# DIFFERENCES IN CRACKING RESISTANCE OF ASPHALT MIXTURES DUE TO AGEING AND MOISTURE DAMAGE

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## ABSTRACT

The ageing phenomenon and moisture damage become key factors to evaluate mixture cracking resistance. In this paper, the effect of ageing and water on cracking resistance and fatigue behavior in a bituminous mixture is studied. Specimens were tested by a direct tensile test (Fénix test) to obtain fracture energy values whereas variation of complex modulus and dissipated energy density was obtained by a strain sweep fatigue test (EBADE test). Results show a significant reduction in cracking resistance and fatigue life of the mixture after ageing (failure strain is reduced approximately by 35%). Water in standard conditions has very little influence.

## KEYWORDS

Ageing; cracking; fatigue; moisture damage.

# 1 INTRODUCTION

Pavement distress is mainly caused by asphalt mixtures cracking [1]. From the mechanical point of view, asphalt mixture cracking mechanisms can be analyzed under monotonic loading at low application rates or under repeated cyclic loading lower than pavement maximum resistance. The former is associated with thermal stress cracking and fracture while the latter is related to failure of the surface due to traffic loading (fatigue).

Asphalt mixture ageing is considered one of the most important factors affecting cracking resistance [2]. This phenomenon brings about changes in bitumen properties [3]. In particular, it is known to increase binder stiffness due to the convergence of various processes during the life of asphalt mixtures [4]. These processes can be attributed to chemical ageing and physical ageing or steric hardening [5, 6].

Chemical ageing is primarily associated with loss of volatiles, but more particularly, to an oxidation process. The sum of these chemical processes leads to mixture hardening and higher brittleness because of ageing of bitumen [7]. The oxidation and volatilization processes, slow at ambient temperature, are accelerated when the bitumen is subjected to high temperatures, such as during the manufacturing process, transportation and laying of the mixture. The surface layer of asphalt mixtures has been shown to age faster than the lower layers of the pavement [8]. This is because of a constant supply of oxygen on the surface due to the high temperatures and UV photo-oxidation.

Steric hardening results from a molecular reorganization process over a long period of time by which asphalt hardens at ambient temperature as time elapses. Thus, steric hardening is a physical process because it changes the rheological properties of bitumen without altering its chemical composition. For this reason, steric hardening is a reversible process. Steric hardening is associated with slow crystallization of waxes at room temperature [9]. Wax crystallization refers to the crystallization of linear alkanes present in asphaltene fractions [7]. This phenomenon causes an increase in viscosity without chemical modification of the constituents. Steric hardening can be reversed by exposure to heat or mechanical work [10].

Bitumen hardening processes result in higher mixture stiffness. This tends to increase load bearing capacity and resistance to permanent deformation of bituminous mixtures. Nevertheless, brittleness increases because of decreased bitumen ductility, causing premature pavement damage and, ultimately, cracking or total failure [11, 12].

From a mechanical standpoint, ageing can be categorized in two stages [13]: short term ageing and long term ageing. Short term ageing takes place during manufacturing and laying of bituminous mixtures [14]. Long term ageing is associated exclusively with deterioration due to environmental factors during the service life of pavement.

Most laboratory bituminous mixture ageing methods are based on maintaining the mixture (compacted or loose) in an oven at a certain temperature for a certain period of time. The ageing procedure established by SHRP is one of the most common methods [15]. It includes short term ageing, STOA (Short Term Oven Ageing), and long term ageing, LTOA (Long Term Oven Ageing). STOA consists in ageing the loose mixture in an oven for four hours at 135ºC whereas during LTOA, the mixture, previously aged by STOA, is compacted and kept in an oven for five days at 85°C. In 2009, a new ageing procedure was established by the RILEM Technical Committee. It consists in maintaining the loose mixture for 4 hours at 135°C for short term ageing and for nine days at 85ºC for long term ageing [16].

Another phenomenon associated with deterioration due to environmental factors affecting asphalt mixture durability is moisture damage [17]. It is generally caused by loss of adhesion between the bitumen and aggregate interface (adhesive failure) and/or loss of cohesion in the mixture (cohesive failure). Moisture damage mechanisms in asphalt mixes start with water transport mechanisms by which water reaches the interior of the material structure and culminate with the various manifestations of this deterioration. Obviously, problems only occur if water penetrates into the mixture. There are three main water transport mechanisms in asphalt pavement mixtures [18, 19, 20]: permeability, capillarity and diffusion. Permeability can be defined as the ability of a porous material to allow the flow of water through its voids [21]. Capillarity is defined as the elevation of a liquid above the level zero of pressure due to the total ascending force produced by the attraction of the liquid molecules to a solid surface. These factors depend on environmental conditions and the structure of voids in the mixture. Lastly, diffusion is the process where water particles (liquid and/or vapor) move through the constituent components of the mixture.

A necessary condition for good behavior of asphalt pavement mixtures is that the binder maintains good adhesion with the aggregate in order to prevent debonding. The following pavement mechanisms, acting individually or together, can produce debonding [22, 23]: detachment, displacement, spontaneous emulsification, pore pressure, hydraulic scouring and pH instability. Detachment consists in microscopic separation of the bitumen film from the aggregate surface by a thin layer of water without any apparent break in the bitumen film. During the displacement phenomenon, the presence of water affects the aggregate-bitumen bond. The debonding rate depends on mixture viscosity and compactness, as well as on the chemical forces and stresses between aggregate and binder. This rate may be very low or even zero [24]. Spontaneous emulsification results from the formation of an inverse emulsion of water droplets in the binder, for example when clay minerals or other additives are present in the mixture [25]. Pore pressure occurs when water is trapped in the air voids of the mixture. Increases in temperature and traffic loads lead to water evaporation, eventually generating sufficient pressure to cause the rupture of the binder film [26]. Hydraulic scouring is due to the action of vehicle tires on a saturated road surface [18, 26, 27]. Finally, pH instability affects the adhesion between aggregate and binder. PH stabilization in the aggregate-binder interface minimizes bond rupture, provides strong and durable links and reduces loss of coating [28].

The most common manifestation of moisture-induced distresses in bituminous mixtures is called stripping or loss of bitumen coating on the aggregate surface produced by adhesion failure. The action of water is also involved in the progressive detachment of aggregates from the mastic caused by the wheel path on the asphalt layer. This kind of distress, known as raveling, includes both adhesive and cohesive failure [29].

Laboratory analysis of asphalt mixture moisture damage tipically consists in placing specimens in a water bath at a certain temperature for a certain period of time. In some procedures, such as the one set out in the old Spanish standard NLT-162 [30], specimens are inmersed in a water bath at 60°C for 24 h or at 49°C for 4 days. Currently, and according to standard UNE-EN 12697-12 [31], samples previously subjected to vacuum are placed in a bath at 40°C for a period of time between 68 and 72 h.

