Asphalt mixture performance and testing

Procedure for the evaluation and comparison of the cracking resistance of bituminous mixtures. Characteristic curve. Fénix diagram

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Abstract

The particularity of the bituminous materials is that their break is ductile and tough. They require a great energy to produce the break since the start (maximum load) until failure. In traditional mechanical tests, only the mechanical response of the material up to maximum load (stiffness modulus or breaking stress) is evaluated and the tenacity of the material is not considered. However, the ductility and tenacity of the mixture are very important in its behaviour and can be estimated in a simple way if the mixture is tested under tensile loading with the Fénix test. The Fénix test is basically a skewed tensile test that gives rise to a slow and controlled crack propagation. It can be carried out at different temperatures, which allows obtaining, in a diagram of stress-displacement - Fénix diagram - the characteristic curve of the mixture. This curve shows the response of a mixture in a wide range of temperatures, indicating when the response is fragile or ductile, not very resistant or very tough. The Fénix diagram makes it possible to differentiate the response of different mixtures and the effect of their composition and the quality of the materials used. It offers an easy and simple methodology for the dosing and design of bituminous mixtures. This paper presents the results obtained after testing different types of bituminous mixtures, AC and BBTM, as well as recycled mixtures with different percentages of RAP.

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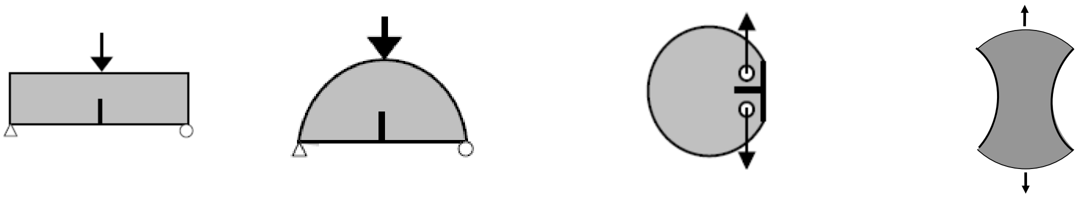
1. INTRODUCTION

Bituminous mixture's characterization and design has not truly been based on properties that bituminous binders present, that is, to agglomerate and bring cohesion to mineral aggregates. Instead, the main scope of them is to primarily avoid mixture's deformation by avoiding to use bitumen which is too soft or to overfill voids generated by the mineral skeleton.

Such design methods do not take into consideration the real distress mechanism of the pavement, that is, its cracking. Even though various tests to assess mixture's cracking strength have been developed, they do not consider the especial mixture's response to cracking failure.

The bituminous materials present a ductile and tough failure. They require a great amount of energy to induce cracking, from the onset of it (maximum load) until failure is reached.

The analysis of mixture's cracking strength has also been conducted by means of monotonic tests which measure the maximum failure load of a mixture when a stress or a strain is applied. Such tests come from the adaptation of procedures and equipment employed for stiff and elastic material characterization (Figure 1). In the case of bituminous mixtures, these tests need to be conducted at low temperatures or at high load application rates, so the response is as stiff and elastic as possible.



Single-edge notched beam	Semi-circular bending test	Disk-shaped compact tension test	Dog-Bone direct tension test

Figure 1: Tests for the assessment of the mixture's cracking resistance [1, 2, 3, 4]

Such tests have been fundamentally used when Paris Law has been applied in the analysis of crack propagation [5].

$$\frac{\Delta c}{\Delta n} = A(K_I)^{(n)}$$

Where $\frac{\Delta c}{\Delta n}$ is the increment of crack length for each load cycle, K_I is the stress intensity factor, and A and n are constants which depend on the material and need to be experimentally obtained. Breaking of specimens with different crack lengths allows obtaining the A and n factors of the Paris Law.

Studies regarding crack propagation in mixtures have shown that when mixtures present a ductile response, resistance drop is slower. Due to this, such parameter has recently been analyzed for AC mixtures by means of an IDEAL-CT indirect tensile test. The test has only been conducted on this type of mixtures at a temperature of 25ºC and using high load displacement rates (50 mm/min). High velocities are necessary in order to get a stiff response of the mixture and to achieve cracking without deforming it too much. This causes the mixture to rapidly fail and thus ductile response can barely be assessed. The test has not been conducted on other types of mixtures which present a more ductile and deformable response [6].

