NEW APPROACH TO CHARACTERIZE CRACKING RESISTANCE OF ASPHALT BINDERS

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Abstract

Asphalt binder characterization is a complex and difficult task due to its rheological behaviour. Indeed it has been traditionally realized by means of simple tests at an established temperature. An added challenge is that low temperatures, as well as binder aging, lead to significant changes in the viscoelastic behaviour of binders. This study aimed to characterize asphalt binders, not through the traditional procedures, but through the ductility and tenacity that they provide to a mixture, being these two properties directly related to the cracking response of the binder. To this end, a new approach for asphalt binder characterization was proposed based on the application of the Fénix test on a standard mixture with a defined aggregate gradation and composition, without fines or filler, manufactured with different types of binders and tested at different temperatures, as well as subjected to accelerated aging in laboratory. The obtained results showed the thermal susceptibility of binders, which evidence the need to characterize binder performance at different temperatures to obtain a reliable cracking response. In addition, binder aging results in a more brittle cracking fracture, being the aging effects more pronounced in high penetration binders.

Keywords: asphalt binder, cracking resistance, aging, temperature, Fénix test

1. Introduction

Asphalt binder characterization has always presented some complexity due to the rheological behaviour of the tested material. Bituminous mixtures show significant variations in mechanical properties with load application speed and temperature due to the thermal susceptibility and viscoelastic behaviour of asphalt binders [1]. At low temperatures and short load application times, binder response is elastic, while at high temperatures and long periods of load application the response is viscoplastic. Likewise, binder aging also changes its rheological behaviour [2].

Due to the complexity of such a study, characterization of asphalt binder behaviour has been classically realized by means of simple tests, which partially assess the binder properties at an established temperature (penetration, softening point, ductility, fragility point, viscosity, among others).

However, the aim of this research is to characterize asphalt binders, not by these traditional procedures, but through those characteristics that are directly related to the properties that binders have to provide to the asphalt mixture for an appropriate performance of the pavement. And probably, the most representative characteristic of asphalt binders' performance, which differentiates them from other binders such as cement, is their rheological properties, such as ductility and tenacity that represent the ability to withstand tensile stresses that can lead to cracking failure and fracture of pavement [3].

Therefore, this paper evaluates the ductility and tenacity that different types of asphalt binders provide to a mixture under different environmental conditions by applying the Fénix test [4] [5]. This test, developed by the Road Research Laboratory of the Technical University of Catalonia, evaluates the crack resistance of asphalt mixtures by calculating the dissipated energy during mixture cracking [6].

However, the cracking resistance of a mixture, as most mechanical properties, is not only influenced by the binder type and content, but also by a wide range of factors such as the type and content of filler that constitutes the mastic or the amount and nature of the fines.

Recently, numerous researchers have investigated the influence of asphalt binders on the cracking resistance of mixtures by establishing a correlation between the rheological properties of the binders using conventional tests, e.g. elastic recovery test, bending beam rheometer or dynamic shear rheometer, and the cracking performance of asphalt mixtures at a defined temperature, e.g. overlay tester or indirect tension test [3] [7]. Others have tried to establish a correlation between the critical cracking temperature for both asphalt binders and mixtures at low temperatures [8] [9]. However, relationships between binder tests and mixtures tests have not been fully established due to significant differences in the test temperature. Based on the encountered discrepancies, this study aims to directly characterize the cracking resistance that different asphalt binders withstand by applying a direct tensile stress under different test temperatures.

In order to isolate the effect of the asphalt binder, the cracking resistance provided by the asphalt binder has been evaluated on a standard mixture with a defined gradation and composition, without fines or filler, where only the binder content is providing the cohesion of the mineral skeleton. This test methodology, which consists of isolating the effect of asphalt binder through a defined standard mixture, has attracted significant researchers' attention who have used it to evaluate the bonding ability provided by the binder in the aggregate-asphalt matrix, as well as the effect of temperature, moisture damage and aging of binder on the adhesion mechanism [10]. This methodology was named the UCL method (Universal Binder Characterization) [11]. Under these conditions, the cracking performance of the mixture will be exclusively influenced by the type of binder. In other words, the role of the mineral skeleton is to become a holder to characterize the performance of the binder type.