Quantifying the influence of ageing and moisture on the behavior of bituminous mixtures is not easy. Normally, it is evaluated separately on the mechanical and chemical properties of mixtures. However, both factors are dependent on each other. Lu and Harvey [32, 33] showed that pavement ageing has a strong influence on moisture damage.

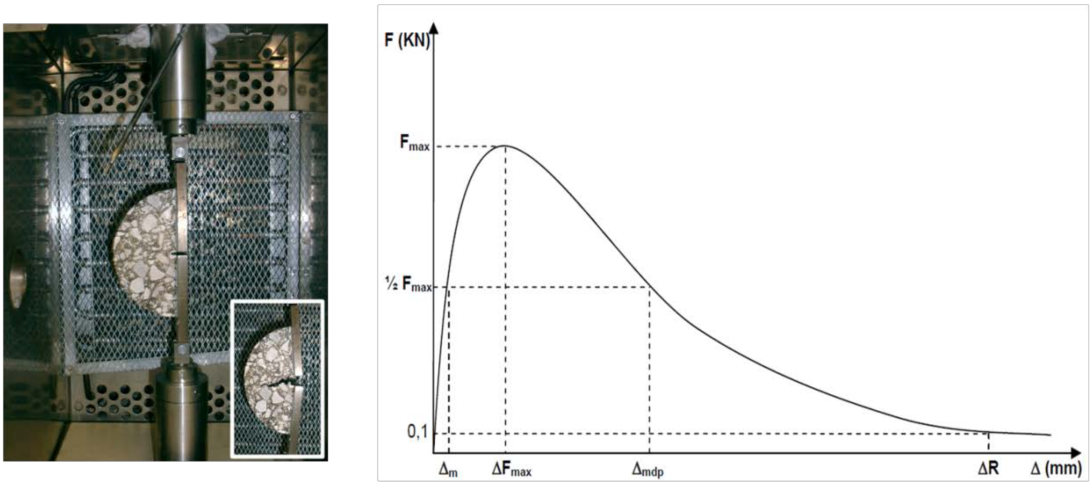
The present paper studies the effect of ageing and moisture damage on bituminous mixture cracking resistance. Two new tests are used: a direct tension test, i.e. Fénix test, and a cyclic strain sweep test, i.e. EBADE test. The former determines monotonic load cracking resistance whereas the latter studies fatigue. The aim of this work is to show the suitability of both tests to evaluate the effect of ageing and moisture damage on cracking resistance due to monotonic and cyclic loading. The study also provides insights into the cracking resistance behavior of bituminous mixtures under different environmental conditions.

These two tests (Fénix and EBADE) were developed to eliminate deficiencies found in other tests in the literature. One of the main advantages of the Fénix test is that it gives a realistic simulation of crack propagation in bituminous mixtures subjected to thermal and traffic stresses. Moreover, the test is very easy to perform both Marshall specimens and samples extracted from the pavement. As regards the EBADE procedure, advantages over other fatigue tests include shorter test duration, use of prismatic specimens to facilitate the estimation of material parameters, wide range of test temperatures, realistic simulation of fatigue behavior under thermal and traffic stresses and good test sensitivity to variation in parameters.

## 2 METHODOLOGY

Two tests developed by the Road Research Laboratory of the Technical University of Catalonia, i.e. Fénix and EBADE tests, were applied on a dense mixture to evaluate its fracture resistance and fatigue behavior under slow monotonic loading and fast cyclic loading, respectively. Furthermore, the effect of ageing and moisture damage on these two properties was determined.

The Fénix test [34] is a monotonic tensile test at constant displacement rate. A tensile effort is applied on a semicylindrical specimen which is fixed in its diametral plane by two steel plates attached to a loading platen (Fig. 1). The specimen has a notch in the middle of its flat side to facilitate cracking in that area. The test was conducted at a constant displacement velocity of 1 mm/min and 20ºC (although it can be done at other temperatures). The force applied as a function of the imposed displacement was recorded throughout the test.



(a) (b)

*Fig. 1. (a) Fénix test and cracking of the specimen after testing, and (b) load-displacement curve [35]*

The three parameters related to mechanical and resistance characteristics of the mixture tipically defined from the load-displacement curve of the Fénix test are tensile stiffness index, fracture energy and toughness index.

$$IRT = \frac{F_{50} - F_{25}}{(d_{50} - d_{25})} \tag{1}$$

$$G_D = \frac{\int_0^{d_f} F(x)dx}{S} \tag{2}$$

$$IT = \frac{\int_0^{d_f} F(x)dx}{S} \cdot \left(d_{0,5PM} - d_M\right) \tag{3}$$

where:

- $IRT$: tensile stiffness index, kN/mm
- $F_{50}$ and $F_{25}$: 50% and 25% of the peak load, kN
- $d_{50}$ and $d_{25}$: displacement values at 50% and 25% of the peak load, mm
- $G_D$: fracture energy during cracking, J/m$^2$
- $F$: load, N

- $x$: displacement, m
- $S$: surface fracture, m$^2$
- $df$: displacement at the end of the test, m
- $IT$: toughness index, J/m$^2$·mm
- $d_M$: displacement at the peak load, mm
- $d_{0,5PM}$: displacement at 50% of the post-peak load, mm

The EBADE test (strain sweep test) is a cyclic tension - compression test where a strain sweep is performed [36]. A number of cycles are applied at a constant strain level, 25 µm/mm, which is progressively increased by 25 µm/mm until failure occurs. The number of cycles in each step is 5000 and are applied at a frequency of 10 Hz. Specimens were tested at 20ºC (although it can be tested at other temperatures).

The test is conducted on a prismatic specimen with two notches in the center to reduce its area in the middle section and induce failure. Strain on this area is measured by two extensometers (Fig. 2).

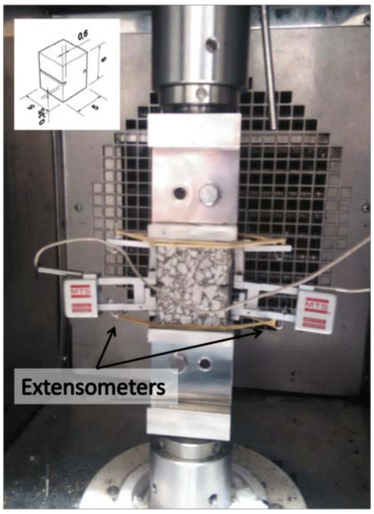


***Fig. 2. Specimen set-up during EBADE test***

Three main parameters can be obtained during each test cycle: maximum stress, $\sigma_{máx}$, complex modulus, |*E**|, and dissipated energy density, *DED*. Complex modulus is obtained from the maximum stress and strain, $\varepsilon_{max}$, by the equation

$$\varepsilon = \varepsilon_{max}\sin(\omega t) \tag{4}$$

$$\sigma = \sigma_{max}\sin(\omega t + \delta) \tag{5}$$

$$|E^*| = \sigma_{max}/\varepsilon_{max} \tag{6}$$

where equation (4) represents the strain input signal, equation (5) the stress output signal, and $\delta$ the delay between them.