The cracking tests for bituminous mixtures should be able to assess the response of the mixture once its maximum load is achieved. The Road Research Laboratory of the Universitat Politècnica de Catalonia (UPC) has developed a test which allows to study such behavior of the mixture, the Fénix Test. A new design method which analyzes the response of the mixtures at its range of service temperatures has been established.

2. FÉNIX TEST. PARAMETERS MEASURED

The Fénix test is a skewed tensile test in which the force applied to the base of a semi-cylindrical specimen to produce its breakage is measured. During this loading process, the failure of the specimen occurs slowly and progressively, as the crack propagates radially from the notch created in its base, Figure 2. This allows the obtainment of not only the mechanical characteristics of the specimen when the mixture is in good condition (stiffness of the mixture and resistance), but also how the bitumen is able to maintain the resistance of the mixture as it deforms and the crack propagates (toughness). The deformation increases and the load that maintains the mixture is measured.

The semi-cylindrical specimen is obtained by sawing in half a cylindrical specimen manufactured by compaction, either by impact, vibration or gyration. The diameter of the specimen is 101.6 mm and its thickness can be variable, being normally between 3 and 6 cm. In the flat part of the specimen, coinciding in direction and position with the axis of the cylindrical specimen, a notch of 4 ± 1 mm in width and 5 ± 1 mm in depth is made with the saw. The purpose of this crack is to induce an area for the beginning of the crack during the test. The specimen is glued to plates that are bordering the notch.

The test is carried out at a displacement speed of 1 mm/min, with the plates where the specimen is fixed connected through a ball joint to the press. This allows rotation and avoids the transmission of moments and other stresses on the specimen. The test can be performed at any temperature as its variation has no influence on the shape or manner of applying the load [7, 8].

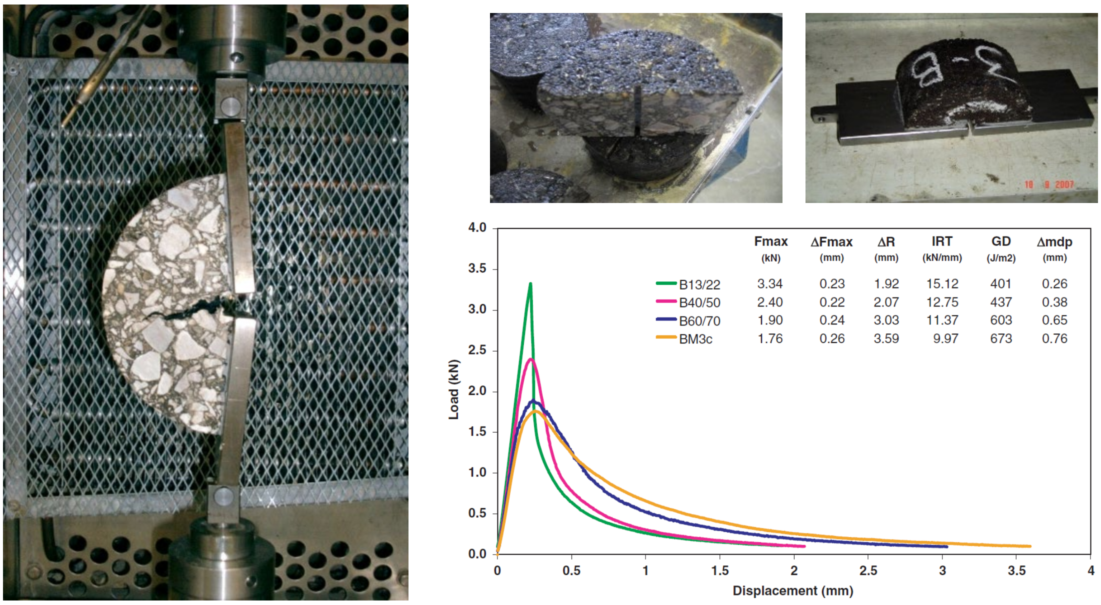


Figure 2: Fénix test pictures and example of the load-displacement curve obtained

From the test curve, Figure 3, several parameters that assess the following mixture features can be obtained:

- Mechanical and resistant: RT (maximum strength) and IRT (tensile stiffness index).
- Ductility: $d_{máx}$ (deformation at maximum load), d_{50pm} (post peak deformation at 50% of the maximum load) and DT (d_{50pm}-$d_{máx}$).
- Energy and toughness: G_D (energy, area below the curve), T (toughness, post peak area) and IT (toughness index, T*DT).