It is worth pointing out that cracking resistance may become critical at low and intermediate temperatures due to the thermal susceptibility and viscoelastic behaviour of asphalt binders [9] [1]. Under this temperature range, asphalt binder hardening process results in higher mixture stiffness; thus, brittleness increases due to the decreased binder ductility. Similarly, this change in binder properties may also occur due to the long term aging of the binder [12]. This process can be attributed to chemical aging, mainly explained by the thermal-oxidation and photo-oxidation, or steric hardening [13].

Generally, the aging process brings about mechanical and chemical changes in binder properties, leading to an increase in asphalt binder stiffness, impoverishing its adhesive capacity and reducing its coating properties [14]. If this loss of ductility is combined with the effect of low temperatures, consequences can be even more severe.

Therefore, in order to fully characterize cracking resistance of asphalt binders, the test will be performed under a wide range of working temperatures to evaluate their thermal susceptibility, especially under low temperatures when asphalt binder becomes significantly more brittle, as well as the consequences of the aging process.

Hereafter, a description of the followed methodology and Fénix test applied on five different asphalt binders, under a wide range of temperatures, as well as the influence of aging, is provided.

2. Methodology and materials

The aim of this research is to characterize asphalt binders by evaluating the ductility and tenacity that they provide to a mixture through the application of the Fénix test. In particular, two aspects have been considered: (1) the effect of binder typology and (2) the effect of binder aging.

It is worth noting that the Fénix test is a direct tensile strength test that evaluates the cracking resistance of asphalt mixtures, a property that is influenced by many other factors beside the type of binder. Therefore, in order to isolate the effect of the binder, the cracking resistance provided by the asphalt binder has been evaluated on a standard mixture with a defined gradation and composition, without fines or filler, the same type of aggregate and characterized by a high void content. Then, the only variable was the type of binder, so the differences observed in the cracking response of the standard mixture were due entirely to the binder type.

To this aim, five asphalt binders covering a large portion of the current market were evaluated: four conventional binders, B15/25, B35/50, B70/100 and B160/220, and a polymer modified binder, PMB 45/80-65. Thus, a wide spectrum of binder consistencies is covered and conventional binders can be compared to the modified binder. Binders' specifications are shown in table 1.

Table 1 Properties of the evaluated asphalt binders

Test	**Unit**	**B15/25**	**B35/50**	**B70/100**	**B160/220**	**PMB 45/80-65**
Penetration at 25ºC	(0.1 mm)	24	39	80	184	57
Softening point R&B	(ºC)	62	53.6	46.0	39.2	65.3
Penetration index	(ºC)	-0.19	-0.90	-1.11	-0.74	-
Elastic recovery at 13ºC	(%)	-	-	-	-	74

The standard mixture had a defined composition, without fines or filler, a fixed binder content of 4.5% (by weight of the aggregate) and a gradation composed of 80% of aggregated size between 2.5 and 5 mm and a 20% of aggregate size between 0.63 and 2.5 mm. Only porfidic aggregates were used. Marshall specimens were manufactured with 50 blows per side and the air voids content was around 28%. This aims to minimize the effect of any other factor on the cracking response of the mixture other than the binder type.

Table 2 Aggregate gradation

Sieve size (mm)	**% passing**
5	100
2.5	20
0.63	0

In order to evaluate the cracking resistance that, in these conditions, the different asphalt binders provide to the mixture, the Fénix test was applied. The Fénix test procedure consists of subjecting one half of a 101.6 mm diameter cylindrical specimen prepared by the Marshall method to a tensile stress at a constant displacement velocity (1 mm/min) and specific temperature [6]. A 6 mm-deep notch is made in the middle of its flat side where two steel plates are fixed. The specimen is glued to the steel plates with an adhesive mortar containing epoxy resins. Each plate is attached to a loading platen so that they can rotate about fixing points.