The dissipated energy density in each cycle is obtained as

$$DED = \frac{1}{2}|(\sigma_1\varepsilon_2+\sigma_2\varepsilon_3+\cdots+\sigma_{n-1}\varepsilon_n+\sigma_n\varepsilon_1)-(\sigma_2\varepsilon_1+\sigma_3\varepsilon_2+\cdots+\sigma_n\varepsilon_{n-1}+\sigma_1\varepsilon_n)| \tag{7}$$

where $\sigma_i\varepsilon_i$ are the stress and strain values at each cycle.

The total sum of the dissipated energy densities is named cumulative dissipated energy density:

$$DED_c = \sum_{i=1}^{n} DED_i \tag{8}$$

As an illustrative example, Fig. 3 represents dissipated energy density versus number of cycles for the mixture tested at 20ºC. As the imposed strain level increases, the dissipated energy increases up to a certain strain level from which it drops rapidly. Failure strain is obtained as the step in which the dissipated energy decreases below 50% of the peak value during the test. The value "n" in equation (8) is defined as the number of cycles related to this step.

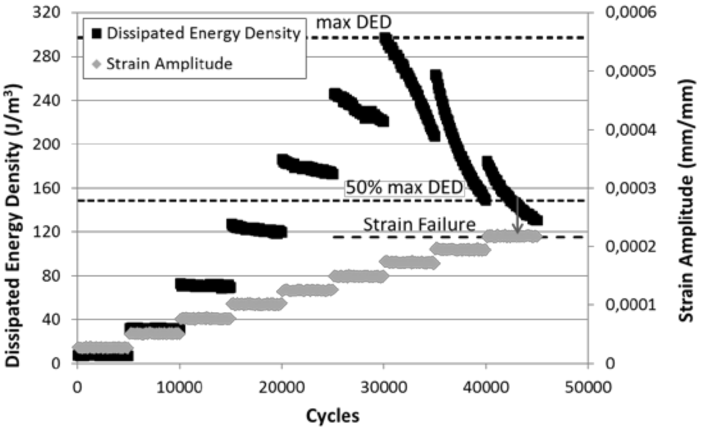


***Fig. 3. Dissipated Energy Density and strain amplitude versus number of cycles in the EBADE test at 20ºC and 10 Hz [37]***

Two dense asphalt mixtures with a maximum aggregate size of 16 mm (AC16S, according to the European nomenclature) were selected to study the effect of ageing and water on fatigue behavior. The selected aggregate gradation is at the center of the grading envelope, see Table 1. Both mixtures were prepared with the same type of aggregate and gradation but different asphaltic bitumen, a conventional one (50/70) and a polymer-modified one (PMB 45/80-65), with the characteristics shown in Table 2. The bitumen content was 4.5 % by mixture weight and mixture air voids were 3%.

***Table 1. Aggregate gradation (AC16S)***

| **Sieve (mm)** | 22 | 16 | 8 | 4 | 2 | 0.5 | 0.25 | 0.063 |
|---|---|---|---|---|---|---|---|---|
| **Passing (%)** | 100 | 95 | 67.5 | 42.5 | 31 | 16 | 11 | 5 |

***Table 2. Properties of Asphalt Binders***

| Properties | Unit | Standard | 50/70 | PMB 45/80-65 |
|---|---|---|---|---|
| **Original Bitumen** | | | | |
| Penetration at 25ºC | (0.1 mm) | EN 1426 | 61 | 57 |
| Softening Point R&B | (ºC) | EN 1427 | 50.9 | 65.3 |
| Fraass breaking point | (ºC) | EN 12593 | -14 | -15 |
| Flash Point | (ºC) | EN 2592 | 280 | 290 |
| **Residue after RTFOT** | | | | |
| Mass variation | (%) | EN 12607-1 | 0.1 | 0.29 |
| Penetration at 25ºC | (% p.o.) | EN 1426 | 66 | 64 |
| ∆ Softening Point | (ºC) | EN 1427 | 7.6 | 10 |

The study was performed on four groups of specimens: unconditioned, subjected to moisture damage, aged and subjected to moisture damage after ageing. At least three Fénix and three EBADE tests were performed for each type of conditioning (Fig. 4).

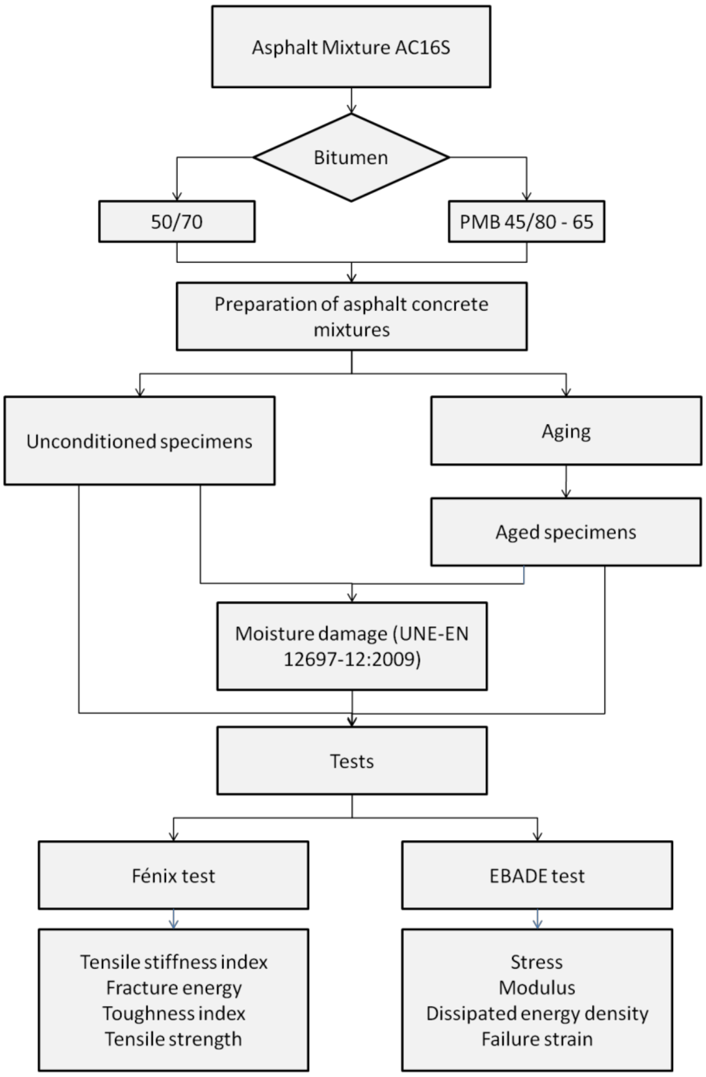


***Fig. 4. Flow chart of the study***

To simulate long term ageing, the mixture was kept loose in an oven at 85°C for 7 days. During ageing, the mixture was stirred three times, on days 2, 4 and 5. The time interval between agitations had to be over 24 hours. After ageing, the mixture became compacted.

