency sweep is performed in order to get information about undamaged material properties and evaluate the rheological characteristics of the bituminous material. Step two: the damage characteristics of the bituminous material are measured employing a linear amplitude strain sweep test.

In the current study, frequency sweeps were conducted at a strain amplitude of 0.1% with a range of frequencies from 0.2 to 30 Hz according to AASHTO TP101. Amplitude sweep test was conducted of a linearly increasing strain amplitude from 0% to 30% over 3100 cycles of loading under a constant frequency of 10 Hz. These tests were performed by using DSR device with an 8 mm diameter and 3 mm gap at 15 ºC. At least two replicates were performed on each material. The number of cycles to failure was calculated using Equation 10 with the failure definition of 35% reduction in the initial modulus.

$$N_f = A(\gamma_{\max})^B \tag{10}$$

where, A and B are VECD model coefficients that depend on the material characteristics.

Parameter A represents the materials ability to keep its integrity during loading cycles and due to accumulated damage. This parameter is directly related to the storage modulus. In other words, by decreasing the storage modulus thorough loading cycles, the A parameter decreases, which indicates the low bituminous material resistance in maintaining its integrity during loading and due to accumulated damage. In Equation 10, when the strain level was equal to 1, the fatigue life will be equal to parameter A, hence, parameter A can be considered as the fatigue life of the binder at the strain level of 1 (100%).

The sensitivity of the bituminous material to strain level change can be described by parameter B. Higher absolute values of parameter B indicates that the fatigue life decreases at a higher rate when strain level amplitude increases. Generally speaking, higher A combined with a lower absolute B indicate a better fatigue resistant material.

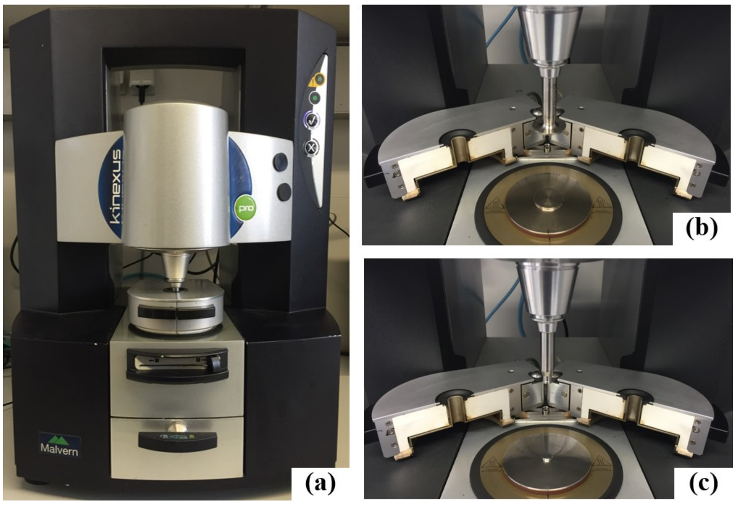


Figure 8. (a) DSR device; (b) 25 mm gemeotry and (c) 8 mm gemeotry.

In this study, the entire set of asphalt mortars listed in Table 2 was attempted to be tested. However, a pre-test found that all the asphalt mortars mixed with the PmB 40/100-65 bitumen were damaged before reach the designed strain level (30%) in the LAS test. Hence, only the mortar designed with the straight bitumen 50/70 were measured and evaluated in the current study. An example of the mortar with PmB 40/100-65 bitumen is illustrated in Figure 9, it was found that the bitumen sample was damaged when the strain level just reached 1%.

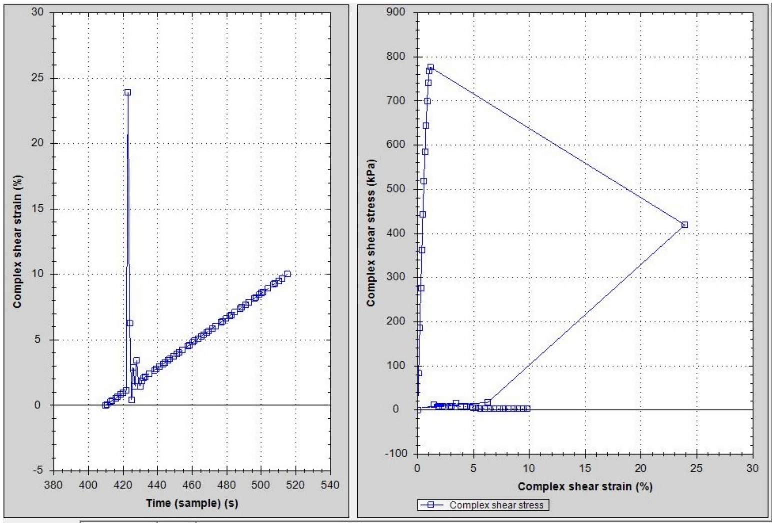


Figure 9. An example of testing for asphalt mortar prepared with PmB 40/100-65 bitumen.

3.2.1.3 Accelerated Fatigue Test (AFT)

In the initial testing plan, two experimental methods were proposed to evaluate the fatigue properties of asphalt mortar. Besides the LAS method, time sweep method, which developed during the NCHRP Project 9-10, is an option. This method was developed based on the linear viscoelastic properties of bituminous material (i.e., $|G^*|\cdot\sin\delta$), it is an alternative experimental approach to the conventional fatigue criterion. It has been confirmed in plenty of previous studies that the time sweep tests can be used to evaluate the fatigue behavior of bituminous material. However, in this study, the time sweep method showed substantial limitations since modified bitumen was used to prepare the related asphalt mortar, the nonlinear response to the loading may lead to unreliable results. Moreover, the time sweep test is rather time-consuming as it consists of repeated cyclic loading at a fixed stress/strain amplitude, it took more than one week to perform a single time sweep test on the PA mortar prepared with the

PmB bitumen in the pre-test. Considering the laboratory testing efficiency, a newly proposed testing method named Accelerated Fatigue Test (AFT) was introduced instead of the time sweep test in this study.

In 2010, Johnson proposed a modification of the time sweep method to predict the undamaged material's response. In addition, to reduce the extremely long testing duration observed for high performing bitumen, he suggested the use of Linear Amplitude Sweep (LAS) test in combination Viscoelastic Continuum Damage (VECD) concepts to ultimately predict the material behavior. In the recent past, a fatigue testing method based on the same concept of LAS but relying on stress control mode was proposed as an alternative to time sweep test in the Braunschweig Pavement Engineering Centre, Germany.

For AFT test, the initial shear stress of 150 kPa was applied to the specimen and then increased stepwise by 50 kPa every 4000 load cycles until the failure criterion is reached. A constant frequency of 10 Hz is imposed while the testing temperature is kept constant at 20 ºC. The entire set of asphalt mortar listed in Table 3 was tested in this study. At least three specimens are tested for each condition. AFT makes use of the 8 mm geometry with a 3 mm measurement gap in this study. To analyses of fatigue properties, two parameters are used for this purpose: fatigue failure at N_{Macro} (critical number of cycles) when the energy ration (*ER*) reaches the peak proposed by Rowe in 2000; and the conventional fatigue failure criterion, N_{f50}, in which $|G^*|$ decreases to 50% of the initial value of G_0. In Figure 10, two curve examples of $|G^*|$ vs. the number of load cycles and ER vs. the number of load cycles are illustrated. Regular peak points can be observed in the left plot, this is due to the step mode in the increase in stress level during testing. The curve of $|G^*|$ and *ER* vs. *the number of load cycles* are fitted by a continuous function using the built-in fitting equation of Polynomial of sixth order in Microsoft Excel to fit the raw experimental data and to obtain a smooth curve. It was found that the AFT procedure can provide consistent experimental measurements.

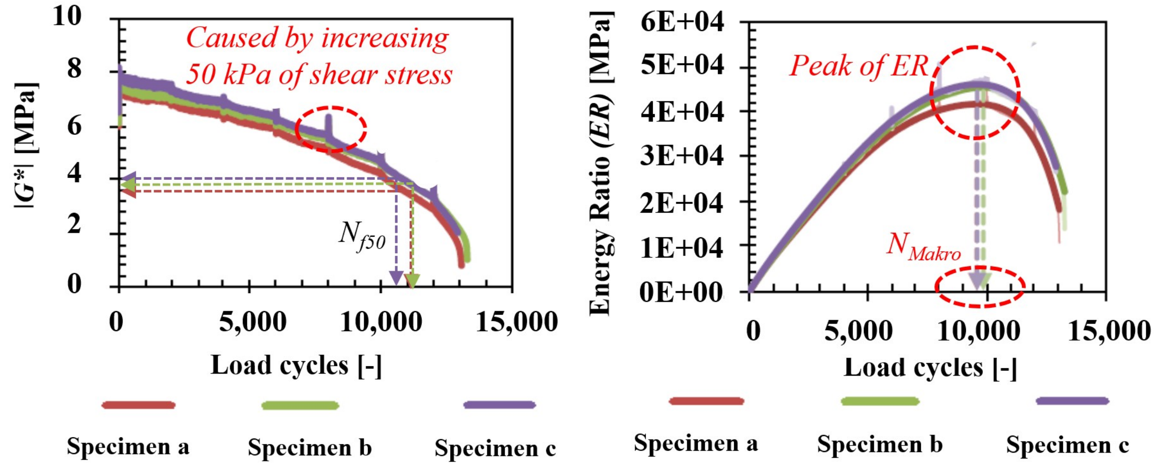


Figure 10. |*G| (Complex shear modulus) and Energy Ratio vs. number of loading cycles during the AFT test.**

3.2.1.4 Bending Beam Rheometer (BBR)

Bending Beam Rheometer (BBR) tests were conducted on the entire set of asphalt mortar listed in Table 2 based on the active AASHTO standard T313. An available BBR standard device (Figure 11a) is used to perform all the tests in ethanol (Figure 11b). The constant loading of 1 N and three testing temperatures: -12°C, -18°C and -24°C, were applied with a conditioning time of 1 h. The creep stiffness, $S(t)$, and relaxation parameter, *m*-value, are measured/calculated and compared. For each material and temperature, at least three replicates were performed.

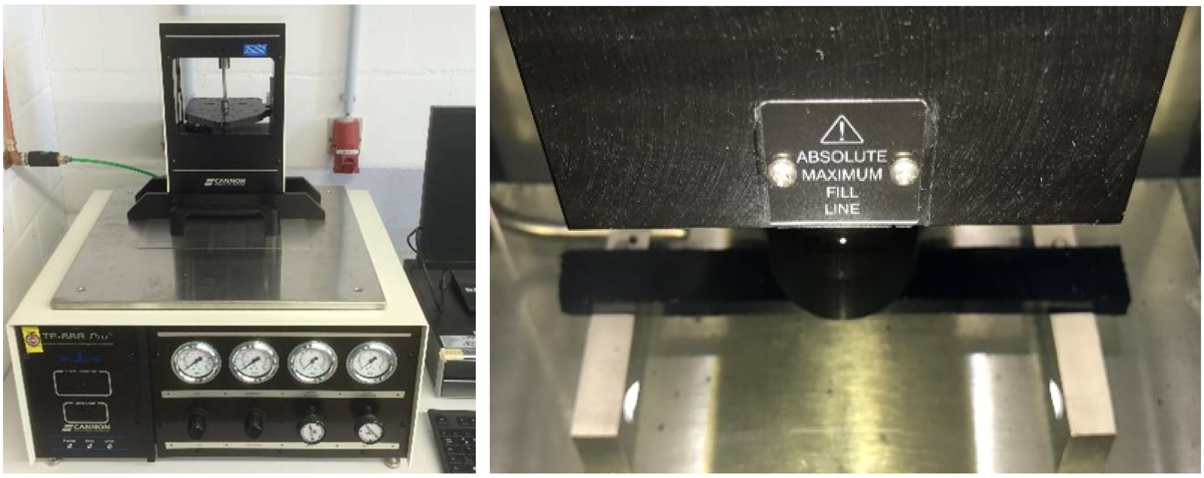


Figure 11. (a) BBR device, and (b) BBR configuration.

3.2.2 Fracture parameters of PA mortar

The Indirect Tensile Test (IDT) was performed according to the European standards (EN 12697- 23). The stress-strain curves were recorded, and energetic parameters of fracture measured, as in the case of PA mixture. Three different fibre content of each fibre were tested at three different temperatures. Figure 12 summarizes the control factors of the test.