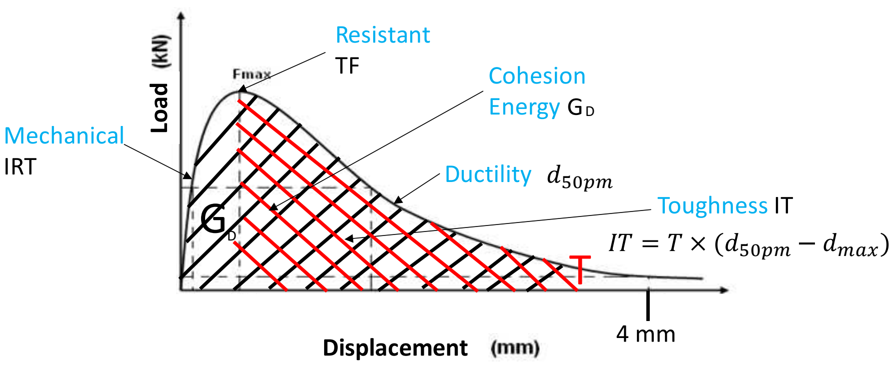


Figure 3: Parameters obtained from the Fénix load-displacement curve

3. BITUMINOUS MIXTURES DESIGN. FÉNIX STRESS-STRAIN DIAGRAM©. CHARACTERISTIC CURVE

On the basis of the Fénix test, a procedure has been established for the characterisation and design of bituminous mixtures. The Fénix test makes it possible to analyse at the same time two very important parameters of the mixture in order to define its behaviour. This is the maximum stress (RT) obtained at break and the deformation (DT) between the value for 50% of the maximum load at post peak (d_{50pm}) and the corresponding value to the maximum load (d_{max}). The first is related to the mechanical properties of the mixture (strength and stiffness) and the second one (DT) is an indicator of its ductility.

These two parameters also vary in the opposite way as the temperature increases; the RT decreases and the DT increases. By jointly analysing the variation of these parameters with temperature in a stress-deformation diagram, Figure 4, a curve is obtained for each mixture that defines its response. This characteristic curve for each mixture allows observing how the characteristics of the mixtures modify when changing the aggregate gradation or the bitumen type or content.