Specimens subjected to moisture damage were conditioned according to UNE-EN 12697-12 [31] for analysis of water sensitivity in asphalt mixes. This moisture sensitivity method involves placing test samples previously subjected to vacuum at an absolute pressure of 6.7 kPa for 30 min in a water bath at 40°C for 72 h. After water conditioning, samples were dried at room temperature for three days and subsequently tested for cracking resistance.

# 3 RESULTS AND DISCUSSION

## 3.1 Fénix test

The Fénix test evaluates changes in mixture cracking resistance due to external factors. In this study, the effect of ageing and/or moisture damage was determined. Fig. 5 plots the stress undergone by the material against displacement. A significant increase in stress is observed for the aged mixture whereas the effect of moisture is hardly noticeable.

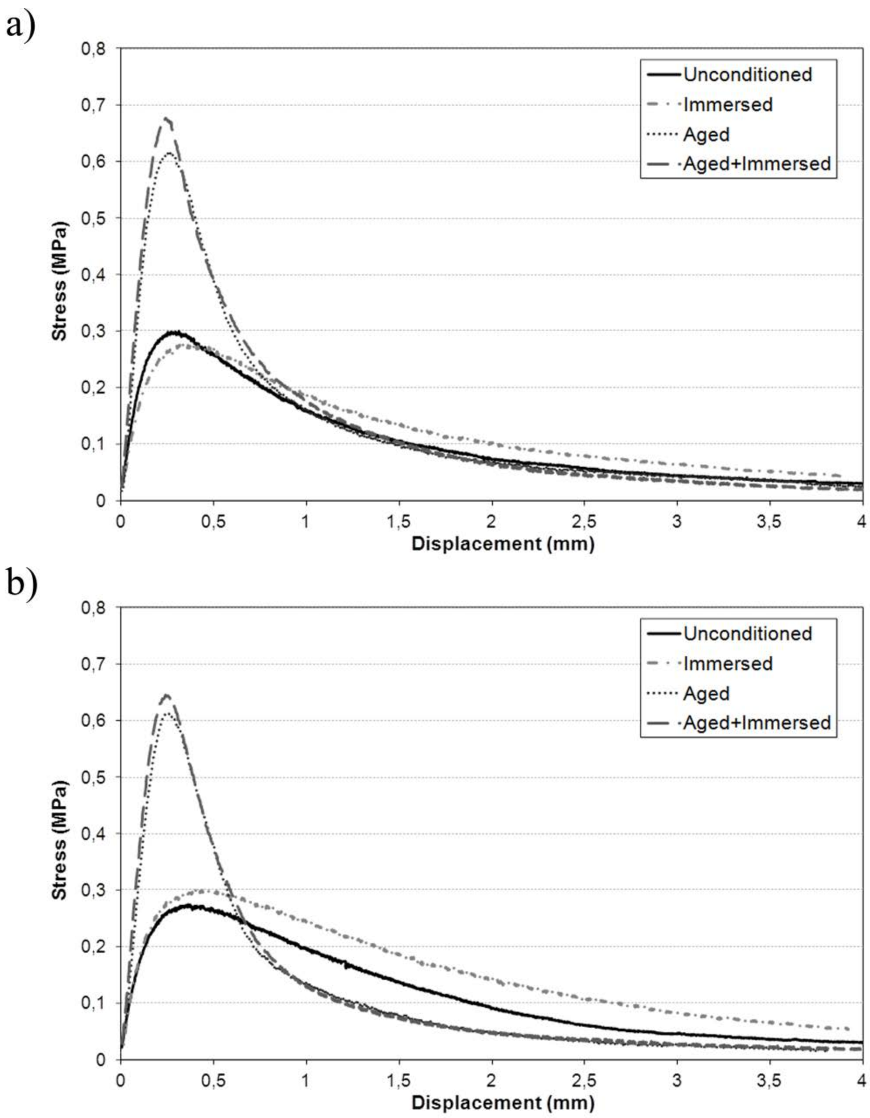


***Fig. 5. Fénix test results for all conditioning types (a) 50/70 and (b) PMB 45/80-65***

Fig. 6 shows the relationship between tensile stiffness index, $I_{RT}$, and fracture energy, $G_D$. As can be seen, a large difference in stiffness between unconditioned mixtures (unaged) and aged mixture is obtained. However, the effect of water on stiffness is minimal. Fracture energy, which represents the work required for crack initiation, tends to increase slightly with ageing. The rise in stiffness after ageing leads to an increase in the stress that the mixture can withstand, as shown in Fig. 5. This is more pronounced for bitumen 50/70 mixtures. Although the energy of PMB 45/80-65 mixtures is initially higher than of bitumen 50/70 mixtures, this trend is reversed after ageing.

Furthermore, analysis of the effect of water shows that water causes a slight increase of both stiffness and energy for unaged mixture. After ageing, the effect is the same for PMB 45/80-65 mixture, but stiffness decreases slightly (and energy increases) for bitumen 50/70 mixture. These results seem to indicate that mixtures subjected to moisture damage have greater cracking resistance than unconditioned mixtures. At medium temperatures, ageing generally results in increased stiffness, as reflected by the increase in the maximum stress that the mixture can withstand. This increase leads to an increase in fracture energy. Therefore, the increase in stress is higher than in toughness. The effect of ageing depends on the temperature and/or type of bitumen. In this study, at a test temperature of 20ºC, the effect of ageing is more pronounced in bitumen 50/70 mixtures than with PMB 45/80-65 mixtures. The effect of water on unaged mixtures follows this pattern, although the increase in stiffness is lower than that caused by ageing. The action of hot water may cause slight ageing of the bitumen. Thereby, if stiffness increases, energy also increases (a slight reduction of stiffness can be observed for bitumen 50/70 mixture). For unaged mixtures, the effect of water is less strong. However, it seems that stiffness in the PMB 45/80-65 mixture could increase further than in the bitumen 50/70 mixture. For these reasons, the effect of moisture damage on this AC16S mixture (dense, made with limestone aggregate, with good adhesion and low void content) causes slight ageing [38] but not enough to cause severe damage. Thus, the mixture seems to behave better. This effect fits with the "washing effect" defined by Das *et al*. [39], according to which the microstructure of aged mixtures improves after subjecting them to the action of water. However, this change in the microstructure results from the removal of products generated by the ageing process by the water. This eventually reduces bitumen or mastic thickness in the asphalt mixture. Consequently, degradation of the asphalt mixture owing to ageing is worsened by moisture damage. For this reason, if the water immersion were longer, the effect of water on the mixture would problably be completely different. However, this point is not reached in the tests.