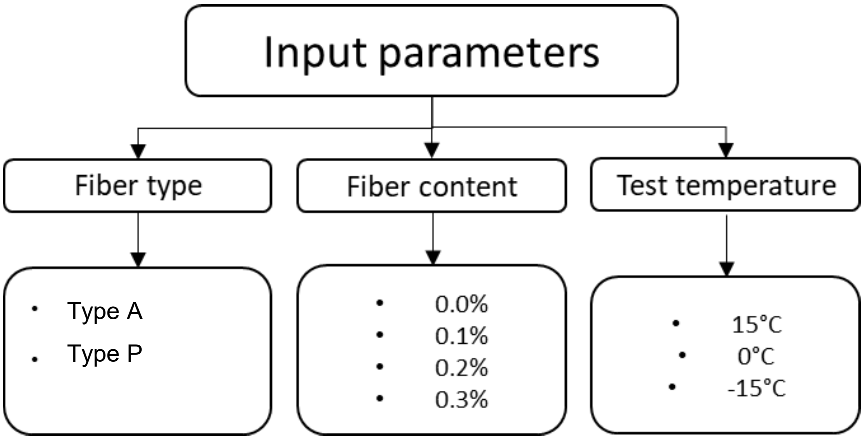


Figure 12. Input parameters considered in this research on asphalt mortar mixes

4 Experimental results and analysis

4.1 Testing for the conventional asphalt mixtures

4.1.1 Asphalt Concrete (AC) mixture

4.1.1.1 Water sensitivity

The comparison results between dry and wet conditions are illustrated with the indirect tensile strength (ITS) in Figure 13. It can be seen that the asphalt mixture prepared with both fibres result in a higher ITS compared to the ones without fibres (control and reference) in both dry and wet conditions. The highest ITS value was found for the FRAM with Type P fibre, then followed by the FRAM with Type A fibre with similar values to the control mixture prepared with PmB. The reference mixture prepared with the straight bitumen 50/70 obtained the lowest ITS value. It can be clearly observed the influence of the incorporation of fibres on the strength which could be attributed to a reinforce effect in the experimental FRAM.

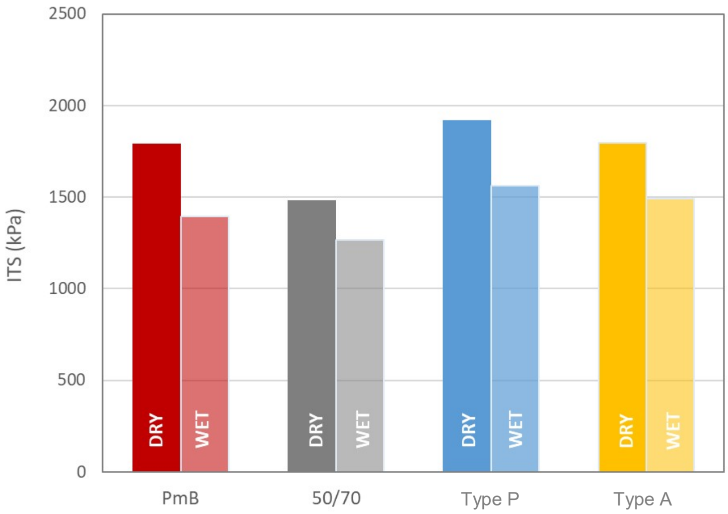


Figure 13. Indirect Tensile Strength (ITS) results for the mixtures in dry and wet conditions.

The results of water sensitivity tests using the indirect tensile strength ratio (ITSR) are shown in Figure 14. A different trend was found in ITSR compared to the previous observation. It can be seen that FRAMs obtained similar ratios compared to the control mixture (PmB). In this case, regarding the ITSR, the reference mixture prepared with the straight bitumen 50/70 showed the best moisture resistance capability. To conclude, it was confirmed that FRAMs would fulfill the Swiss normative requirements of ITSR by reaching rates higher than 70%, which indicates reliable moisture distress resistance.

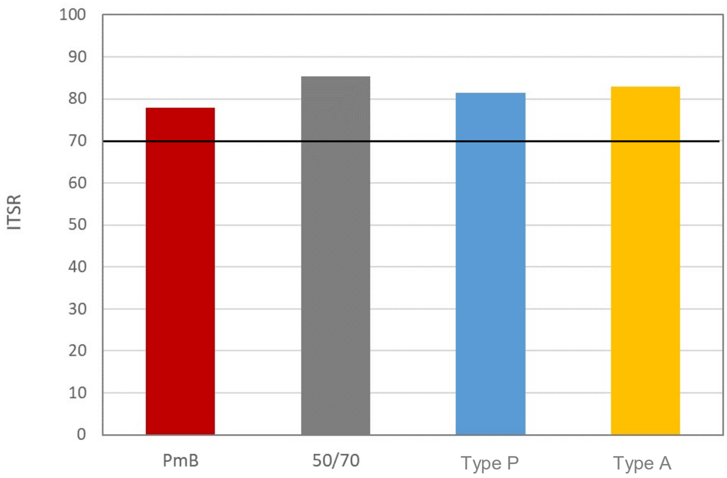


Figure 14. Water sensitivity testing results by using ITSR in percentage

4.1.1.2 Rutting resistance

In Figure 15, the rutting depth (%) results are illustrated for all the four different mixtures. FRAM modified with fibre type P showed a similar performance in comparison to the control mixture (PmB). Nevertheless, the FRAM with type A fibre obtained a worse response against rutting deformation, while the hardness of the straight bitumen led to a remarkable rutting resistance of the reference mixture. Again, it can be observed the significant influence of the fibres addition on the response of the mixtures. As conclusion, it should be remarked that FRAM modified with Type A fibres would not fulfill Swiss requirements for this type of mixtures which require values lower than 7.5% after 30,000 cycles.

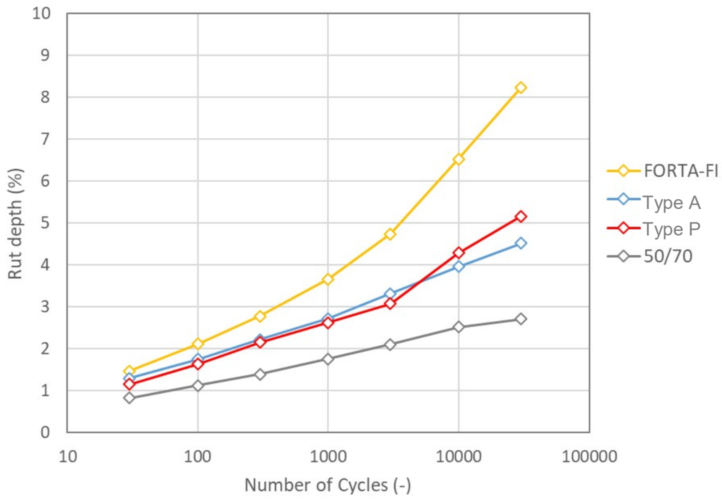


Figure 15. Rutting (wheel tracking) testing results for different mixtures.

4.1.1.3 Resistance of fatigue

Figure 13 displays all the testing results based on the fatigue experimental measurements according to the European standard EN 12697-24. In Figure 16a, to determine the Wöhler lines, the number of loading cycles to fatigue failure N_{macro} (Fatigue life) were recorded and then plotted in a log-log plane against the initial strain level ε_{el} at a loading frequency of 10Hz. Moreover, the initial stiffness obtained for the four different materials is shown and compared as a bar chart in Figure 16b. Finally, the number of cycles until failure regarding the different stress levels applied during the tests are presented in Figure 16c.

The results of fatigue tests indicate that good repeatability was achieved at each strain level for all materials tested. The fatigue line calculated with an exponential fit and the correlation coefficient R^2 are shown in the Figure 16a. All R^2 values are greater than 0.9 indicating a good correlation which satisfies the requirement by the standard which is 0.8 for base courses. The overall results that the addition of fibres in the FRAMs could improve the fatigue response for lower strains whereas similar results to the reference mixture were obtained for higher strain levels. In this case, concerning fatigue resistance performance, FRAMs did not reach the performance observed for the reference mixture (PmB). This fact could be related to the higher stiffness values observed for the FRAMs in comparison to the values for reference mixture.

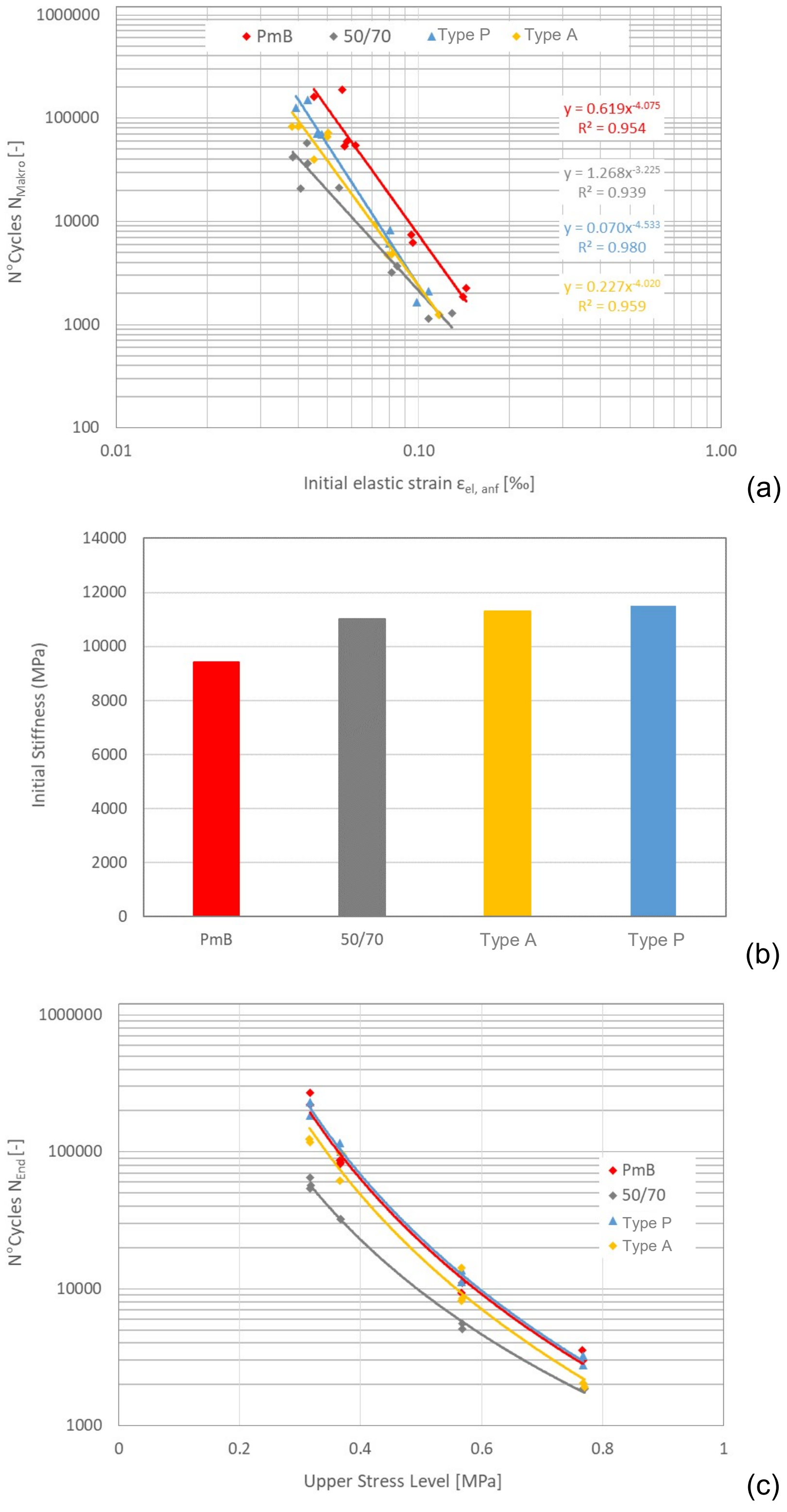


Figure 16. Fatigue testing results for three different loading amplitudes at *f*=10 Hz and at a test temperature of 20°C: (a) loading cycles to fatigue failure N_{macro} vs. initial strain level ε_{el}; (b) initial stiffness; (c) loading cycles to end N_{end} vs. upper stress level.

4.1.2 Porous Asphalt (PA) mixture

4.1.2.1 Volumetric properties and permeability

The results concerning the volumetric properties and the permeability of the studied PA mixtures are summarized in Figure 17 and Figure 18 respectively. According to the results, the addition of the fibre affected slightly both the permeability and volumetric properties. From the graph it can be seen that the standard deviation from the mean is indicated by an error bar. Although the addition of fibres could reduce the total air voids in the mixture, its functionality is not affected severely. All the mixtures have total air voids greater than 20%. Regarding permeability results, the trend suggests that adding fibres, decrease the permeability of the mixtures. However, the permeability values observed in fibre modified PA mixtures are higher than 100 m/day (1.2 mm/s).