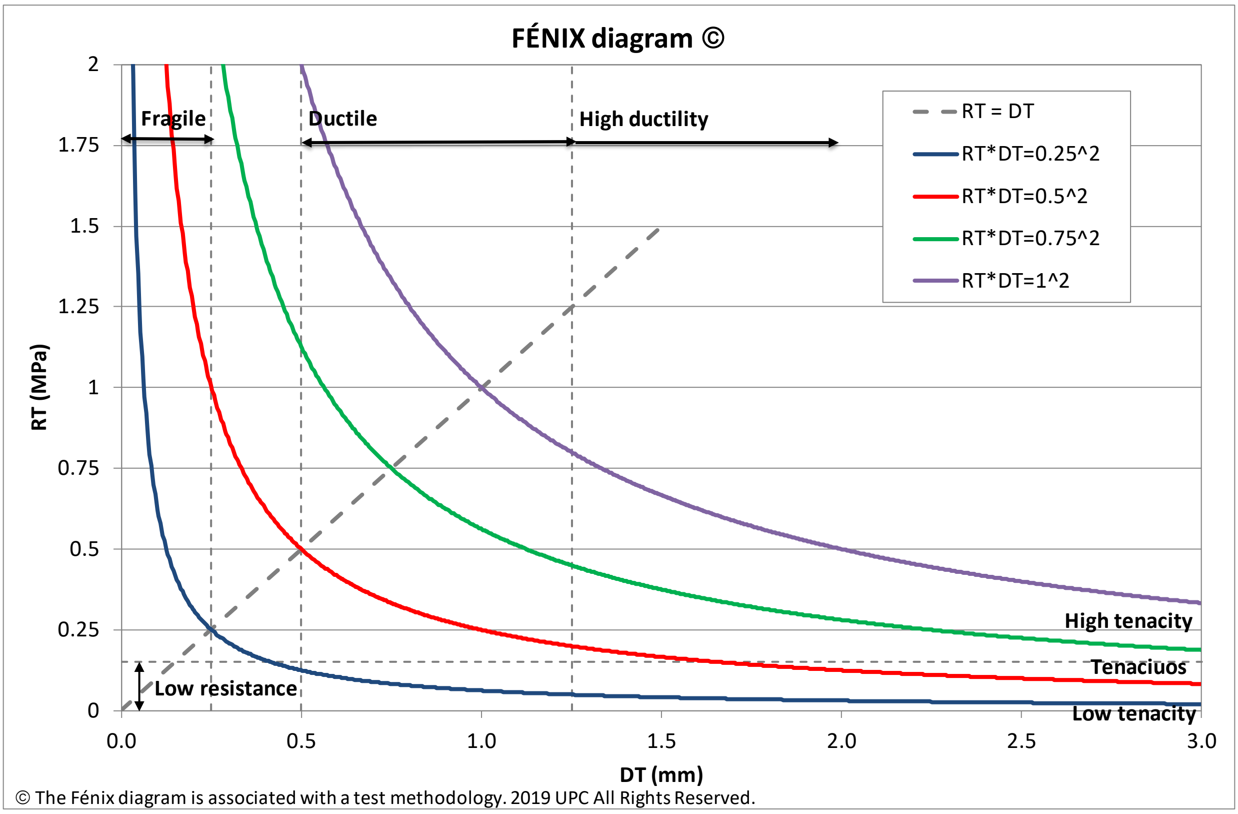


Figure 4: Fénix Stress-Strain Diagram ©

Hyperbolic lines related to the tenacity of the mixture have been included in the same diagram. These equation curves:

RT*DT = constant (0.25^2; 0.5^2; 0.75^2; 1^2) MPa.mm

are indicative of the tenacity that the mixture can have in the test.

The toughness area GT in the test can be assimilated to a right-angled triangle, one of whose legs would be RT and the other would be twice DT (assuming that the stress loss is linear). The area of this triangle would be RT*DT and these curves help to estimate the tenacity of the mixture. These curves have been associated with three levels of toughness:

- 0.25^2 MPa.mm. Low tenacious mixtures. Mixtures below this line would have deficient toughness.
- 0.5^2 MPa.mm. Tenacious mixtures. Mixtures above this line offer good toughness.
- 0.75^2 MPa.mm. Very tenacious mixtures. Above this line there would be mixtures with a high toughness.

Limits for RT and DT have also been set in this graph:

RT - 0.15 MPa. Low resistance. Below this value the mixture hardly presents resistance, practically that of a soft and ductile mastic deforming.
DT - 0.25 mm. Fragile. Below these values the breakage of the mixture is considered fragile.
DT - 0.5 mm. Ductile. From this value upwards the mixture presents a ductile break.
DT - 1.25 mm. Very ductile. The breakage of the mixture is characterized by its ductility.

In this Fénix diagram three important characteristics of the mixture can be analysed at the same time:

- Maximum resistance RT. This parameter is also directly related to its stiffness. The higher the RT, the higher the IRT.
- Ductility DT. Range of displacement in which the mixture maintains its resistance up to 50% of the maximum load.
- Toughness. Energy applied to achieve its failure from the moment it begins to break.

By representing in this Fénix stress (RT)-displacement (DT) diagram the results of a mixture at different temperatures (normally 20, 5 and -5 ºC) the characteristic curve that defines the mixture behaviour and that differentiates it from the response of other mixtures can be obtained. Through these curves it is easier to appreciate the effect of the aggregate gradation or the bitumen type or bitumen content.

4. ANALYSIS OF THE EFFECT OF BITUMEN CONTENT

Based on the Fénix test and the Fénix diagram, a mixture design method has been implemented in which the effect of bitumen content on the strength, ductility and tenacity of the mixture is analysed through the characteristic curves of the different mixtures studied [9, 10]. We can thus determine the bitumen contents in which the mixture has a brittle response and the necessary content to achieve a ductile and tenacious response.