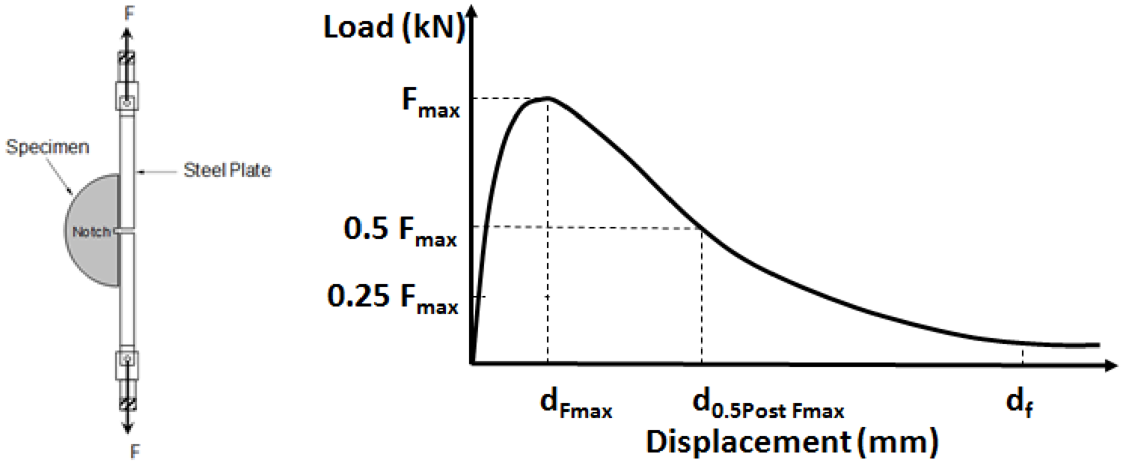

Figure 1 Fénix test set-up and stress-displacement output curve [4]

Stress and displacement data are recorded throughout the test, and based on this output curve, the parameters involved in the cracking process are obtained: tensile stiffness index, fracture energy and toughness index.

The Tensile Stiffness Index (IRT) represents the slope of the stress-displacement curve between 25% and 50% of the peak load, and it is related to the mixture modulus. It is obtained using the following equation (1):

$$\mathrm{IRT} = \frac{0.5F_{max} - 0.25F_{max}}{d_{0.5Fmax} - d_{0.25Fmax}} \qquad (1)$$

where

IRT: tensile stiffness index (kN/mm)

F_{max}: peak load (kN)

$d_{0.25Fmax}$ and $d_{0.5Fmax}$: displacement before peak load at 25 and 50% of the peak load (mm), respectively

Fracture energy (G_F) during cracking is calculated by Eq. (2):

$$G_F = \frac{\int_0^{d_f} F(u) \cdot du}{S} \qquad (2)$$

where

G_F: fracture energy (J/m^2)

F: load (kN)

u: displacement (mm)

S: fracture surface (m^2)

d_f: displacement at the end of the test (mm). It is considered that the test ends at $4 \cdot 10^{-2}$ m of displacement.

The toughness index (TI) is defined as the fracture energy during the post-peak part of the curve, weighted by the displacement between the maximum load and 50% of maximum post-peak load, eq. (3):

$$\mathrm{TI} = \frac{\int_{d_{Fmax}}^{d_f} F(u) \cdot du}{S} \cdot (d_{0.5PostFmax} - d_{Fmax}) \qquad (3)$$

where

TI: toughness index (J·mm/m^2)

F: load (kN)
u: displacement (mm)
S: fracture surface (m^2)
d_{Fmax} and $d_{0.5PostFmax}$: displacement at maximum load and displacement at 50% post-peak load (mm), respectively

Finally, the displacement at 50% post-peak load ($d_{0.5PostFmax}$) has been considered as a parameter directly related to the ductility of the mixture, since it allows evaluating the type of fracture [15].

To assess the influence of temperature on each cracking parameter, the test has been performed at different temperatures: 20, 10, 5 and -5ºC. Apart from the above test temperatures, other temperatures were selected for testing certain binders, i.e. 30ºC for the low penetration binders and -15ºC for the high penetration binders. Before testing, specimens were kept for a minimum of 12 hours at the test temperatures. The obtained results for each cracking parameter at every single test temperature have been represented to obtain the state curve of each binder, which allows visualising their thermal susceptibility.

Finally, it is intended to evaluate the effect of aging on the cracking resistance, and in particular the combined effect of aging and low temperatures. To simulate the effect of long term aging (LTOA) on cracking resistance, the standard mixtures manufactured with two types of conventional binders (B15/25 and B70/100) were subjected to a LTOA procedure established by the RILEM Technical Committee, which consists of maintaining the loose mixture for nine days at 85ºC [16]. However, in this study the specimens were kept for 7 days in accordance with the conclusions from the Van der Bergh research, which concluded that the results obtained with 7 days aging are similar to those with 9 days [17]. After aging, the specimens were compacted and tested at the same temperatures as the unconditioned specimens.

At least three replicate samples were tested at each temperature for each binder type to ensure the repeatability of the results.