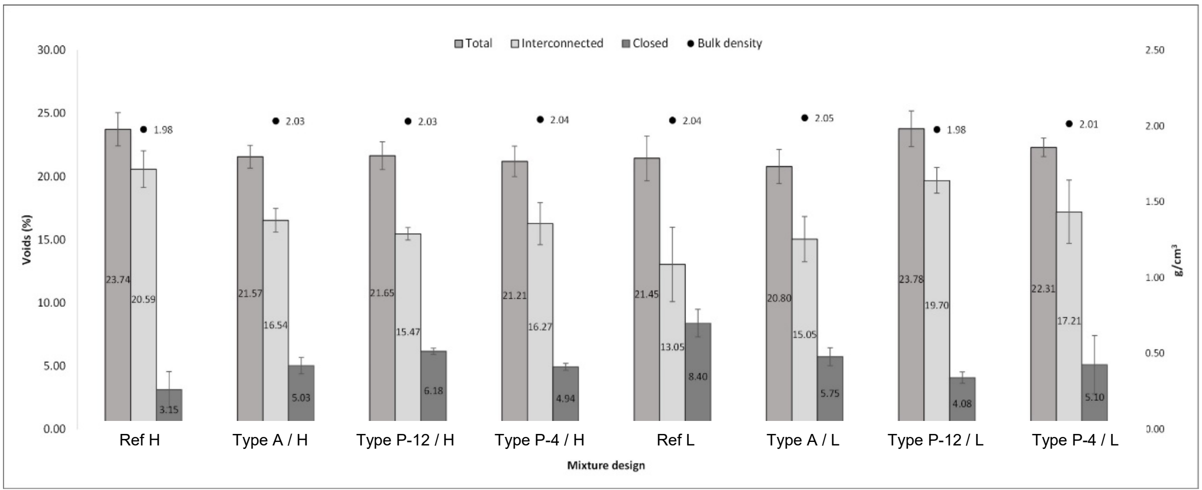


Figure 17. Volumetric properties of the PA mixture designs.

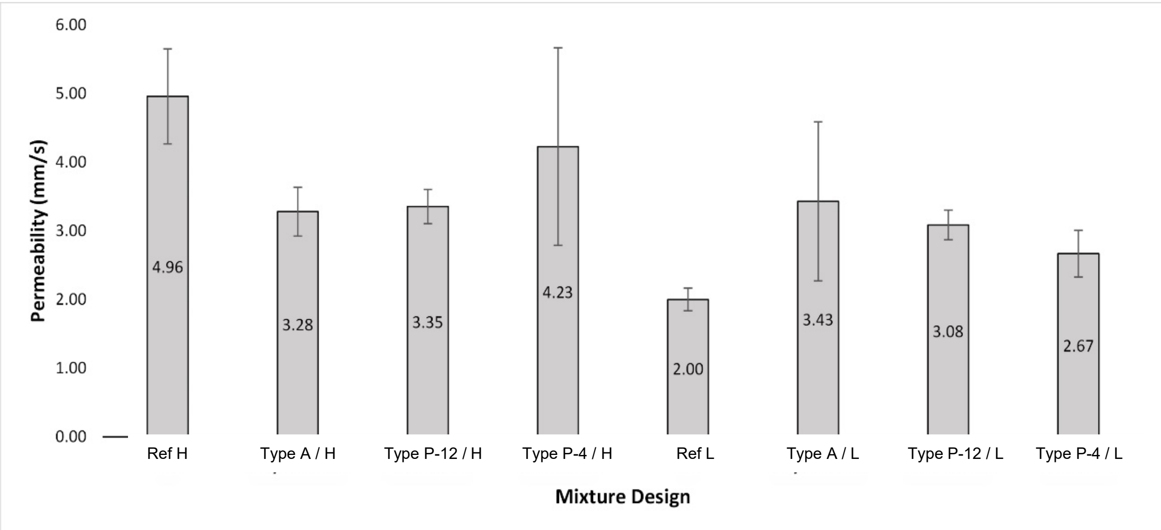


Figure 18. Mean permeability values of PA mixture designs.

4.1.2.2 Cantabro test

The particle loss in dry and wet conditions are displayed in Figure 19. In spite of the slights differences in the percentage of voids, the use of fibres in the PA mixture positively affected its particle loss resistance only in dry conditions. The samples type A / H and type P-4 / H showed particle loss improvements of 33.7% and 15%, respectively, respect the reference mixture Ref H. The addition of type A fibres to the PA mixtures with lower filler content showed a higher increase in the particle loss resistance, observing a rise of 40-41% comparing to the reference mixtures Ref L. Furthermore, type P fibres provided similar results, specifically, Type P-12 / L and typeP-4 / L improved the resistance to particle loss by 31.7% and 22.3%, respectively. The fibres did not improve the ravelling resistance in wet conditions. Probably an increase of the binder content could be considering a suitable alternative to coat the fibre-matrix aggregates better and to prevent their exposition to the weather conditions.

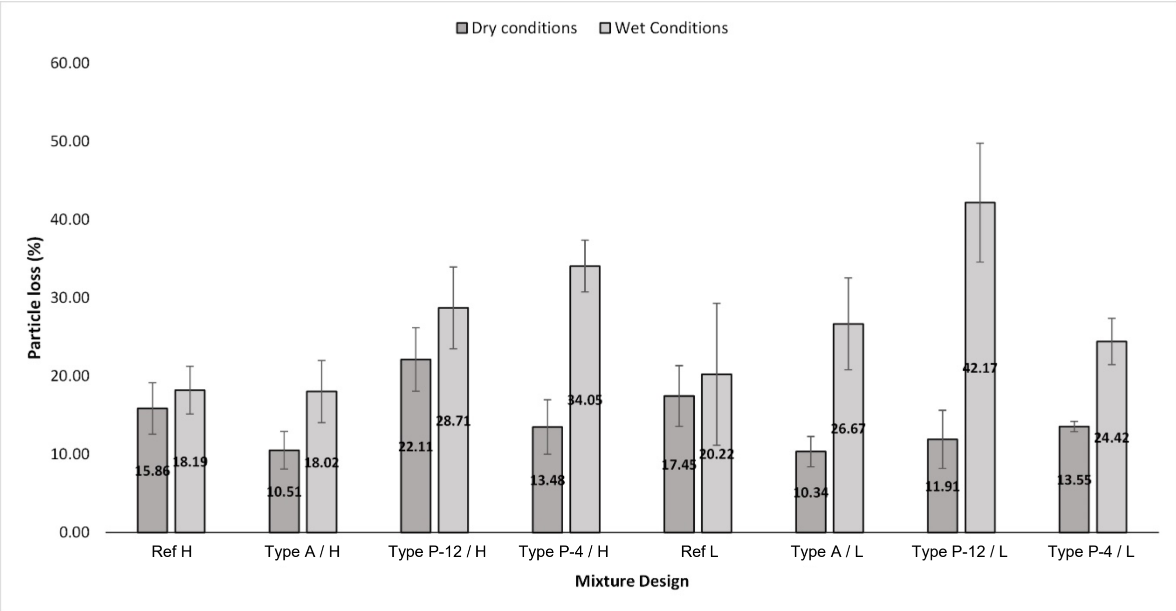


Figure 19. Mean values of the Cantabro loss particle in dry and wet conditions.

4.1.2.3 Indirect tensile test and energetic parameters of fracture

The indirect tensile strength results are shown in Figure 20. As it can be observed, adding type A fibres leads to an increment in the ITS values in dry conditions. Regarding type P fibres, the effect is not significantly enhanced when compared with reference mixtures. As it happens with the Cantabro test, the resistances are not increased in wet conditions, which results in a general ITSR reduction.

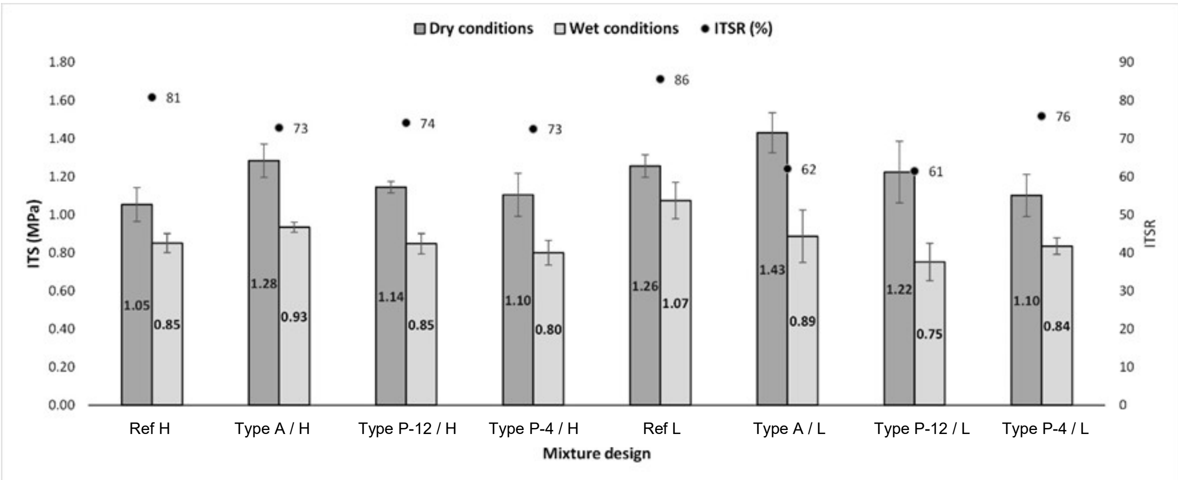


Figure 20. Mean values of the Indirect Tensile Test (ITT).

As commented in the mortar section, from the ITT different fracture energy parameters can be measured such as FE, PE and toughness that can be defined as the sum of the FE and PE. Figure 21 Shows the fracture parameters obtained for all mixtures designs in both conditions (dry and wet). According to the results, the mixture design called Type P-4 / H exhibited the major fracture energy with an increase of 46% with respect to the reference mixture Ref H. Similarly, this mixture reported increments of 23.5% and 32.1% in PE and toughness. Improvements with Type A fibres were also observed, especially when there was a reduction in the filler content. For example, the greatest PE and toughness were reported with this fibre. Higher values of toughness means a more ductile behavior of the mixture. Similarly, the increment of these parameters suggests that propagation of cracks can be retarded with the addition of fibres. In wet conditions, main differences were not observed between all mixture designs.

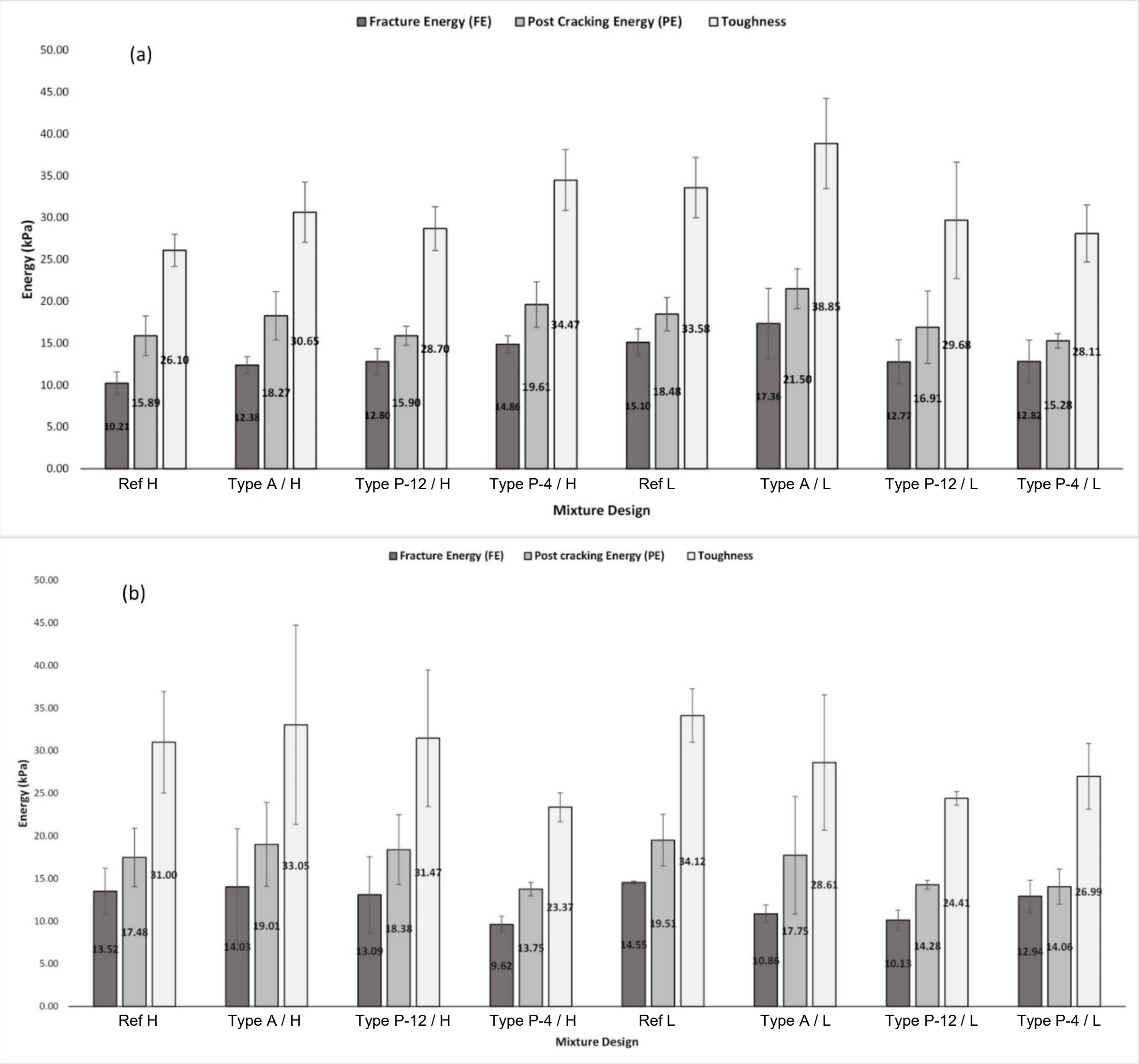


Figure 21. Fracture energy parameters for fibre-modified PA mixtures. (a) Dry conditions; (b) wet conditions.