4.1. Bituminous mixtures AC (asphalt concrete)

Figures 5, 6 and 7 show the Fénix diagrams corresponding to the design of three mixtures of continuous gradation, type AC16S, in which three different bitumens were used. Figure 5 shows the results for the mixture with an intermediate penetration bitumen (B50/70), Figure 6 presents the results for a mixture with a crumb rubber modified bitumen (BC50/70) and Figure 7 displays the results for a mixture with a hard penetration bitumen (B15/25). In all three mixtures, the effect of the same bitumen contents was studied: 3, 4, 5 and 6% by weight of aggregate. The void content of these mixtures is shown in table 1.

Table 1. Air void content of the AC mixtures

Bitumen Type	**Bitumen Content (% by weight of aggregate)**			
	3	4	5	6
B 50/70	10	6.5	3	1
BC 50/70	10.5	7.5	4	2
B 15/25	10	7	3.5	1.5

The characteristic curves of the four mixtures with different binder contents clearly show the effect of the bitumen content to improve their strength characteristics. They also show the change in properties with temperature. Thus, AC mixtures with bitumen B50/70 have a ductile break at 20°C, although there is a significant gap between 3% bitumen and 4, 5 and 6%, Figure 5. Mixtures with these higher bitumen contents also have a higher tenacity, which is very similar. It is also observed that bitumen variation hardly affects the strength of the mix.