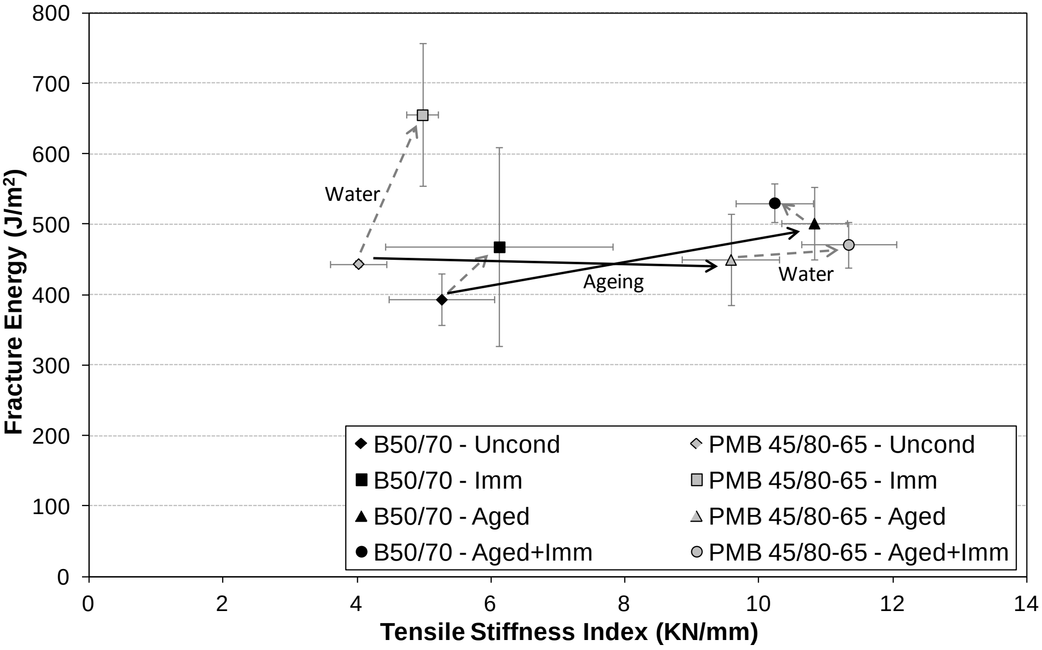


***Fig. 6. Fracture energy ($G_F$) versus tensile stiffness index ($I_{RT}$) for all conditioning types. Fénix test***

The toughness index assesses the fracture type (more or less ductile) of the mixture. A comparison of the results for the two bitumens shows that the unaged PMB 45/80-65 mixture exhibits higher values of toughness index than the bitumen 50/70 mixture, Fig. 7. These values are consistent with the low values of tensile stiffness index. This indicates that the fatigue life of the unaged PMB 45/80-65 mixture will be higher than that of the bitumen 50/70 mixture. Mixture ageing, irrespective of bitumen type, leads to increased stiffness and decreased toughness, hence the brittle behavior of aged mixtures. With regard to moisture damage, an increased in toughness (and in stiffness) is observed for unaged mixtures. This effect is more pronounced for PMB 45/80-65 mixtures than bitumen 50/70 mixtures. However, moisture damage in aged mixtures barely changes toughness values. As with energy, the effect of water on aged mixtures is similar to that of slight ageing, i.e. insufficient to damage the mixture. Energy and toughness increase with the increase in stiffness and stress, leading to some improvement in mixture behavior. However, the effect of water on toughness after ageing, when the mixture is damaged, is hardly noticeable.

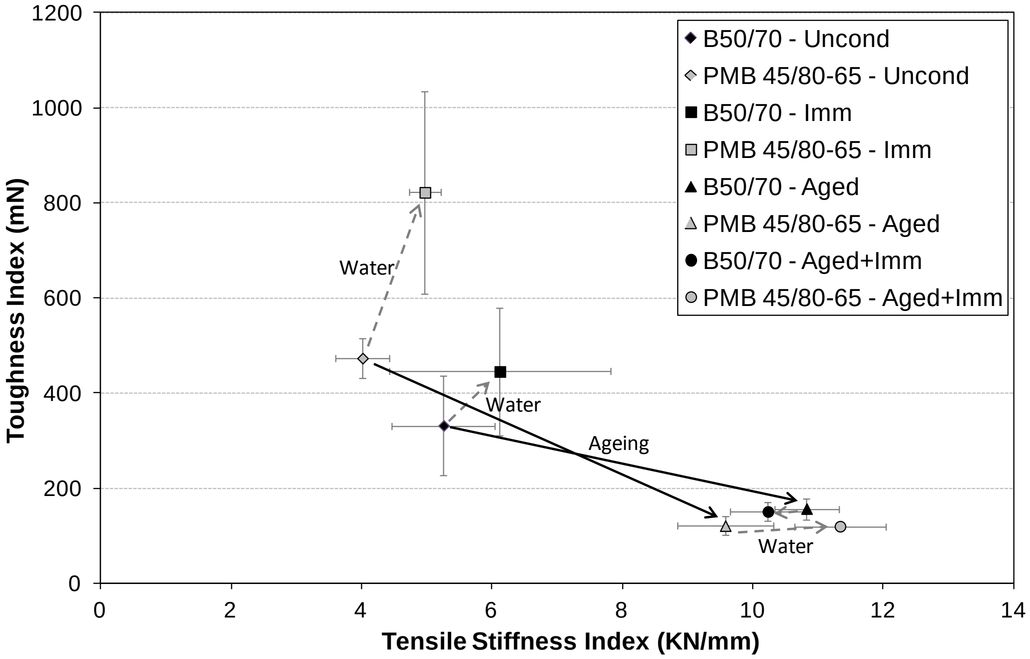


*Fig. 7. Toughness index (IT) versus tensile stiffness index ($I_{RT}$) for all conditioning types. Fénix test*

## 3.2 EBADE test

The EBADE test results are presented. Fig. 8 shows the variation in stress for the unconditioned mixture and after being subjected to moisture damage, aged, and subjected to moisture after ageing for all strain steps applied. For the same strain level, stress values are higher for aged mixtures (subjected or not to moisture damage). These differences in stress values are more notable for bitumen 50/70 mixtures. When these mixtures are subjected to ageing, stress values tend to fall sharply after specimen failure. As expected, specimen failure in aged mixtures occurs after a fewer number of cycles. Although they show similar patterns of behavior, PMB 45/80-65 mixtures have lower stress values and require a greater number of cycles to failure. After ageing, PMB 45/80-65 mixture stress values tend to fall faster but more gradually than for bitumen 50/70 mixtures, showing that PMB 45/80-65 mixtures perform better against ageing. On the contrary, differences between mixtures subjected or not to moisture damage are hardly insignificant, as shown by Fénix results.