4.2 Testing for the Porous Asphalt (PA) mortar

4.2.1 Rheological tests of PA mortar

4.2.1.1 Multiple Stress Creep and Recovery Test (MSCRT)

MSCRT was performed on the entire set of asphalt mortars described in Table 3. The experimental results for asphalt mortar designed with Type P fibre with PmB and straight bitumen under the stress level of 0.1 kPa and 3.2 kPa are illustrated in Figure 22 as an example.

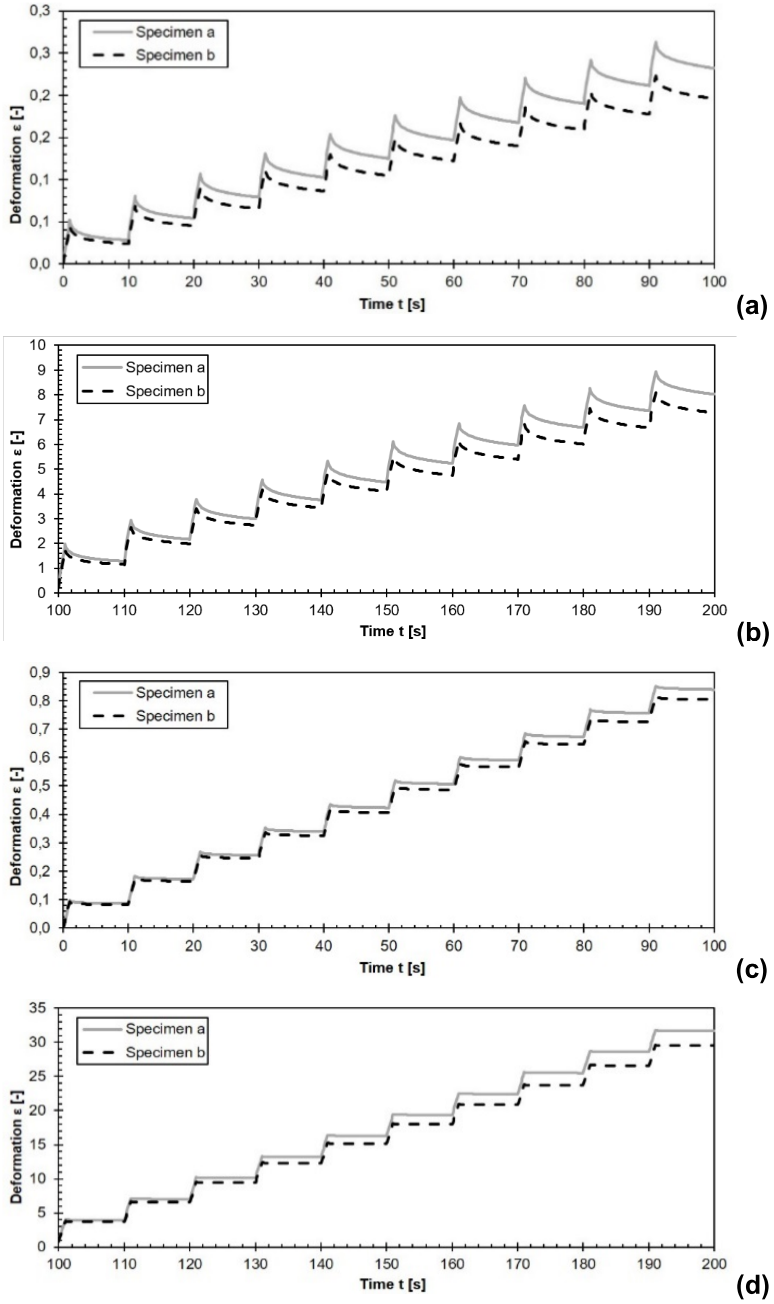


Figure 22. Creep-recovery curve: (a) Fresh asphalt mortar prepared with Type P fibre and 40/100-65 bitumend under 0.1 kPa; (b) Fresh asphalt mortar prepared with Type P fibre and 40/100-65 bitumend under 3.2 kPa; (c) Fresh asphalt mortar prepared with Type P fibre and 50/70 bitumend under 0.1 kPa; (d) Fresh asphalt mortar prepared with Type P fibre and 50/70 bitumend under 3.2 kPa.

As shown in Figure 22, good repeatability can be observed under different testing conditions for different mortars. Moreover, a significantly higher percent recovery, *R* (%), can be found for the mortar prepared with 40/100-65 bitumen. Besides the simple visible comparison, detailed numerical results for mortar designed with PmB bitumen and the straight bitumen, 50/70, are reported in Table 5 and 6 in terms of, *R*, percent recovery (%) and Non-recoverable compliance, J_{nr}, respectively.

Table 5. Summary of the MSCRT results for Mortar designed with 40/100-65 bitumen.

Asphalt mortar		*R* percent recovery [%] under the loading stress [kPa]					Non-recoverable compliance, J_{nr} under the loading stress [kPa]				
		0.1	3.2	6.4	12.8	25.6	0.1	3.2	6.4	12.8	25.6
No fibre	Fresh	51.96	52.23	50.45	43.71	34.05	0.287	0.215	0.424	0.859	1.745
	RTFOT	56.27	51.82	50.55	44.11	34.28	0.143	0.149	0.294	0.588	1.207
	1PAV*	70.22	67.84	64.48	61.83	54.72	0.020	0.023	0.051	0.109	0.260
	2PAV*	82.69	75.36	73.63	68.29	59.06	0.008	0.009	0.019	0.049	0.138
Type A	Fresh	56.41	49.25	44.20	37.26	28.57	0.227	0.267	0.567	1.155	2.279
	RTFOT	61.30	54.77	49.31	42.85	33.93	0.103	0.134	0.327	0.727	1.522
	1PAV*	74.20	71.08	68.16	61.42	49.97	0.015	0.020	0.046	0.126	0.356
	2PAV*	84.22	76.42	72.60	72.77	63.78	0.004	0.007	0.015	0.035	0.102
Type P	Fresh	57.55	54.25	52.46	45.38	35.19	0.202	0.215	0.424	0.861	1.755
	RTFOT	60.56	52.88	52.20	46.51	37.09	0.095	0.116	0.235	0.472	0.966
	1PAV*	69.96	66.31	64.38	60.27	52.30	0.022	0.026	0.051	0.120	0.287
	2PAV*	76.60	71.13	67.71	61.29	48.30	0.008	0.011	0.026	0.064	0.190

1PAV*: RTFOT+PAV; 2PAV*: RTFOT+2PAV.

Table 6. Summary of the MSCRT results for Mortar designed with 50/70 bitumen.

Asphalt mortar		*R* percent recovery [%]		Non-recoverable compliance, J_{nr}	
		0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa
No fibre	Fresh	10.56	3.53	0.758	0.837
	1PAV*	11.63	4.71	0.554	0.602
Type A	Fresh	8.86	1.50	0.832	0.992
	1PAV*	11.00	3.71	0.697	0.771
Type P	Fresh	12.21	3.87	0.822	0.930
	1PAV*	11.27	4.18	0.596	0.661

1PAV*: RTFOT+PAV.

Based on Table 5 and Table 6, it can be observed that in the case of 40/100-65 mortar, the value of *R* (%) is about five to eight times higher than the mortar designed with the straight bitumen in all the aging conditions. For the mortar prepared with 40/100-65 bitumen, in most of the conditions, including stress levels and aging conditions, Type A fibre and Type P fibre show an overall lowest and highest value of *R* (%), respectively. These results indicate that fibre Type P may be capable of enhancing the high temperature properties of asphalt mortar. As the stress level increases, it is not surprising that *R* (%) decreases for all the different aging conditions and fibre types. In addition, for a higher degree of aging, all mortars show increasing *R* (%). This appears to be more remarkable when the materials undergo the first long term aging procedure.

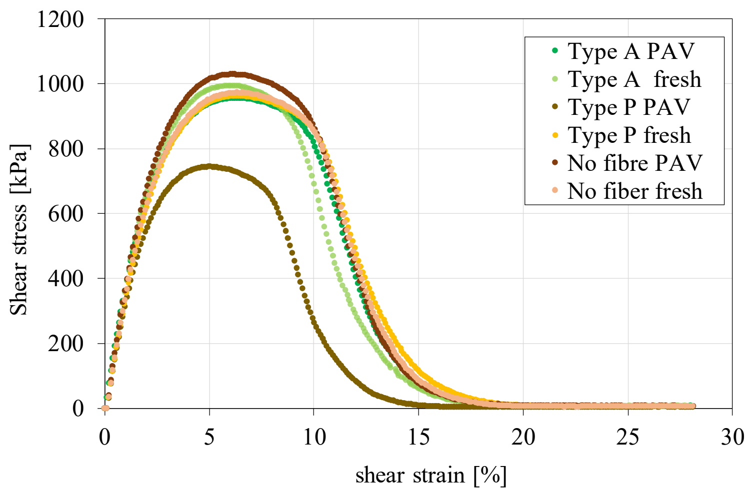
In the case of 50/70 mortar, a similar trend was observed, Type A fibre and Type P fibre present overall lowest and highest value of *R* (%), respectively. This seems to confirm the benefit of fibre Type P on the high temperature properties of asphalt mortar. Similar considerations in terms of degree of aging as in the case of 40/100-65 mortar can be drawn resulting in higher *R* (%) for more severe aging levels.

For all the aging condition and stress levels, fibre Type A designed mortar and fibre Type P designed mortar present the highest and lowest values of J_{nr}, respectively, this is consistent with the results of *R* (%). This appears to confirm a more consistent contribution of P fibre to the performance of the mortar at high temperature.

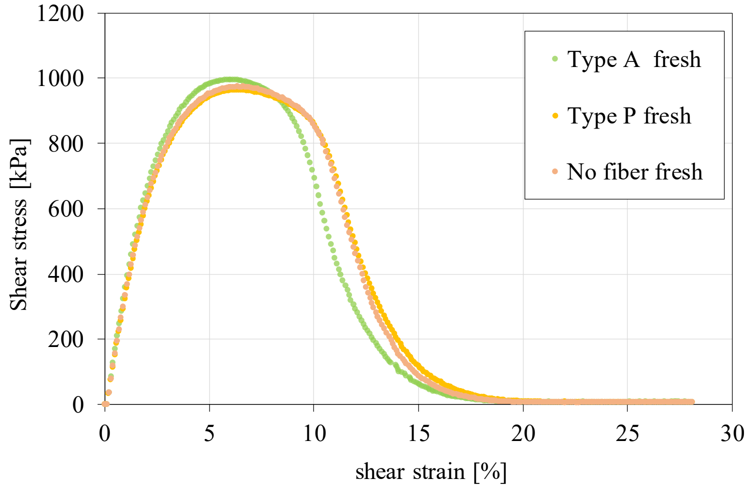
These results can be explained by the special characteristic of fibre Type P which is made of polyacrylonitrile. This not only shows characteristically capable to increase the bonding between asphalt material and fibre but may also provide higher rutting stability with higher tensile strength characteristic compared to other fibres. This is also supported by previous studies on the use of Polyacrylonitrile fibre-reinforced asphalt mixture.