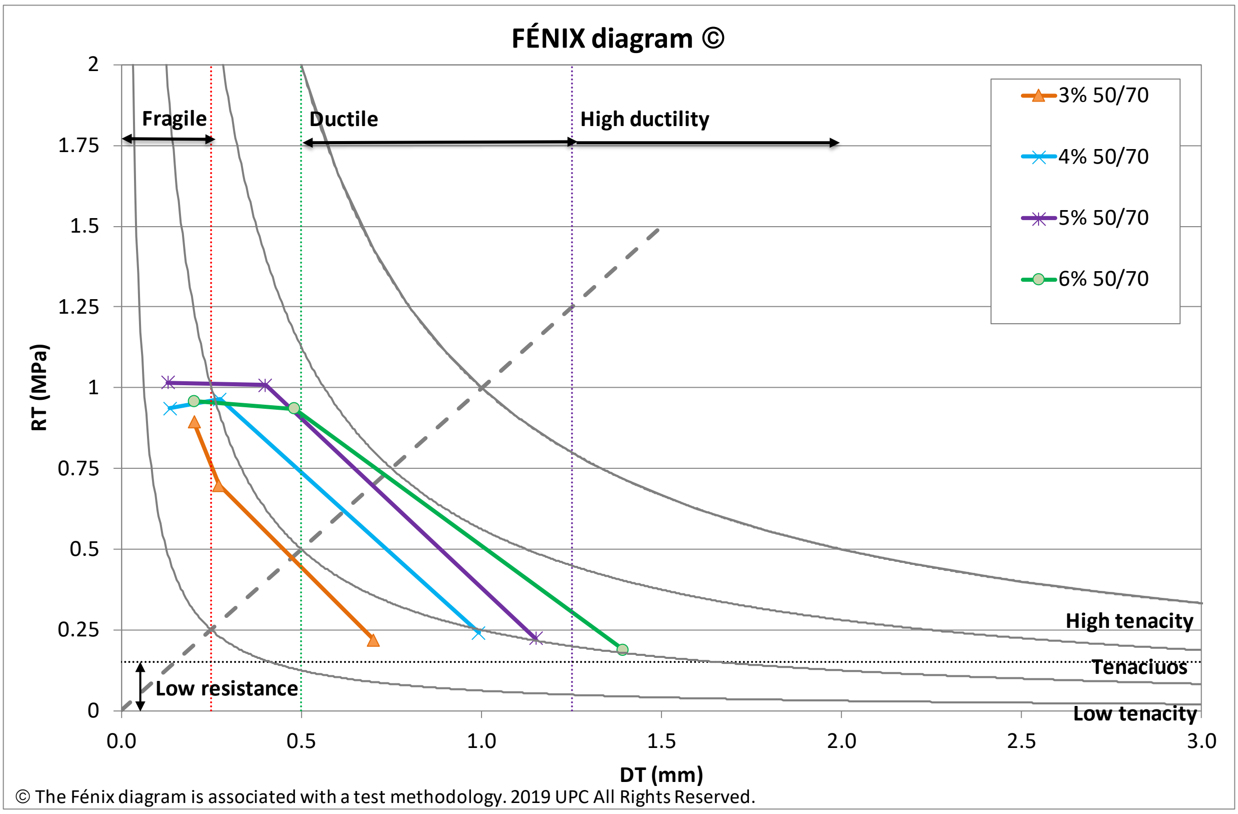


Figure 5: Bituminous mixtures AC with different 50/70 bitumen contents

At 5ºC the two mixtures with the lowest contents break up in a fragile way, especially the one with 3% bitumen content, with less resistance and tenacity. A greater deformation is observed in the two mixtures with 5 and 6% bitumen, and their response can be considered almost ductile. The breaking strength increases (with respect to the lower contents 3% and 4%) and again (like at 20ºC) it is observed that it does not vary with the bitumen content 5% and 6%. Tenacity for these two percentages also increases.

As the test temperature drops further, -5ºC, the four mixtures have a brittle break. DT deformation is very low, RT is the same as at 5ºC and the tenacity decreases.

According to these results, the mixture can present brittleness problems at very low temperatures, -5ºC, regardless of the percentage of bitumen used. For higher temperatures, 5ºC, the mixture already has a more ductile response, although bitumen percentages equal to or greater than 4% should be used. At 20ºC it is also convenient to use percentages equal to or higher than 4% to have a ductile and tenacious behaviour. Taking also into consideration the variation of the voids content of the mixture with the percentage of binder, 4.75% bitumen could be selected in principle, although the mixtures resistance to plastic deformations should always be checked.

The dosage of this type of mixtures is currently being done in this range of binder content, 4.5 - 5%. These mixtures have a better response in the Mediterranean climate than in the cold areas of the plateau, where a greater cracking is observed.

The use of another type of bitumen can modify the response of the mix. Figure 6 shows the response of the same mixture using a crumb rubber modified bitumen of the same penetration, BC50/70. The characteristic curves of the mixtures manufactured with 3, 4, 5 and 6% binder show the same trends as in the previous case, although a slight improvement in the ductility of the mixtures at 20 and 5ºC and a lower resistance at these temperatures is observed. Again, the binder content influences the ductility of the mixture, but not its resistance. At -5ºC the four mixtures have a fragile break. The tenacity of the four mixtures presents, as in the previous case, a maximum at 5ºC.