3. Results and discussion

3.1. Asphalt binder type analysis

The application of the Fénix test to each (unaged) binder under different temperatures plots the stress undergone by the standard mixture against displacement. As an example, the Fénix test results for all tested binders at 5ºC are given in figure 2.

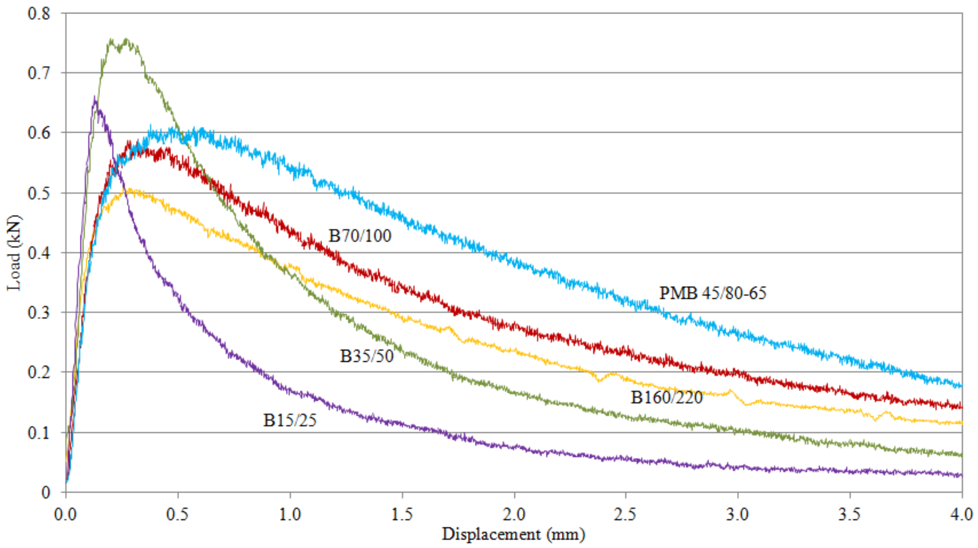

Figure 2 Stress-displacement curve at a test temperature of 5ºC

Fig. 2 shows the difference in behaviour between tested binders. The initial increased slope of the stress-displacement curve represents the stiffness while the rapidly dropping post-peak curve provides a sense of the brittleness of the binder. Thus, it can be observed that the B15/25 binder reflects the higher stiffness and brittleness at a test temperature of 5ºC.

Based on this output curve, the parameters involved in the cracking process are obtained. The mean values for fracture energy, tensile stiffness index, toughness index and displacement at 50% post-peak load were obtained from three individual results.

3.1.1. Fracture energy (G_F)

Fig. 3 illustrates the change in fracture energy, which represents the work required for crack initiation, with temperature for all the tested binders: B15/25, B35/50, B70/100, B160/220 and PMB 45/80-65.

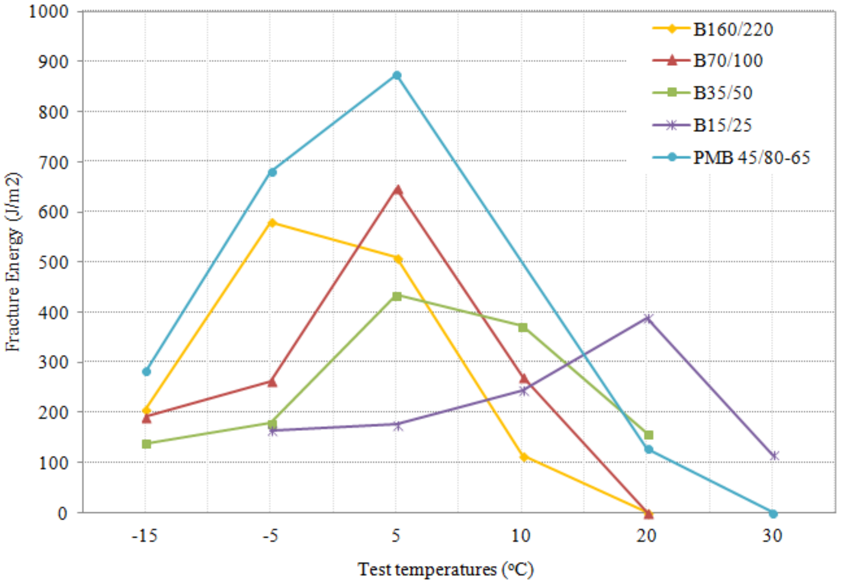

Figure 3 Fracture energy versus temperature for all binders

The fracture energy clearly varies on the basis of the type of binder and the test temperature. It is observed that asphalt binders reach a maximum of the fracture energy at different temperatures depending on their nature.