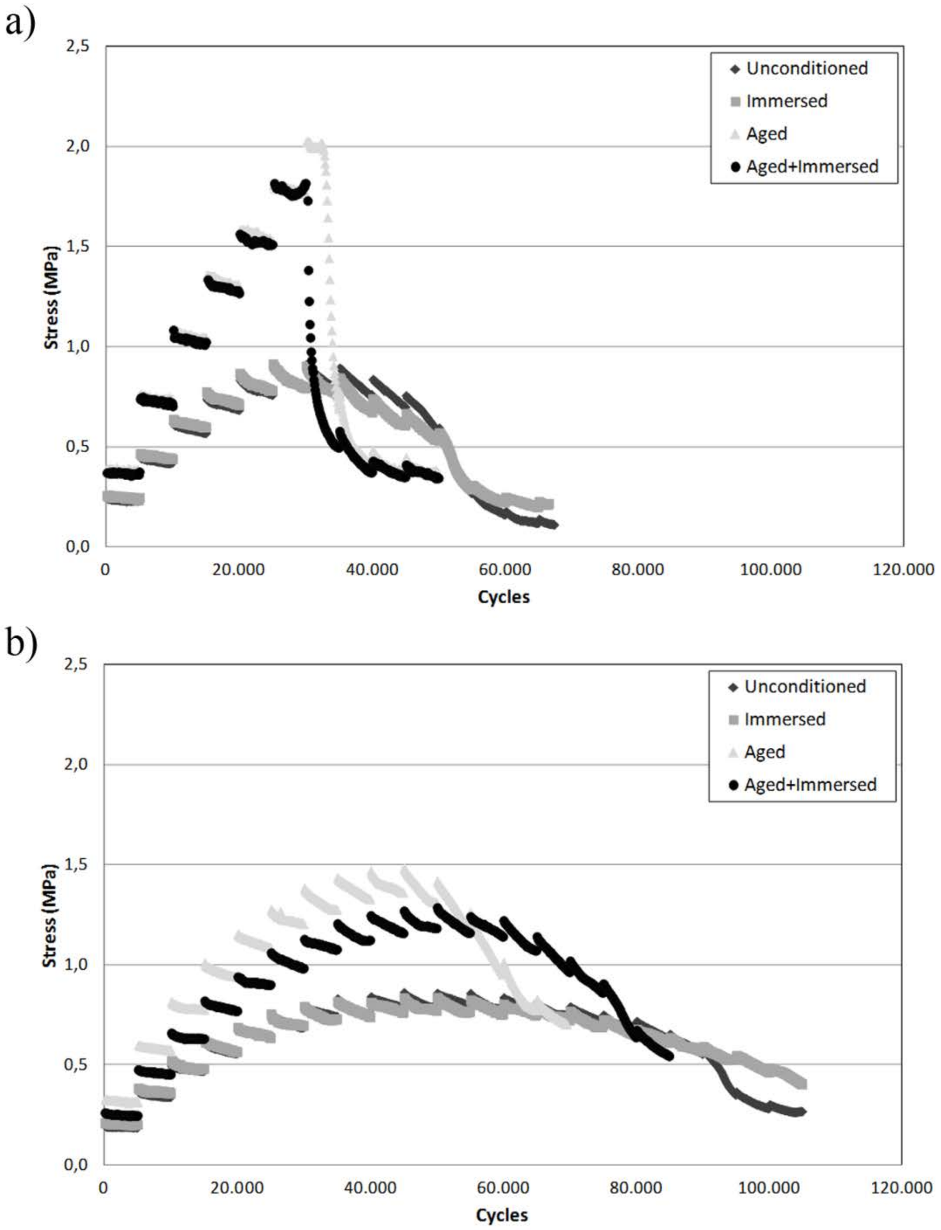


***Fig. 8. Stress versus number of cycles for all conditioning types (a) 50/70 and (b) PMB 45/80-65. EBADE test***

The evolution of modulus during the test is represented in Fig. 9. The set of curves shows the progressive deterioration of mixtures during fatigue. The initial modulus of aged mixtures subjected or not to moisture damage is significantly higher than that of unconditioned mixtures or those subjected to moisture damage.

A variance analysis of the effect of conditioning and bitumen on the initial modulus was conducted. A stadistically significant effect on the initial modulus was obtained F(7,19)

= 41.14, $p<0.05$, $\eta^2=0.94$. The comparison of values indicates that there are statistically significant differences between unconditioned and aged bitumen 50/70 mixtures $t(4) = -4.94$, $p <0.05$ and PMB 45/80-65 mixtures $t(4) = -8.39$, $p<0.05$.

Moreover, the modulus of aged mixture (or aged and subjected to moisture damage) tends to remain constant during the first strain steps. By contrast, the modulus of unconditioned mixtures decreases progressively with the number of cycles. Above a certain strain level, the modulus tends to decrease sharply, thus explaining the differences in brittle behavior of the aged and unaged mixtures, which is similar to the toughness behavior obtained from Fénix test.

The effect of ageing on bitumen 50/70 mixture is stronger than on PMB 45/80-65 mixture. On the other hand, the PMB 45/80-65 mixture exhibits more ductile and less brittle behavior.

Finally, mixtures subjected and not subjected to moisture damage behave similarly. This again indicates that the effect of water (for the imposed conditioning and mixture type) is minimal.