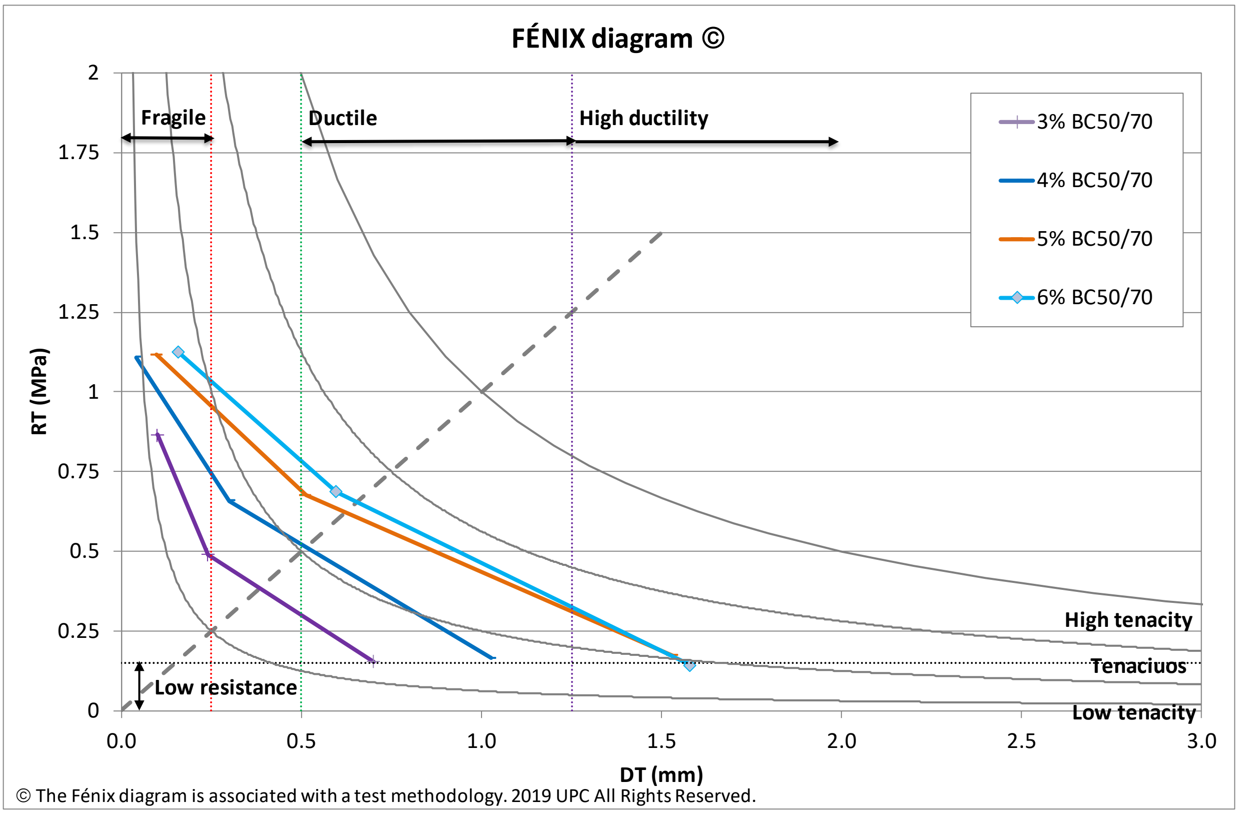


Figure 6: Bituminous mixtures AC with different BC50/70 bitumen contents

The minimum content to be used with this mixture should be higher than 4% and, considering its effect on the void content, up to 5% could be considered. The higher the binder content, the better; provided that the mixture resistance to plastic deformation is kept.

If a hard bitumen with a 15/25 penetration is used, the characteristic curves show the strong brittleness experienced by these mixtures, Figure 7. Only at 20ºC and for the higher binder contents, 5 and 6%, they show a slight ductility. However, at 5ºC and -5ºC they present a fragile break with very low deformation and low toughness. The resistance and toughness of these mixtures at 20ºC is higher than the previous ones and this could lead us to consider this type of mixtures better, as in the case of high modulus mixtures with RAP, if we do not carry out the tests at lower temperatures.