In the case of conventional binders, maximum values occur at lower temperature as the penetration degree of the binder increases. Likewise, high penetration binders present greater values of fracture energy, and consequently the highest resistance to the cracking process. On the other hand, the polymer-modified binder presents maximum values and, thus, the highest resistance to crack-propagation almost over the whole range of studied temperatures due to its greater ductility.

At low temperatures (-15ºC) all curves tend to converge at the same value, around 200J/m^2. This is due to the thermal susceptibility and viscoelastic behaviour of the binders. Under this temperature range, the binder hardening process increases the load bearing capacity as well as the brittleness, so fracture occurs very rapidly and similarly for all binders.

3.1.2. Tensile Stiffness Index (IRT)

The tensile stiffness index assesses the tested specimen modulus or the stiffness of the mixture.

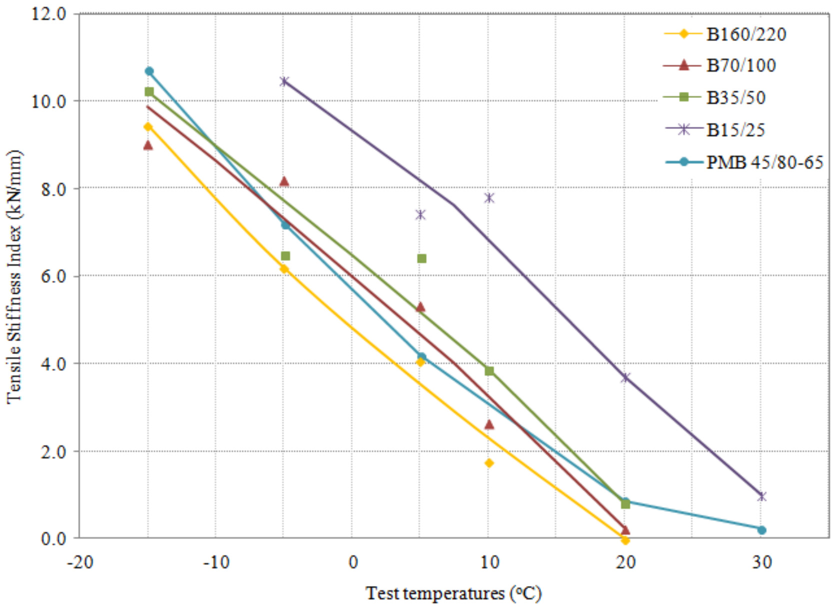

Figure 4 Tensile stiffness index versus temperature for all binders

Tensile stiffness index values strongly increase with decreasing temperature for all asphalt binders. The obtained results are clear evidence of the hardening process that asphalt binders undergo as temperature decreases, leading to an increase of the binder stiffness.

The same trend is observed for all the tested binders. Unlike the fracture energy, there are no significant variations between the modified binder and conventional binders, except for the B15/25 binder that shows the greatest values due to its higher stiffness.

3.1.3. Toughness Index (TI)

The toughness index gives a measure of the ability of the binder to resist cracking fracture after reaching maximum resistance. In other words, it assesses whether the type of fracture is more or less ductile.