4.2.1.2 Linear Amplitude Sweep (LAS)

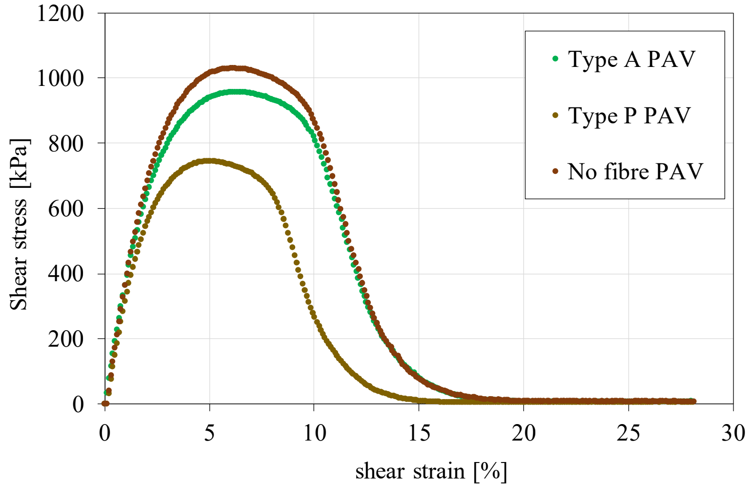
As previously mentioned in chapter 3.2.2, LAS tests were only performed on the mortar mixed with straight bitumen 50/70 listed in Table 3. At least three specimens are tested for each condition, good repeatability was found within the three samples under different condition. The shear stress vs. shear strain curves was plotted for all the materials for the evaluation purpose. In Figure 23, the curves are compared for different conditions.



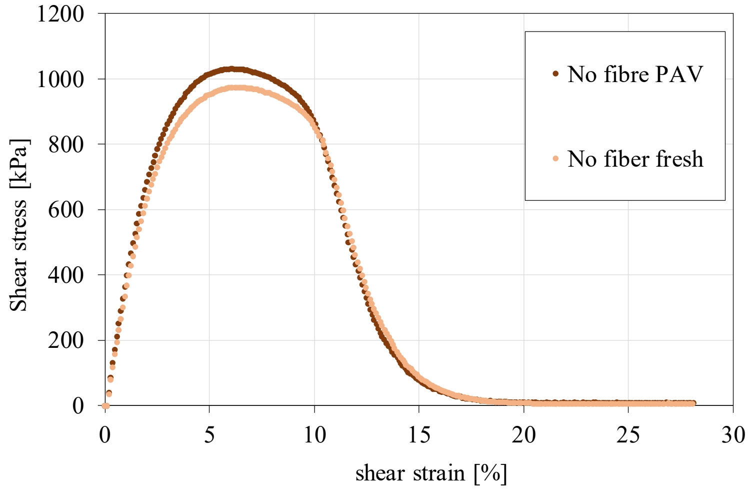
(a)


Shear stress [kPa]
shear strain [%]
Type A fresh
Type P fresh
No fiber fresh

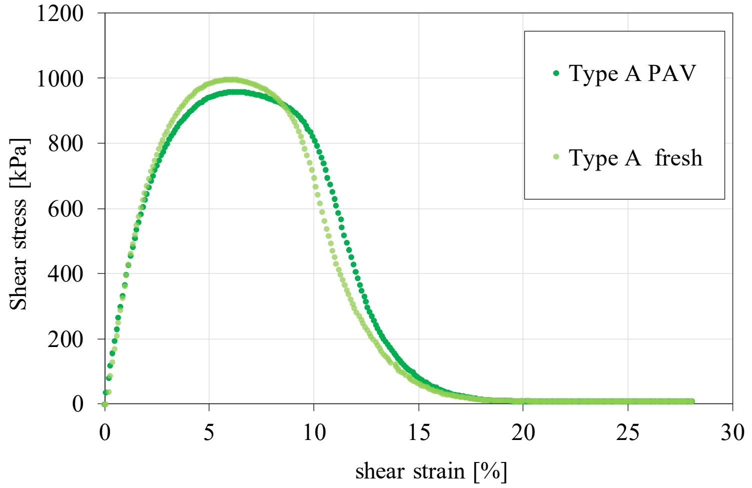
(b)


Shear stress [kPa]
shear strain [%]
Type A PAV
Type P PAV
No fibre PAV

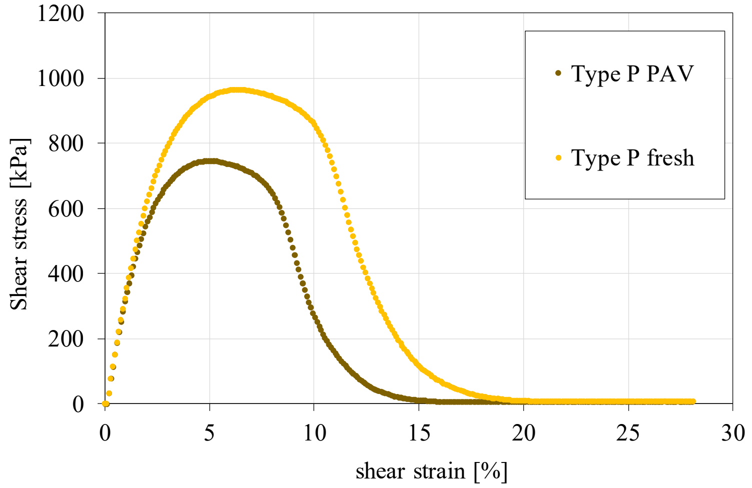
(c)


Shear stress [kPa]
shear strain [%]
No fibre PAV
No fiber fresh

(d)



(e)



(f)

Figure 23. LAS testing results of shear stress vs. shear strain curve: (a) comparison for all the three materials under fresh and PAV aging condition; (b) comparison for all the three materials under fresh aging condition; (c) comparison for all the three materials under the PAV aging condition; (d) comparison for no fibre mortar under fresh and PAV aging condition; (e) comparison for fibre Type A mortar under fresh and PAV aging condition; (f) comparison for fibre Type P mortar under fresh and PAV aging condition.

In Figure 23a, It was found that except the Type P fibre mortar under the RTFOT+PAV aging condition has a different trend, all the other materials indicate very similar curves even under the different aging conditions. A closer observation in Figure 23b shows that no remarkable differences within these three fresh mortars; while in the case of RTFOT+PAV condition, mortar without fibre show the best fatigue properties, a limited decrement is found in the mortar designed with fibre Type A, and a significant reduction in the fatigue performance was found in the one prepared with fibre Type P. Furthermore, in Figure 23d,23e and 23f, it was confirmed that the aging process only leads to only limited effect on the fatigue properties on the mortars mixed without fibre and with fibre Type A, the significant effect was only found in the mortar designed with fibre Type P.

4.2.1.3 Accelerated Fatigue Test (AFT)

As explained in chapter 3.2.3, the new proposed Accelerated Fatigue Test (AFT) test was performed on the entire set of mortars described in Table 3. In this study, the initial stiffness modulus, G_0, and the corresponding conventional fatigue failure parameter, N_{f50}, were selected as two parameters to judge the effect on fatigue performance of asphalt mortar. In addition, the highest value of energy ratio (ER) (Equation 3), ER_{max}, and the related numbers of loading cycles, N_{macro}, were also used to evaluate the fatigue properties. The curves of $|G^*|$ and energy ratio (ER) vs. the number of load cycles are plotted and displayed for comparison purpose, respectively. In Figure 24, three materials were chosen as an example.

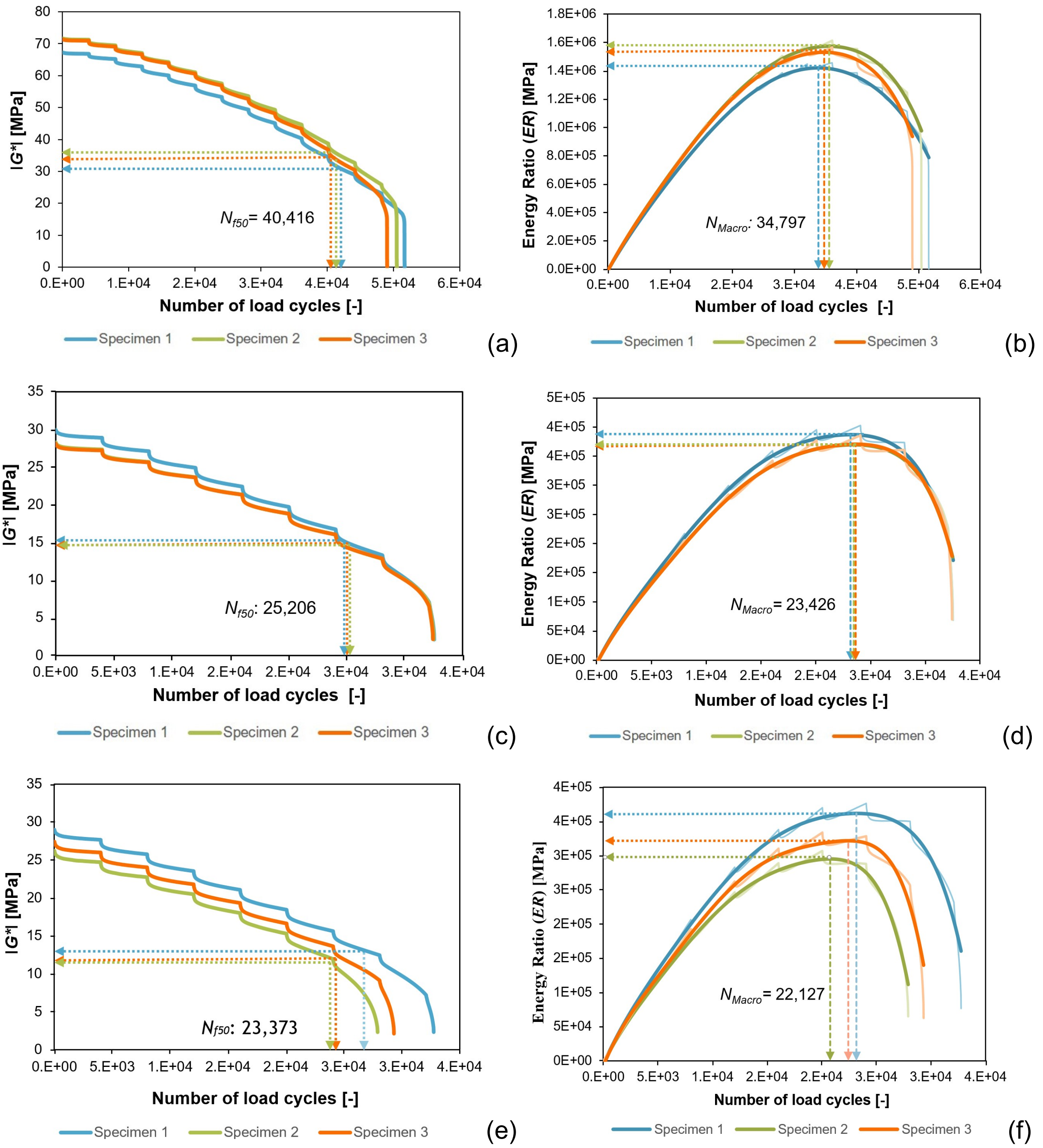


Figure 24. AFT results for mortar designed with PmB 40/100-65 bitumen of |*G| vs. number of load cycles: (a) Type A with 2PAV; (c) Type A with RTFOT; (e) No fibre with fresh; and *ER* vs. number of load cycles: (b) Type A with 2PAV; (d) Type A with RTFOT; (f) No fibre with fresh.**

Good repeatability can be observed for each material. However, only simple visible curves were unable to indicate the effect of fibre and aging conditions. Hence, detailed numerical results are listed in Table 7 and 8 with the summary of the N_{f50}, G_0, N_{Macro} and ER_{max} for the entire set of asphalt mortars.

Table 7. Summary of the AFT results for asphalt mortar designed with PmB bitumen 40/100-65.

Asphalt mortar		Results (average)			
		N_{f50}* [-]	G_0 [MPa]	N_{Macro}* [-]	ER_{max}* [MPa]
No fibre	Fresh	23,373	27.312	22,127	3.26E+05
	RTFOT	26,245	31.845	24,209	4.21E+05
	1PAV*	38,665	60.051	33,944	1.18E+06
	2PAV*	38,818	71.332	34,542	1.52E+06
Type A	Fresh	20,533	22.356	17,958	2.07E+05
	RTFOT	25,206	29.165	23,426	3.76E+05
	1PAV*	32,725	52.468	29,889	9.13E+05
	2PAV*	40,416	69.864	34,797	1.51E+06
Type P	Fresh	14,223	21.165	14,196	1.50E+05
	RTFOT	18,775	31.542	17,725	1.99E+05
	1PAV*	26,093	49.236	24,128	7.04E+05
	2PAV*	37,875	70.165	33,348	1.44E+06

1PAV*: RTFOT+PAV; 2PAV*: RTFOT+2PAV.

Table 8. Summary of the AFT results for asphalt mortar designed with straight bitumen 50/70.