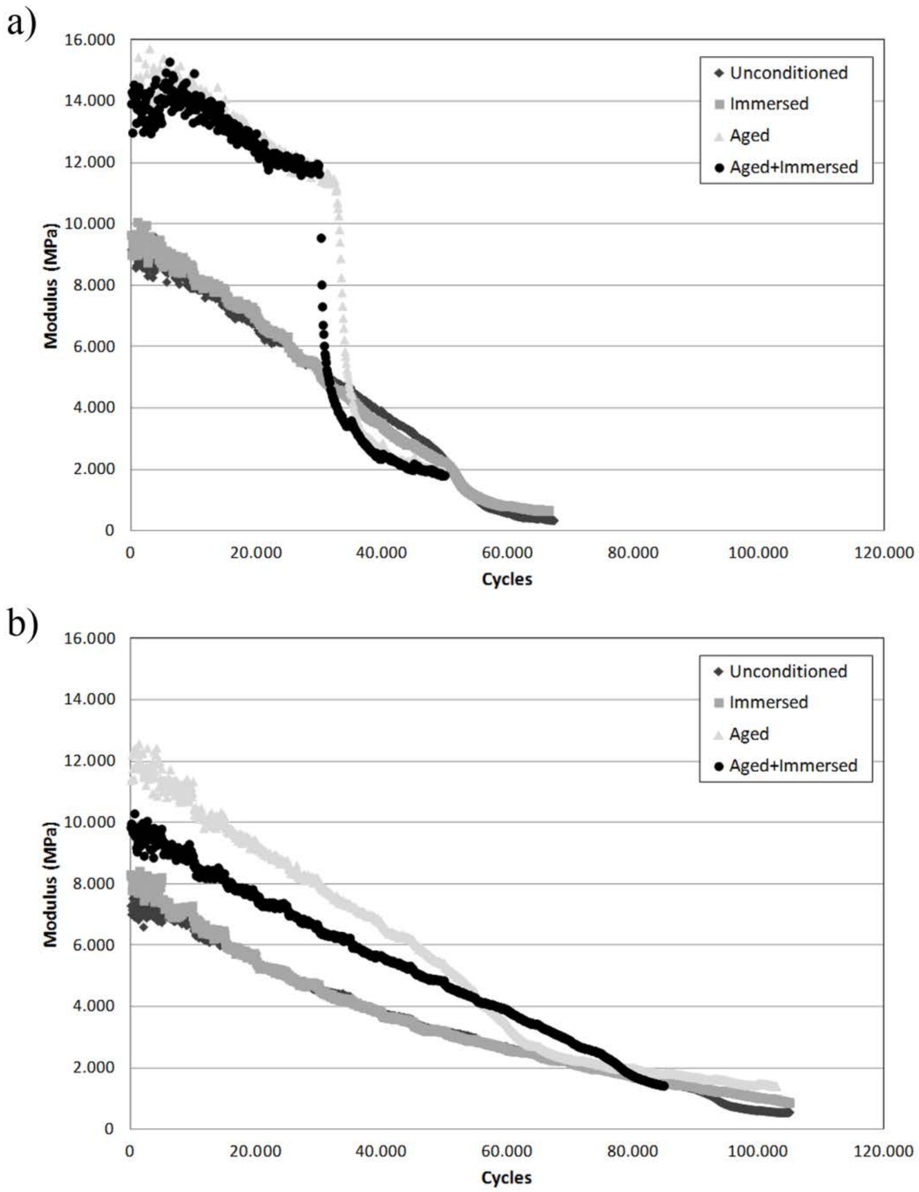


***Fig. 9. Modulus versus number of cycles for all conditioning types (a) 50/70 and (b) PMB 45/80-65. EBADE test***

From the dissipated energy density curve (Fig. 10), the mixture fatigue failure criterion is defined as the strain level at which the dissipated energy is reduced to half its maximum value. According to this criterion, failure of mixtures, unconditioned or conditioned, manufactured with the two bitumens, occurs for the strain values in Table 3. Failure of the mixtures subjected to the action of water is similar or very similar to that of unconditioned (unaged or aged) mixtures. However, failure of aged mixtures decreases significantly compared to that of unconditioned mixtures. It changes from

0.000257 mm/mm to 0.000175 mm/mm for the bitumen 50/70 mixture, and from 0.0005 mm/mm to 0.00035 mm/mm for the PMB 45/80-65 mixture.

Fig. 10 also shows how the two unaged mixtures accumulate much more dissipated energy during the fatigue process than aged mixtures. Once energy begins to decrease in each cycle, it takes several strain steps before failure of unaged mixtures occurs whereas aged mixtures fail faster.

The comparison of mixtures also reveals that the PMB 45/80-65 mixture dissipates more energy than the bitumen 50/70 mixture. Moreover, several strain steps are needed to failure after ageing whereas the bitumen 50/70 mixture normally fails after a single strain step.

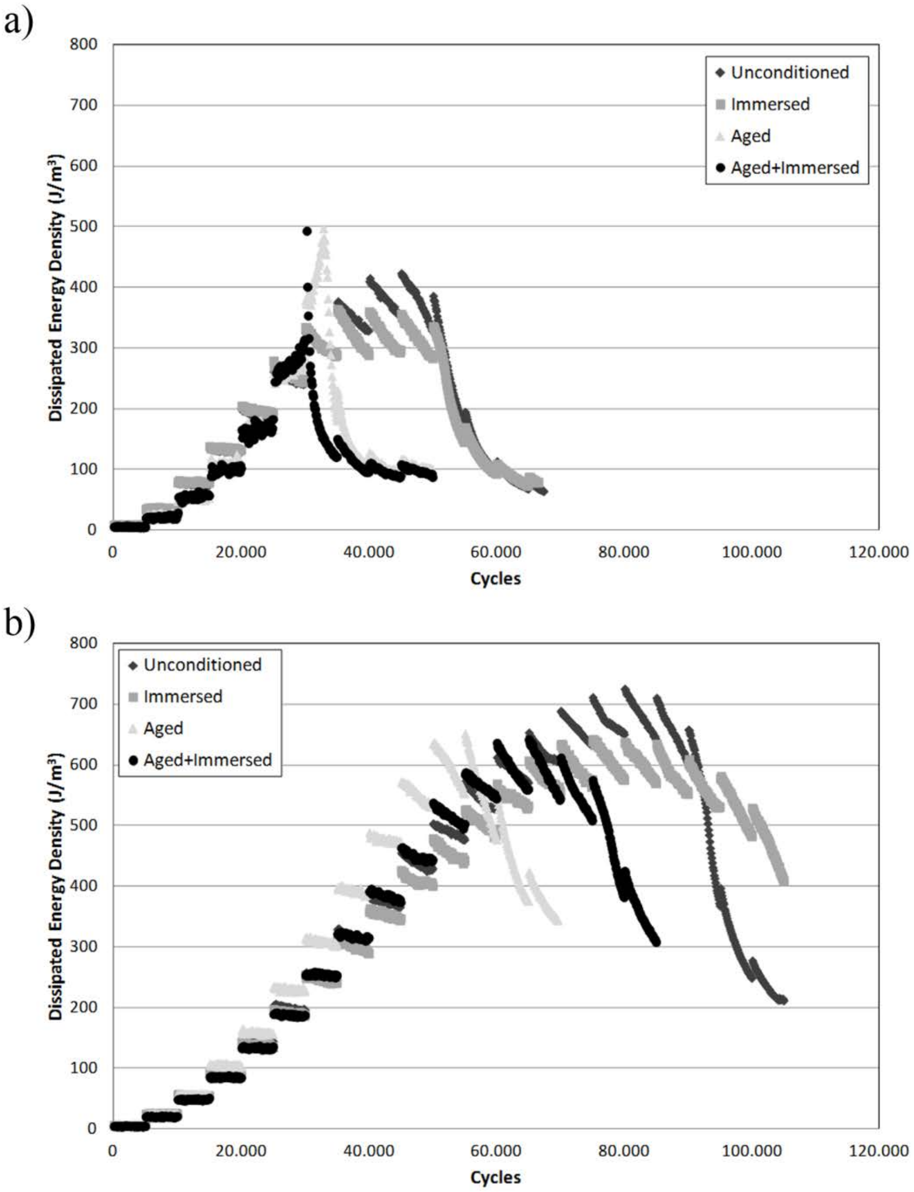


***Fig. 10. Dissipated Energy Density versus number of cycles for all conditioning types (a) 50/70 and (b) PMB 45/80-65. EBADE test***

*Table 3. Failure strain. EBADE test*

| Mixture Bitumen | Conditioning | Failure strain |
|---|---|---|
| **50/70** | Unconditioned | 0.000275 |
| | Immersed | 0.000275 |
| | Aged | 0.000175 |
| | Aged + Immersed | 0.000175 |
| **PMB 45/80-65** | Unconditioned | 0.0005 |
| | Immersed | 0.00055 |
| | Aged | 0.00035 |
| | Aged + Immersed | 0.000425 |

Fig. 11 plots the initial modulus in the first step of 5000 cycles versus failure strain. It is clearly observed that, for aged mixtures, the initial modulus increases significantly whereas failure strain decreases.