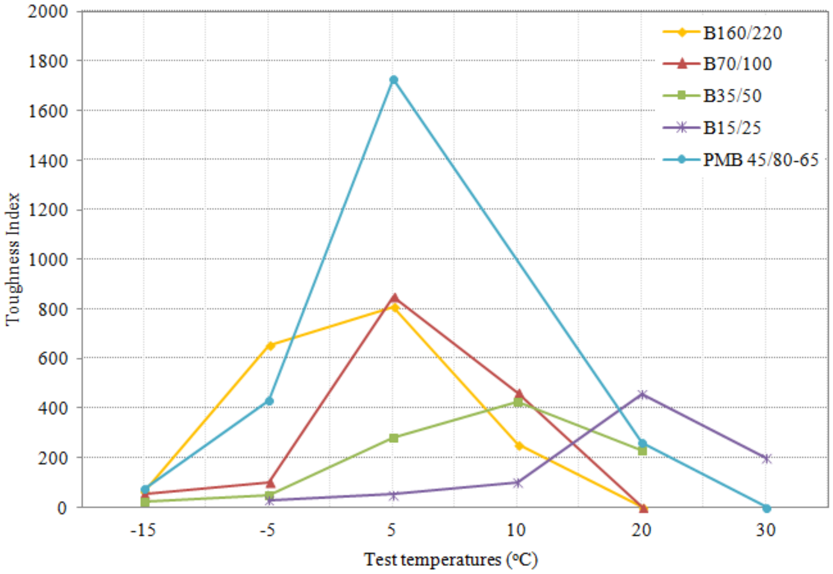

Figure 5 Toughness index versus temperature for all binders

Indeed, the toughness index is defined as the fracture energy after achieving the peak load weighted by a post-peak displacement. For this reason, the obtained patterns are consistent with the energy fracture patterns.

Results indicate that high penetration binders become tougher and more ductile at intermediate temperatures, while low penetration binders present a tougher performance at higher temperatures, although at -15ºC the toughness index is practically the same for all binders due to the hardening process that leads to a reduction in binder ductility that leads to a brittleness fracture. In all cases, high penetration binders reach higher toughness values over almost the whole temperature range due to its nature.

It is worth noting the thermal susceptibility of binders observed in this study. Indeed, the results evidence the need to characterize binder performance at different temperatures. If the test had only been performed at 20ºC, a common test temperature, the results would show a better performance of B15/25 binder over the rest of the binders, while at 5ºC the trend is reversed.

3.1.4. Displacement at 50% of post-peak load ($d_{0.5PostFmax}$)

Fig. 6 illustrates the displacement at 50% of post-peak load and it gives a notion of the work done during the cracking process and a measure of the binder ductility.

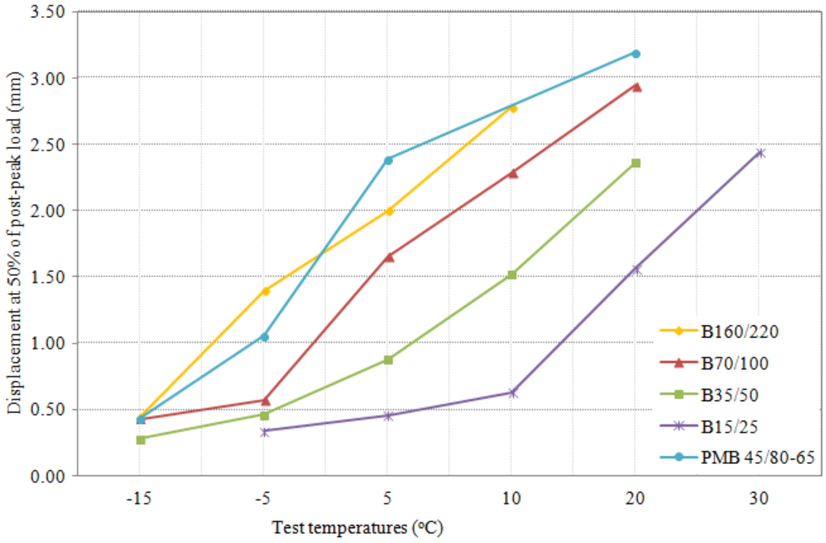

Figure 6 Displacement at 50% of post-peak load versus temperature for all binders

Consistent with the results of the other cracking parameters, at very low temperatures there is no significant difference between all the binders due to the hardening process that leads to a brittle break.

However, as temperature increases distinctive behaviours are observed. Conventional binders present very similar trends with quasi-parallel curves as temperature increases. As expected, high penetration binders show higher displacement values due to their greater ductility.

3.2. Binder aging effect analysis

Hereafter, the change in binder cracking resistance due to the effect of aging will be evaluated. In particular, the aging of a high penetration binder, B70/100, and a low penetration binder, 15/25, has been analysed. As an example, the Fénix test results for unconditioned and aged binders at 20ºC are given in figure 7.