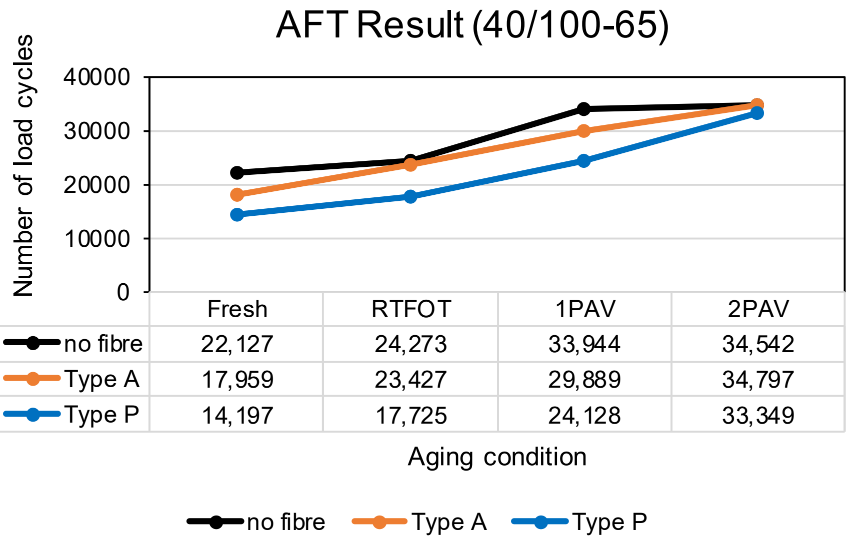
Asphalt Mortar		Results (average)			
		N_{f50}* [-]	G_0 [MPa]	N_{Macro}* [-]	ER_{max}* [MPa]
No fibre	Fresh	14,400	18.005	12,902	1.43E+05
	1PAV*	21,795	21.652	19,262	2.58E+05
Type A	Fresh	17,190	17.246	14,353	1.59E+05
	1PAV*	17,340	18.056	16,738	1.50E+05
Type P	Fresh	19,430	18.215	17,288	1.94E+05
	1PAV*	25,120	22.635	21,306	2.91E+05

1PAV*: RTFOT+PAV

Table 7 and 8 provide the results of fatigue resistance for mortars prepared with 40/100-65 and 50/70 bitumens, respectively. Overall lower N_{Macro} values are observed compared to the N_{f50} values, with a reduction of 8 to 10 %. This quite normal results and have already been confirmed by plenty of previous studies. Even though the values between N_{Macro} and N_{f50} are different, the same trends are found in these two failure criterion parameters; hence, these two results can be used to validate each other. This is strong evidence that the newly proposed AFT method can evaluate the fatigue properties of asphalt mortar in a proper way.

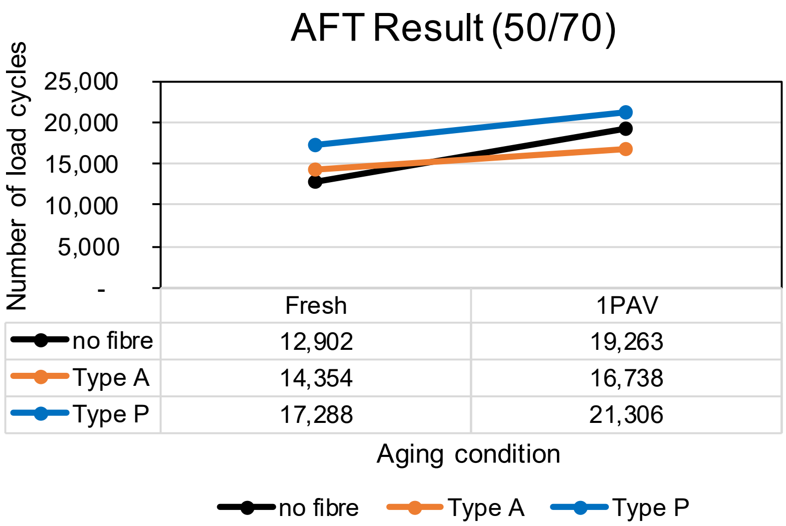
A closer observation indicates that, with 40/100-65 bitumen, mortar prepared with fibres show a relative lower fatigue life compared to the one prepared without fibre. Between the two mortars prepared with different fibres, the experimental results, N_{Makro} and N_{f50}, for fibre type A show better performance compared to fibre P. For the higher level of aging condition, a longer fatigue life is observed with the maximum relative increasment from short term aging to long term aging, this is also found in the results from MSCRT.

In the case of 50/70 bitumen, the behavior of fibre showed some different trend compared to the mortar of 40/100-65. Firstly, in the fresh condition, Type A and Type P mortar show rather better fatigue life than no fibre mortar. In the case of RTFOT+1PAV aged condition, Type P and Type A mortar show relative best and worst fatigue resistance performance, respectively. As the progressed aging condition, the fatigue resistance of all the mortar prepared with straight bitumen 50/70 increased at the same time same as the case of 40/100-65. In addition, the lowest gap of fatigue resistance was found under the RTFOT+2PAV condition. The comparison results between different bitumen, fibre types and aging conditions are also presented in Figure 25.



	Fresh	RTFOT	1PAV	2PAV
no fibre	22,127	24,273	33,944	34,542
Type A	17,959	23,427	29,889	34,797
Type P	14,197	17,725	24,128	33,349

(a)



	Fresh	1PAV
no fibre	12,902	19,263
Type A	14,354	16,738
Type P	17,288	21,306

(b)

1PAV*: RTFOT+PAV; 2PAV*: RTFOT+2PAV.

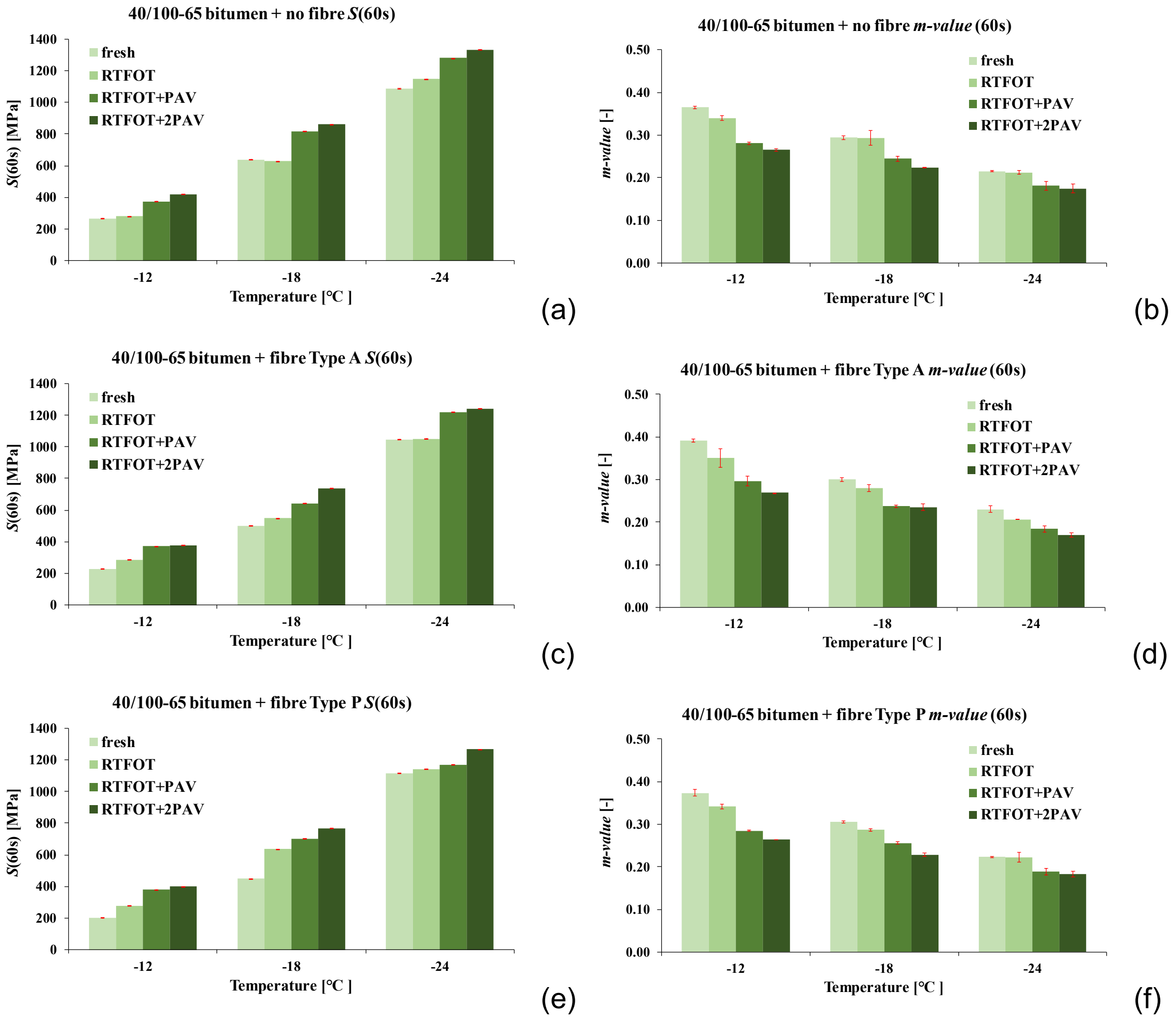
Figure 25. N_{macro} results of AFT tests: (a) 40/100-65 and (b) 50/70

In the combination of Table 7 and 8 and Figure 25, it indicates that fibre Type A showed better performance for the fatigue resistance compared to the fibre Type P with the mortar of 40/100-65. In contrast, it appeared Fibre P with 50/70 mortar has more benefits in enhancing the fatigue resistance than fibre Type A with the mortar of 50/70. In addition, this test result provides a significantly reduced time compared to time sweep in a laboratory test by AFT as described.

These results can be drawn by the characteristic of fibre Type A that is consisted of aramid fibre that works better in a modified bitumen than pain bitumen. This is because this type of fibres provides a three-dimensional reinforcement network while acting like adhesion and dispersing agent cooperated with polypropylene. As mentioned in the beginning, aramid fibre reinforced mixture has shown to result in substantially longer fatigue life. With this reason, fibre Type P showed a little higher effect than fibre Type A to enhance the fatigue resistance with pain bitumen 50/70. This is because fibre Type A cannot expect the cooperating effect between the three-dimensional network of fibre Type P and plain bitumen.

4.2.1.4 Bending Beam Rheometer (BBR)

In Figure 26, BBR tests were plotted for each material for the creep stiffness *S*(60s) and relaxation properties *m*-value(60s) in the bar chart, respectively. In each figure, the measured results were compared under three different testing temperatures and different aging conditions, four aging conditions for mortar designed with PmB 40/100-65 bitumen while only two aging conditions were used for mortar designed with straight bitumen 50/70. Detailed comparison results were listed in Table 9 and Table 10 for all the materials.