However, moisture damage has a much smaller effect on these parameters. Initial modulus and failure strain of bitumen 50/70 mixtures exhibit very similar values before and after subjecting the mixture to the action of water. Differences are greater in PMB 45/80-65 mixtures but far smaller than those produced by ageing. In this case, failure strain after the action of water is slightly higher than for unconditioned mixtures.

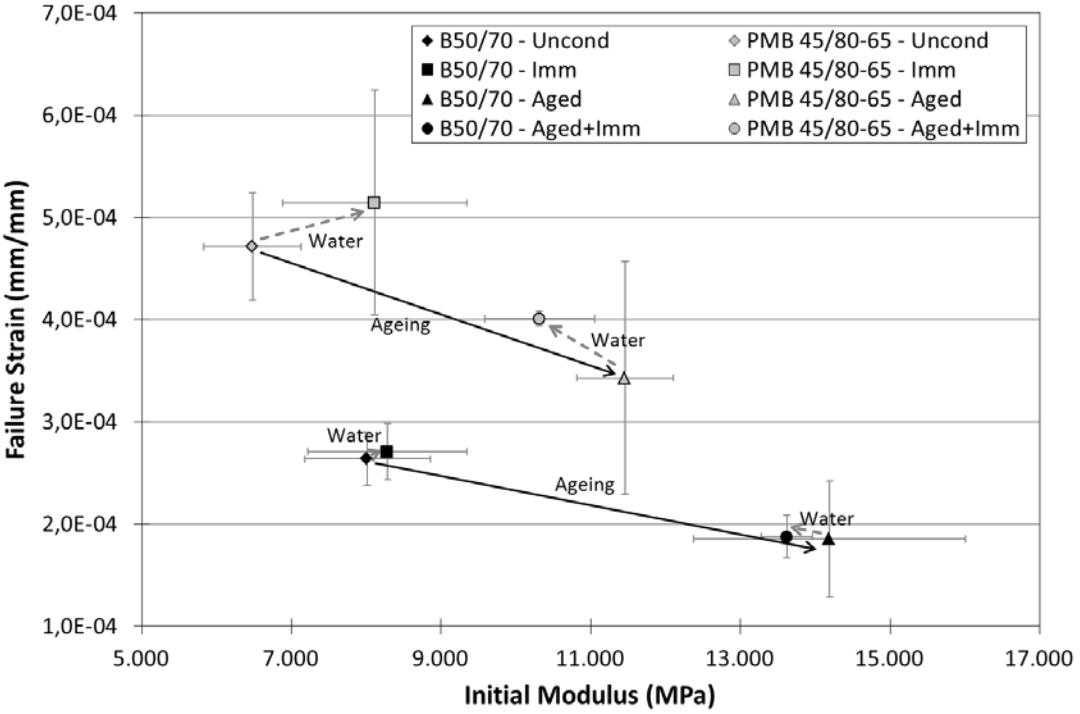


*Fig. 11. Failure strain versus modulus for all conditioning types. EBADE test*

Another observation is Fénix and EBADE results of mixtures subjected to moisture damage, whether unaged or aged, are very similar. Their properties even seem to improve when they are subjected to moisture damage. The reason for this might be that the water conditioning test is not aggressive enough for this mix AC16S type (dense mixture, made with limestone aggregate, with good adhesion and low void content). This causes a visco-plastic response of the bitumen which results in improved aggregate bonding [40]. In addition, the action of water leads to slight ageing of the mixture which apparently improves its behavior. Under these conditions, the effect of water is less than that of ageing, which is applied to the loose mixture. This demonstrates that mixture design properties can become decisive factors in their fatigue behavior against external factors, i.e. water and ageing, which can be evaluated by the EBADE test.

## CONCLUSIONS

An experimental study was performed to evaluate the effect of ageing and moisture damage on cracking resistance and fatigue behavior of a dense mixture (AC16S type) by a monotonic direct tension test (Fénix) and a cyclic strain sweep test (EBADE). The responses of the mixture subjected to moisture damage, aged in laboratory, and then subjected to moisture damage were evaluated and compared with those of the unconditioned mixture.

Toughness index and dissipated energy in the study of the mixture fracture were assessed by Fénix test. Ageing results in higher stiffness and lower toughness, thus increasing brittleness. However, the effect of water is minimal, even with slight increases in stiffness, energy and toughness. This may be due to the fact that water immersion conditions are not aggressive enough for this type of mixture (dense, made with limestone aggregate, with good adhesion and low void content). Water leads to slight ageing of the mixture, which apparently improves its response.

The mixture degrades gradually during fatigue testing, resulting in lower stiffness (modulus) with the number of cycles. In unaged mixtures, the initial modulus decreases progressively with the number of cycles. In aged mixtures, the much higher initial modulus decreases sharply from a certain level of strain, reflecting the brittle behavior of mixtures due to ageing. Furthermore, cumulative dissipated energy density decreases in aged mixtures, which means that they are capable of dissipating less energy during the fatigue process. Likewise, failure strain decreases significantly, and consequently, the number of cycles that the mixture withstands decreases too. As with Fénix, EBADE test shows few differences between mixtures subjected or not to moisture damage.

Variations in stiffness, toughness or failure strain of mixtures due to the action of water are relatively small compared to variations of these parameters before and after ageing (considering that water immersion conditions are mild). This shows that mix composition and mix design properties can become decisive factors in their cracking response to external factors.

The use of different types of bitumen for the same mixture may condition fracture and fatigue responses. The PMB 45/80-65 mixture has a better performance against ageing and moisture damage since it shows lower brittleness and greater failure strain than the bitumen 50/70 mixture.

## ACKNOWLEDGEMENTS

The authors would like to thank the Ministerio de Economía y Competitividad (Spain) for its assistance in the project PROFIS (BIA2012-36508), established within the framework of the VI Plan Nacional de Investigación Científica, Desarrollo e Innovación Tecnológica, co-financed with funds from the European Regional Development Fund (ERDF) of the European Union. The work of the first author was partially funded by the Ministerio de Economía y Competitividad, Spain (Research Grant BES-2013-065678). The authors would also like to acknowledge the company CEPSA for supplying and characterizing the bitumens used in this study.

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