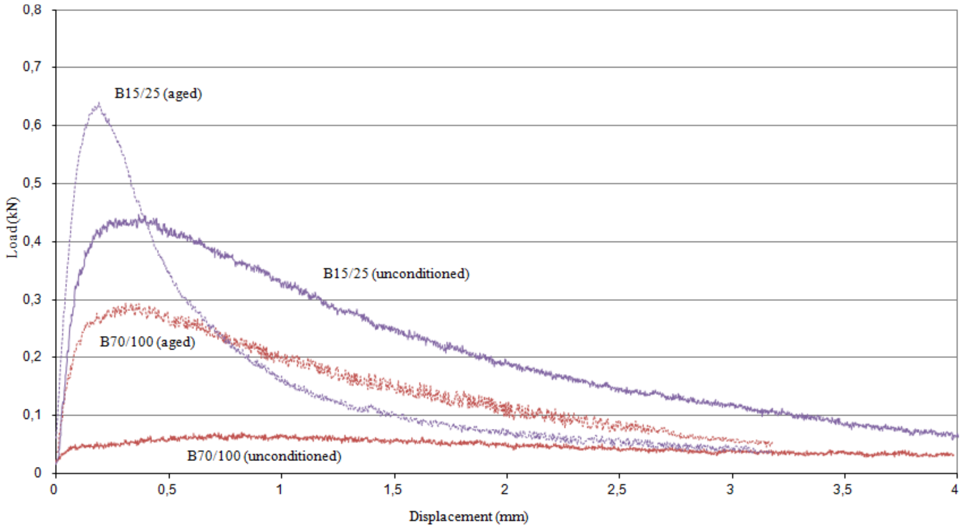

Figure 7 Stress-displacement curve at a test temperature of 20ºC

As it can be observed, large differences between unconditioned and aged binders are obtained. An increased stiffness represented by the higher initial slope, occurs after aging as well as a greater drop-off of the post-peak curve. Moreover, the aging process leads to a sharp increase of the stress that the binder can withstand. This is more pronounced for the high penetration binder.

3.2.1. Fracture energy (G_F)

Fig. 8 shows the variation of the fracture energy due to the effect of binder aging under different temperatures.

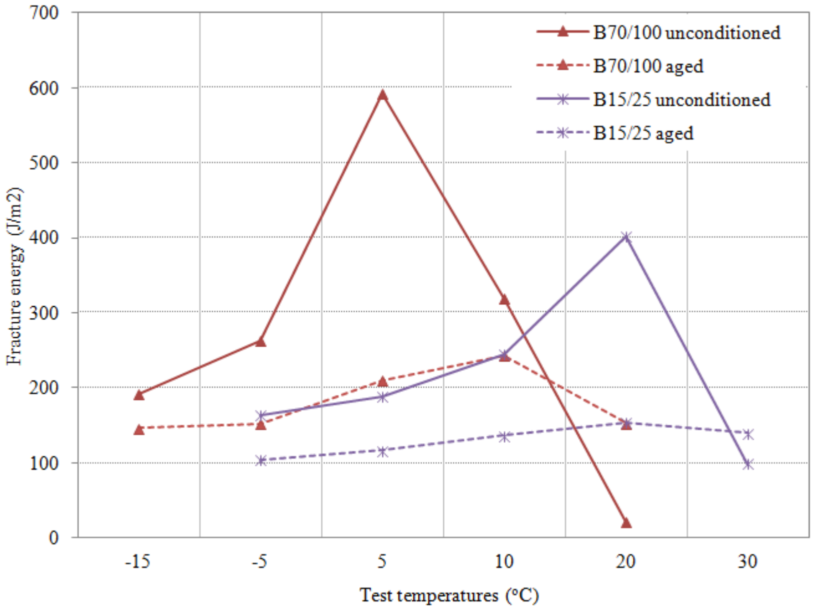

Figure 8 Fracture energy versus temperature for unconditioned and aged binders

The obtained curves evidence how the aging effect varies according to the type of binder and test temperature. The work required for crack initiation drops sharply after aging, and its behaviour becomes less thermally susceptible. Actually, aged high penetration binder presents a maximum value at a higher temperature than the unconditioned specimen, which remains the behaviour of the stiffer binder.

The analysis of the aging effect shows that the aging consequences are more pronounced for the high penetration binder compared to the low penetration binder. Indeed, results show that the behaviour of the aged B70/100 binder is similar to the unconditioned B15/25 binder and even, at certain test temperatures, the behaviour of the aged high penetration binder was equal to the aged low penetration binder.

It is important to highlight that the aging process of binders has serious consequences in terms of cracking resistance because it leads to an increase of the stiffness and the stress that the binders can withstand, which results in a brittle cracking fracture.

3.2.2. Tensile Stiffness Index vs. Displacement at 50% of post-peak load

If the variation of two opposite cracking parameters such as the tensile stiffness index is plotted versus the displacement at 50% of post-peak load, fig. 9 is obtained.