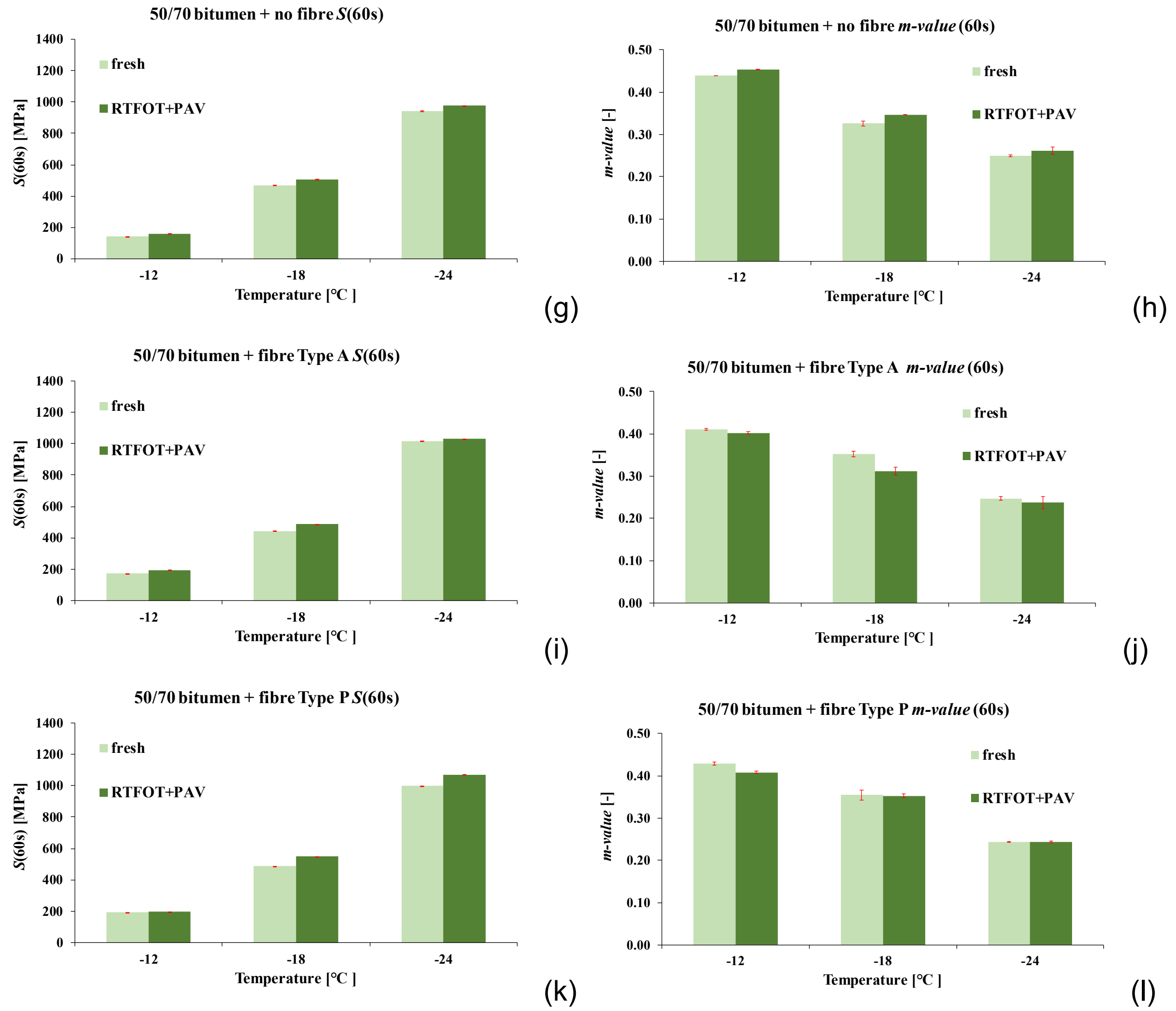


Figure 26. BBR results under different conditions and temperatures: (a) *S*(t) for 40/100-65 mortar withour fibre; (b) *m-value* for 40/100-65 mortar withour fibre; (c) *S*(t) for 40/100-65 mortar with fibre Type A; (d) *m-value* for 40/100-65 mortar with fibre Type A; (e) *S*(t) for 40/100-65 mortar with fibre Type P; (f) *m-value* for 40/100-65 mortar with fibre Type P; (g) *S*(t) for 50/70 mortar withour fibre; (h) *m-value* for 50/70 mortar withour fibre; (i) *S*(t) for 50/70 mortar with fibre Type A; (j) *m-value* for 50/70 mortar with fibre Type A; (k) *S*(t) for 50/70 mortar with fibre Type P; (l) *m-value* for 50/70 mortar with fibre Type P.

Table 9. BBR results for asphalt mortar designed with PmB bitumen 40/100-65.

Asphalt mortar		*S*(60s) [MPa]			*m*-value (60s) [-]		
		-12°C	-18°C	-24°C	-12°C	-18°C	-24°C
No fibre	Fresh	266	639	1087	0.365	0.294	0.215
	RTFOT	279	628	1147	0.340	0.293	0.212
	1PAV*	373	816	1280	0.291	0.244	0.181
	2PAV*	418	861	1330	0.266	0.233	0.175
Type A	Fresh	228	503	1045	0.391	0.301	0.231
	RTFOT	286	549	1050	0.350	0.279	0.206
	1PAV*	371	643	1220	0.296	0.237	0.184
	2PAV*	376	737	1240	0.269	0.235	0.169
Type P	Fresh	202	450	1115	0.374	0.305	0.224
	RTFOT	277	636	1140	0.341	0.287	0.223
	1PAV*	379	700	1170	0.285	0.256	0.189
	2PAV*	400	766	1267	0.264	0.228	0.183

1PAV*: RTFOT+PAV; 2PAV*: RTFOT+2PAV.

Table 10. BBR results for asphalt mortar designed with straight bitumen 50/70.

Asphalt mortar		*S*(60s) [MPa]			*m*-value (60s) [-]		
		-12°C	-18°C	-24°C	-12°C	-18°C	-24°C
No fibre	Fresh	142	469	943	0.439	0.326	0.249
	1PAV*	162	506	977	0.453	0.346	0.261
Type A	Fresh	172	443	1015	0.411	0.352	0.247
	1PAV*	193	486	1030	0.402	0.312	0.238
Type P	Fresh	192	487	997	0.429	0.355	0.244
	1PAV*	196	549	1070	0.409	0.353	0.243

1PAV*: RTFOT+PAV.

In the combination of Figure 26, Table 9 and Table 10. It can be seen that creep stiffness values increased when the testing temperatures went lower and aging conditions went deeper for each material, the opposite trend was found for the results of m-value. A deeper observation in the mortar prepared with PmB 40/100-65 bitumen, only limited difference in both S(t) and m-value can be found within two materials groups: fresh and RTFOT material; RTFOT+PAV and RTFOT+2PAV. Significant differences were observed between RTFOT and RTFOT+PAV. This is true for most of the situations except the one prepared with fibre Type P performed at -18°C and -24°C. In the case of mortar mixed with the straight bitumen 50/70, no remarkable differences were found between fresh and RTFOT+PAV mortars.

4.2.2 Fracture parameters of the PA mortar

Figure 27 and Figure 28 illustrate the ITS values and fracture energy parameters at different temperatures of the study. As the mortar turns brittle at -15 °C, post cracking energy (PE) was not recorded this temperature, so toughness is unable to be calculated. Limited improvements were observed in the different responses. Nonetheless, there is no clarity on whether the data is statistically significant or not. Therefore, in order to evaluate the statistical differences between these results, a statistical analysis was carried with a confidence interval of 95%.

The resistances observed at 15°C and 0°C did not show main differences, showing a high variability independently of the type and quantity of fibres. However, adding fibres to the mortar led to improvements in ITS response at -15°C. At this temperature, it can be observed that as the fibre content increases, the ITS also increases. Concerning type A fibres, the highest improvement was observed adding 0.3% of type A fibres being statistically significant in relation to the reference mortar. Moreover, the increasement of 16.50% and 18.04% were observed when the mixture were designed with 0.1% and 0.2% fibres, respectively. However, these differences proved not to be statistically significant. With regards to type P fibres, mortar samples reinforced with 0.2% and 0.3% of these fibres exhibited an achievement percentage of 32.73% and 31.44%, respectively, respect the reference mortar. However, only the addition of 0.3% of type P fibres proved to be statistically significant.

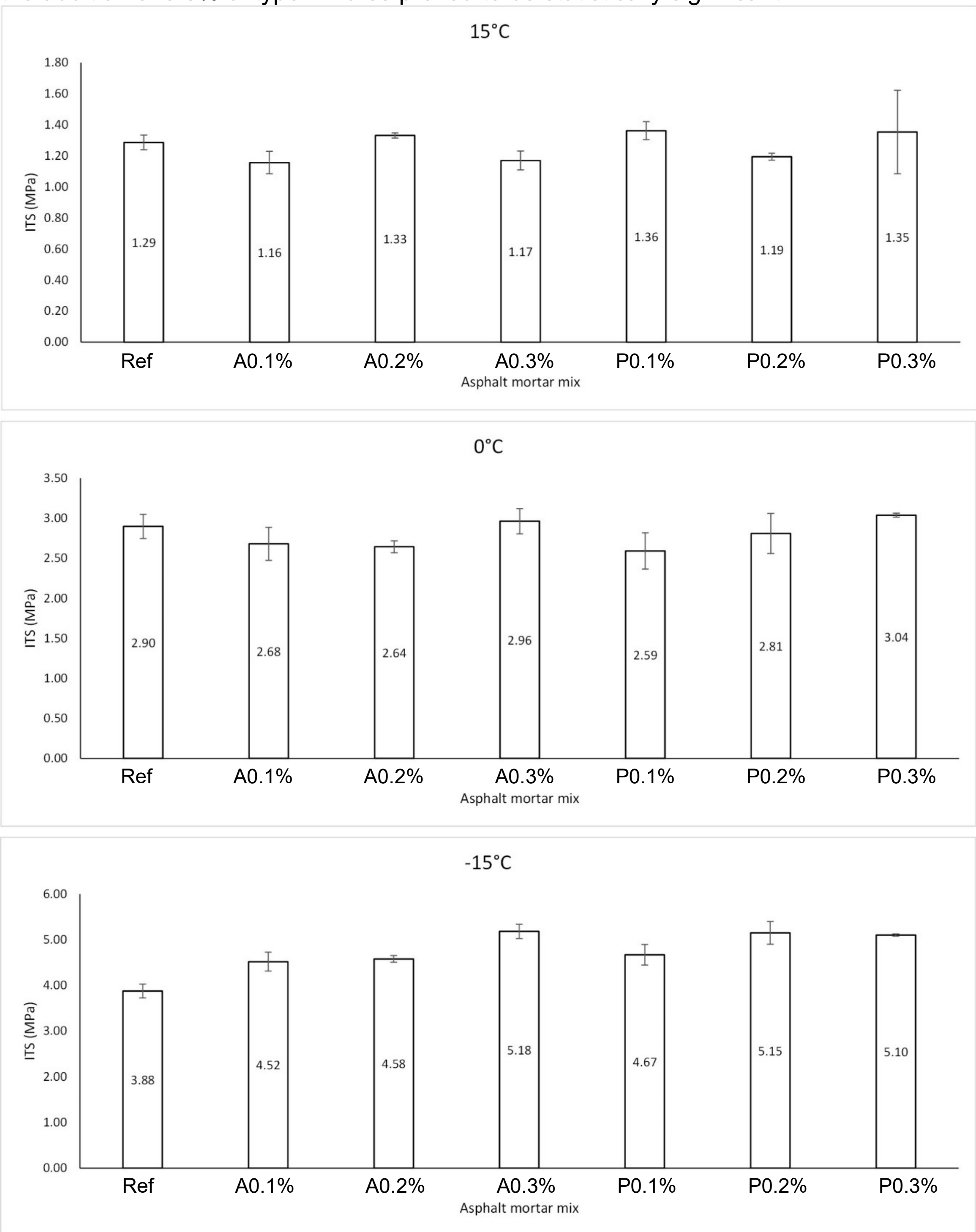
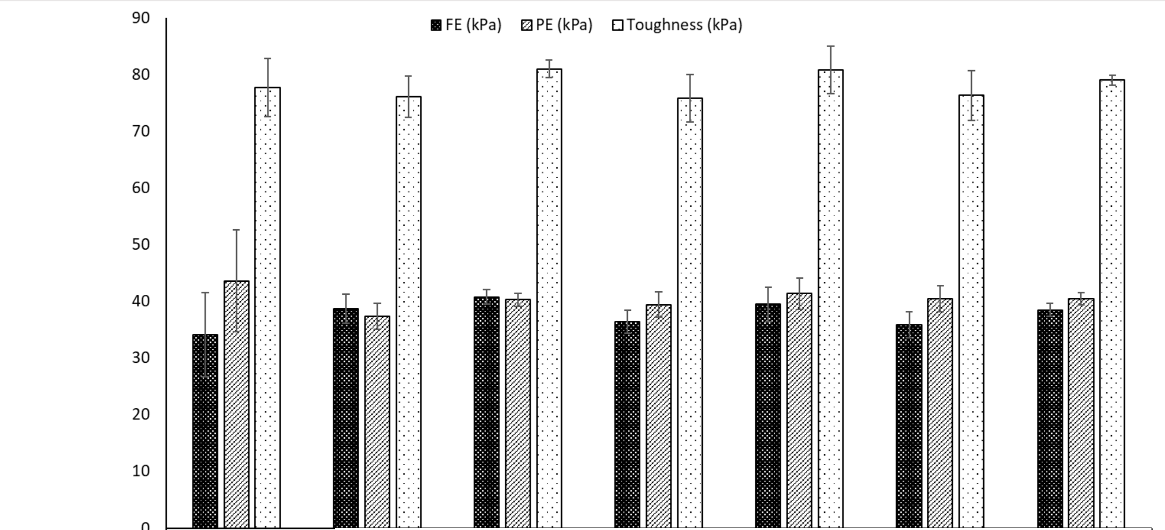
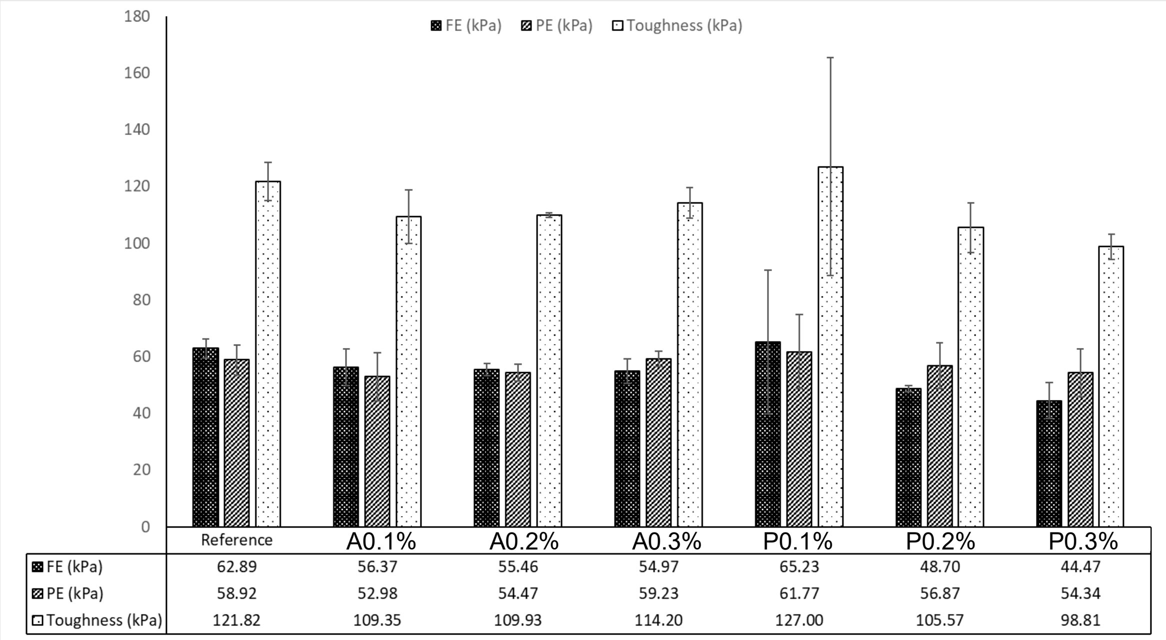


Figure 27. ITS values at 15°C; 0°C; -15°C.

The fracture energy properties are shown in Figure 28. In the case of ITS, the behavior is different depending on the temperatures. At 15 °C, the tendency is to increase the fracture energy properties when fibres are added, which is linked with the amount of energy prior to initiation of cracking. Although it did not present statistical differences. On the other hand, PE that is associated with the amount of energy to resist the crack propagation, is reduced adding fibres. This phenomenon could be due to the fact that in the fibre reinforced mortar a major crack was developed after the peak strength, as long as in the reference mortar, minor cracks was developed and then were merged. Similar than FE response, statistical differences were not observed. Concerning to fracture parameters at 0 °C, none of the types of fibres regardless of their content gives a positive impact on FE properties at this temperature; even in some cases, the results were significantly lower, specially with fibres type P. At -15°C the behavior of the mortar mixes was elastic-brittle, the above means that when the tensile strength reaches its maximum value, the specimens breaks instantly and the stress drops to zero after the first cracking. The FE properties were influenced by the fibre dosing. Compared with reference asphalt mortar mix, improvements of 25.76% and 21.79% were obtained adding 0.3% of type A and type P fibres, respectively, being statistically significant as shown in Table 11. Concerning the other percentages of fibres, although there were no significant differences, there is a clear tendency for higher fibre content, the higher the fracture energy.



	Reference	A0.1%	A0.2%	A0.3%	P0.1%	P0.2%	P0.3%
FE (kPa)	34.11	38.76	40.74	36.45	39.46	35.86	38.50
PE (kPa)	43.60	37.35	40.28	39.41	41.36	40.48	40.51
Toughness (kPa)	77.71	76.11	81.01	75.85	80.82	76.34	79.01



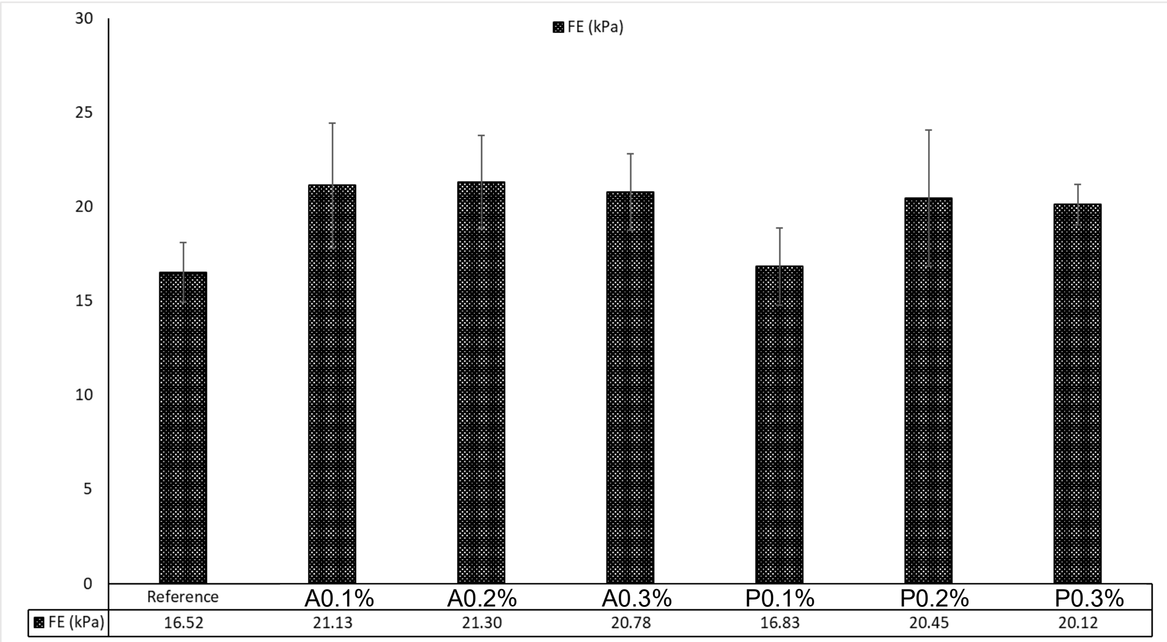


Figure 28. Fracture energy parameters at 15°C; 0°C; -15°C.

Table 11 presents the statistical differences observed between the fibre reinforced asphalt mortars with respect to the reference mortar.

Table 11. Statistical differences of ITS and Fracture energy parameters at 15°C (a) ; 0°C (b) ; -15°C (c).

(a)	ITS (MPa)						
	Reference	POA 0.1	POA 0.2	POA 0.3	PAN 0.1	PAN 0.2	PAN 0.3
p - value	-	0.07	0.255	0.08	0.175	0.093	0.71
Significance	-	NO	NO	NO	NO	NO	NO
	FE (kPa)						
p - value	-	0.413	0.267	0.652	0.367	0.735	0.418
Significance	-	NO	NO	NO	NO	NO	NO
	PE (kPa)						
p - value	-	0.364	0.59	0.515	0.72	0.62	0.615
Significance	-	NO	NO	NO	NO	NO	NO
	Toughness (kPa)						
p - value	-	0.691	0.400	0.663	0.477	0.750	0.710
Significance	-	NO	NO	NO	NO	NO	NO

(b)	ITS (MPa)						
	Reference	POA 0.1	POA 0.2	POA 0.3	PAN 0.1	PAN 0.2	PAN 0.3
p - value	-	0.22	0.043	0.616	0.136	0.623	0.168
Significance	-	NO	**YES**	NO	NO	NO	NO
	FE (kPa)						
p - value	-	0.249	0.024	0.075	0.889	0.004	0.044
Significance	-	NO	**YES**	NO	NO	**YES**	**YES**
	PE (kPa)						
p - value	-	0.366	0.230	0.924	0.756	0.728	0.471
Significance	-	NO	NO	NO	NO	NO	NO
	Toughness (kPa)						
p - value	-	0.147	0.040	0.171	0.839	0.076	0.005
Significance	-	NO	**YES**	NO	NO	NO	**YES**

(c)	ITS (MPa)						
	Reference	POA 0.1	POA 0.2	POA 0.3	PAN 0.1	PAN 0.2	PAN 0.3
p - value	-	0.356	0.146	0.042	0.147	0.079	0.021
Significance	-	NO	NO	**YES**	NO	NO	**YES**
	FE (kPa)						
p - value	-	0.161	0.067	0.045	0.849	0.226	0.048
Significance	-	NO	NO	**YES**	NO	NO	**YES**

5 Summary and conclusions

In this deliverable, the suitable fibre for FRAMs types AC and PA is experimentally investigated. Two commercially available fibres were used for this purpose. Four different AC mixtures with/without fibres were prepared for comparison purposes. Then, water sensitivity, rutting resistance and fatigue resistance tests were performed according to the European standards. Concerning fibre-modified PA mixtures a total of eight experimental designs were prepared for comparison purpose. Different functional and mechanical tests were performed such as total and interconnected air voids, permeability, particle loss in dry and wet conditions, and indirect tensile strength. In the case of rheological properties of PA mortar, in total 18 materials were designed with different bitumen types, and then mixed with/without fibres under different aging conditions. Four different testing methods were applied to measure the rheological properties of asphalt mortar in a wide range of temperatures. Regarding the fracture energy, three different fibre content tested at three different temperatures understand the experimental development of this work. A total of 21 experimental designs were carried out and three replicates per each mixture design was performed in order to observe the statistical differences between the mortar designs. It is worth to mention that the optimization of FRAMs (AC and PA) designs was not the goal of this study.

Based on the testing results, the following conclusions can be drawn:

Regarding asphalt concrete:

- Similar water sensitivity properties were found between the FRAMs prepared with fibres and the reference one prepared PmB bitumen. The positive effect of the addition of the fibres was observed when comparing it with the reference mixture prepared with the same straight bitumen (50/70). In this sense, it was confirmed that FRAMs would fulfill the Swiss normative requirements of ITSR for this type of mixtures by reaching rates higher than 70%.
- After analysing the performance obtained for the rutting resistance test, it can be concluded that the FRAM modified with Type P fibres behaves similarly to the control mixture (PmB). Nevertheless, the FRAM with type A fibres showed deeper ruts at 60°C. This fact would cause a disagreement with the current Swiss requirements.
- The incorporation of both types of fibres improved the fatigue response of the mixture with straight bitumen (reference) at lower strain levels. Nevertheless, this modification would not reach the general performance against fatigue distresses observed for the control mixture prepared with PmB.

Concerning porous asphalt:

- Fibre addition slight decrease the air voids inside the PA mixture designs. However this reduction does not affect significantly the functional performance of the mixture since the porosity was kept at a porosity greater than 20% of voids. Similarly the permeability was maintained in an admissible range.
- Concerning raveling resistance, adding type A fibres leads with a increasing in the particle loss resistance, especially in dry conditions. In wet conditions, limited improvement was observed with all fibres probably because it is required to increase the binder content.
- For the ITS, notably increments were observed adding type A fibres, independently of the filler content. The ITSR decrease when compared to the reference mixtures due to the decrease in the indirect tensile strength in wet conditions.

- The addition of type P-4 / H and type A / L of fibres to the PA mixture showed the highest improvements in terms of the fracture energy, post cracking energy and toughness of the dry conditioned specimens comparing to the reference mixtures Ref H and Ref L respectively. No improvements were observed concerning toughness for the fibre reinforced wet conditioned specimens.
- MSCRT indicates that the percent recovery of 40/100-65 mortar is about five to eight times higher than the values obtained on mortar prepared with the straight 50/70 bitumen. Mortars prepared with fibre Type P show highest value of *R* (%) suggesting a more remarkable benefits in terms of permanent deformation. Aging induces an increase in *R* (%) especially when moving from short term to long term aging level for all bitumen and fibre types.
- For LAS tests, asphalt mortars prepared with straight 50/70 bitumen were tested and evaluated. Only limited difference can be found for mortars prepared with/without mortar under different aging conditions.
- For fatigue propertis performed with the Accelerated Fatigue Test (AFT) test. With respect to two bitumen, fresh mortar prepared with fibres show rather lower fatigue life compared to the one without fibre. In the case of 40/100-65 bitumen, Fibre Type A exhibits better performance in terms of fatigue resistance compared to Type P; while Type P is better when 50/70 bitumen was used.
- For low temperature propertis of PA asphalt mortar. Siginificant differences of creep stiffness can be found only between the RTFOT and RTFOT+PAV conditions for the materials prepared with 40/100-65 bitumen. In the case of 50/70 bitumen designed mortar, no remarkable differences were found.
- At 15°C and 0°C no positive significant differences were reported regarding fracture energy properties. At -15°C due to changes in the behavior of mortar, only ITS and FE property could be measured. Regarding ITS, positive statistical differences were observed adding 0.3% type A fibres and 0.3% type P fibres. Concerning FE, the addition of fibres contributed to increase this value, this trend was clearer in the case of type A fibres.

Although the results obtained in this study are promising, additional experimental support is needed by extending the present research effort to the investigation of more types of asphalt bitumen and fibre types, and to the evaluation of the mechanical properties of fibre reinforced bituminous materials

Overall, considering the obtained results, a better mechanical performance of the FRAM (type AC) was achieved by the addition of type P fibres, since the FRAM with type A fibres showed worse rutting resistance behaviour. In the case of PA mixture reinforced with fibres, the best results were provided by the incorporation of the type A fibres.