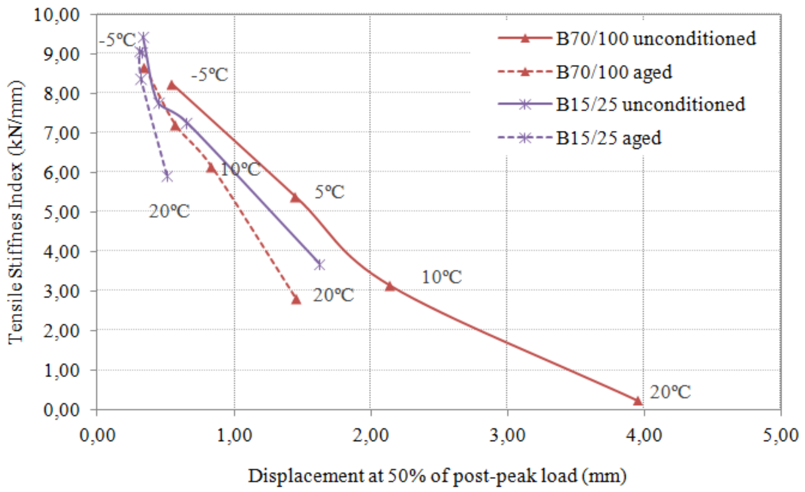

Figure 9 Tensile stiffness index versus displacement at 50% of post-peak load

This figure represents the combination of stiffness and ductility. The slope of this curve gives an idea of the thermal susceptibility of the binder, and the high penetration binder shows a gentler slope leading to a higher susceptibility. After aging, both slopes become steeper because the binder stiffens and loses ductility. Then, they become less susceptible to temperature. This phenomenon is more pronounced at low temperatures due to the hardening process that results in a brittle fracture.

The analysis of the slopes shows that the ductility decrease is more pronounced than the increase in stiffness for both binders between 20 and -5ºC. Indeed, it is observed that this variation is even more pronounced for the B70/100 binder, evincing the major effect of aging on high penetration binders.

4. Conclusions

This paper aims to validate a new approach for asphalt binder characterization by evaluating the ductility and tenacity that binders provide to an asphalt mixture, as well as the effect of asphalt binder aging. To this end, a standard mixture with a defined gradation and composition, without fines or filler, the same type of aggregate and characterized by a high void content has been manufactured to isolate the effect of binder on cracking resistance. Five asphalt binders covering a wide spectrum of binder consistencies have been evaluated: four conventional binders, B15/25, B35/50, B70/100 and B160/220, and a polymer modified binder, PMB 45/80-65, by applying Fénix test. Based on the findings of this research, the following conclusions can be drawn as follows:

- According to the obtained results, Fénix test can be considered as adequate to characterize the cracking resistance of asphalt binders under different conditions since it has a great sensitivity to compare binders with similar properties, and more quickly than a conventional tests.
- Regarding the binder type effect it can be concluded that the cracking behaviour of binders is strongly dictated by their nature and test temperature. It is observed

that each binder type reaches a maximum of the fracture energy at different temperatures.

- The results of the study reflect that conventional binders present maximum values of fracture energy and toughness at lower temperature as the penetration degree of binder increases. Polymer-modified binder presents maximum values over the whole temperature range and thus, the highest resistance to crack-propagation due to its greater ductility.
- Considering the tensile stiffness index results, there is clear evidence of the hardening process that all asphalt binders undergo as temperature decreases, leading to an increase of the binder stiffness. Indeed, at low temperatures (-15ºC) all curves tend to converge to the same area.
- Regarding the aging binder effect it can be concluded that the aging process leads to a sharp increase of the stress that the binder can withstand, a higher stiffness and a lower toughness, leading to a more brittle fracture. This phenomenon is more pronounced at low temperatures due to the hardening process.
- Asphalt binders become less susceptible to temperature after aging. Variations in the cracking parameters of the high penetration binders are significantly greater than the results from the low penetration binders; evincing the major effect of aging on high penetration binders.

These results show the need to characterize binder performance at different temperatures to obtain a reliable cracking response, evidencing the importance of choosing the more accurate binder based on the environmental conditions to increase mixture resistance to cracking. For a successful pavement design, it is vital to know the in service temperature and temperature gradient that will affect the pavement because a particular binder type may present an enhanced performance compared to another.

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