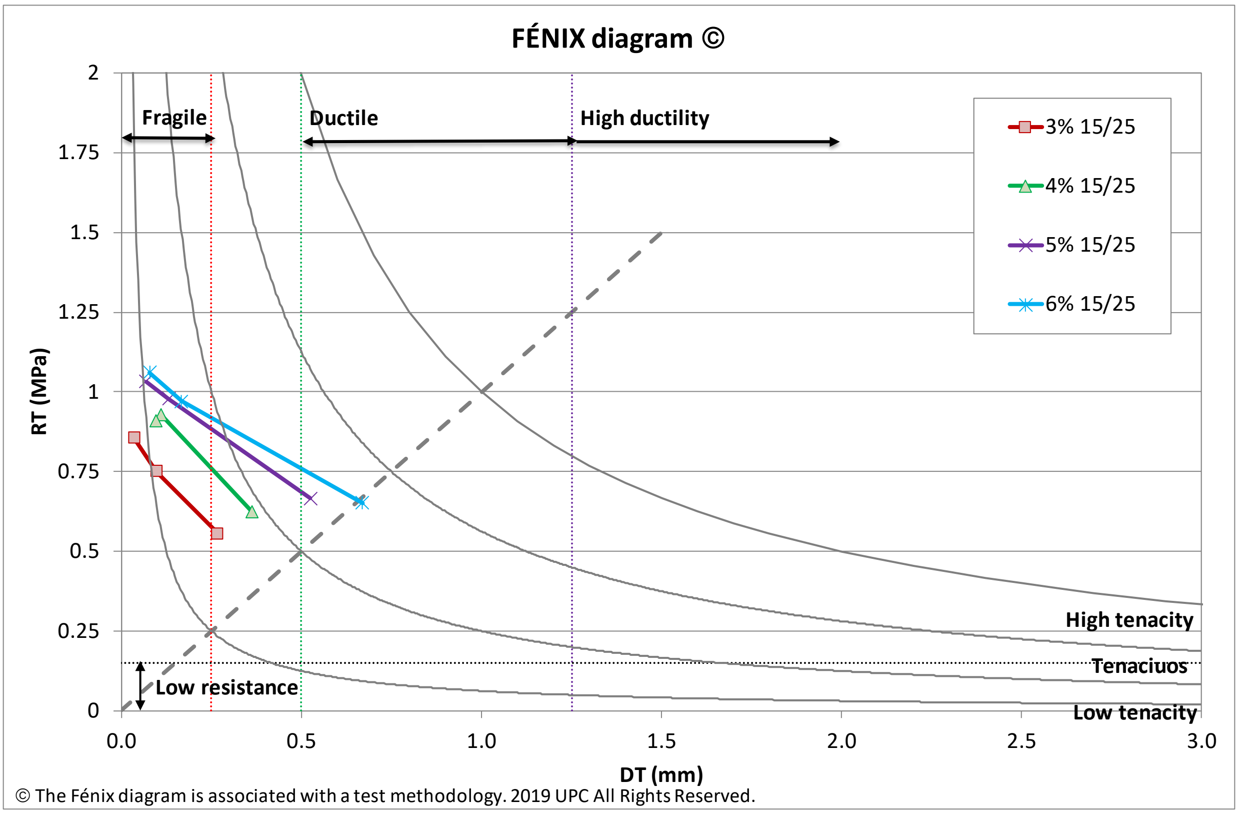


Figure 7: Bituminous mixtures AC with different 15/25 bitumen contents

If the tests are carried out only at 20ºC, it would be advisable for the mixtures to have a DT ≥ 1 mm and for their result (RT* DT) to be above the curve known as tenacious, 0.5^2 MPa.mm.

4.2. Bituminous mixtures BBTM (gap-graded gradation)

The ductility of the mixture can be increased by changing the gradation of the mixtures and by increasing the percentage of voids as in the case of gap-graded mixtures. However, the type of binder is the factor that has the greatest effect in improving the ductility of the mixture, especially at low temperatures. To achieve this effect we can benefit from modified bitumens that are more ductile and tenacious at low temperatures and that also maintain their tenacity and consistency at medium and high temperatures.

Figure 8 shows the characteristic curves of four mixtures corresponding to the study of the design of a BBTM 11B type mixture with a polymer modified binder (BM3c). The binder percentages used were 3, 4, 5 and 6% by weight of aggregate and the percentage of voids in these mixtures was 18, 15, 13 and 12%, respectively, considerably higher than those of the AC mixtures.

The characteristic curves of these four mixtures show the increase in ductility and tenacity at the three test temperatures: 20, 5 and -5ºC. At 20ºC the mixture with 3% bitumen is already very ductile and tenacious. As the percentage of binder increases, toughness and deformation at break increases with a DT greater than 2.5 mm for 5 and 6% bitumen. Again, it is observed that the bitumen content has hardly any effect on the maximum stress and that this is slightly lower than that corresponding to AC mixtures, although their toughness is higher.

At 5ºC the mixture continues to present a ductile response for the three lowest binder contents and a very ductile response for mixtures with 6% bitumen. Resistance increases and is similar for the four binder contents, 0.5 MPa. Toughness also shows a significant increase. Mixtures with the lowest contents are found within the lines that mark the response of tenacious and very tenacious mixtures, but the one with 6% exceeds by far the very tenacious curve.

At -5ºC there are two mixtures, those with the lowest contents of bitumen, which have a fragile break, while the other two, especially the one for 6% bitumen, maintain a response with a greater deformation, almost ductile and tenacious.

The mixtures with low binder contents present problems of ductility and tenacity at low temperatures, especially with 3%. Given that in this case it is not likely that there will be problems due to plastic deformations, as it has a higher percentage of voids, high bitumen contents should be chosen as they offer the best response to cracking failure at the three studied temperatures. The mixtures with 5 and 6% bitumen are the ones currently being used with this type of mixes, which guarantees these percentages for the mixtures design.

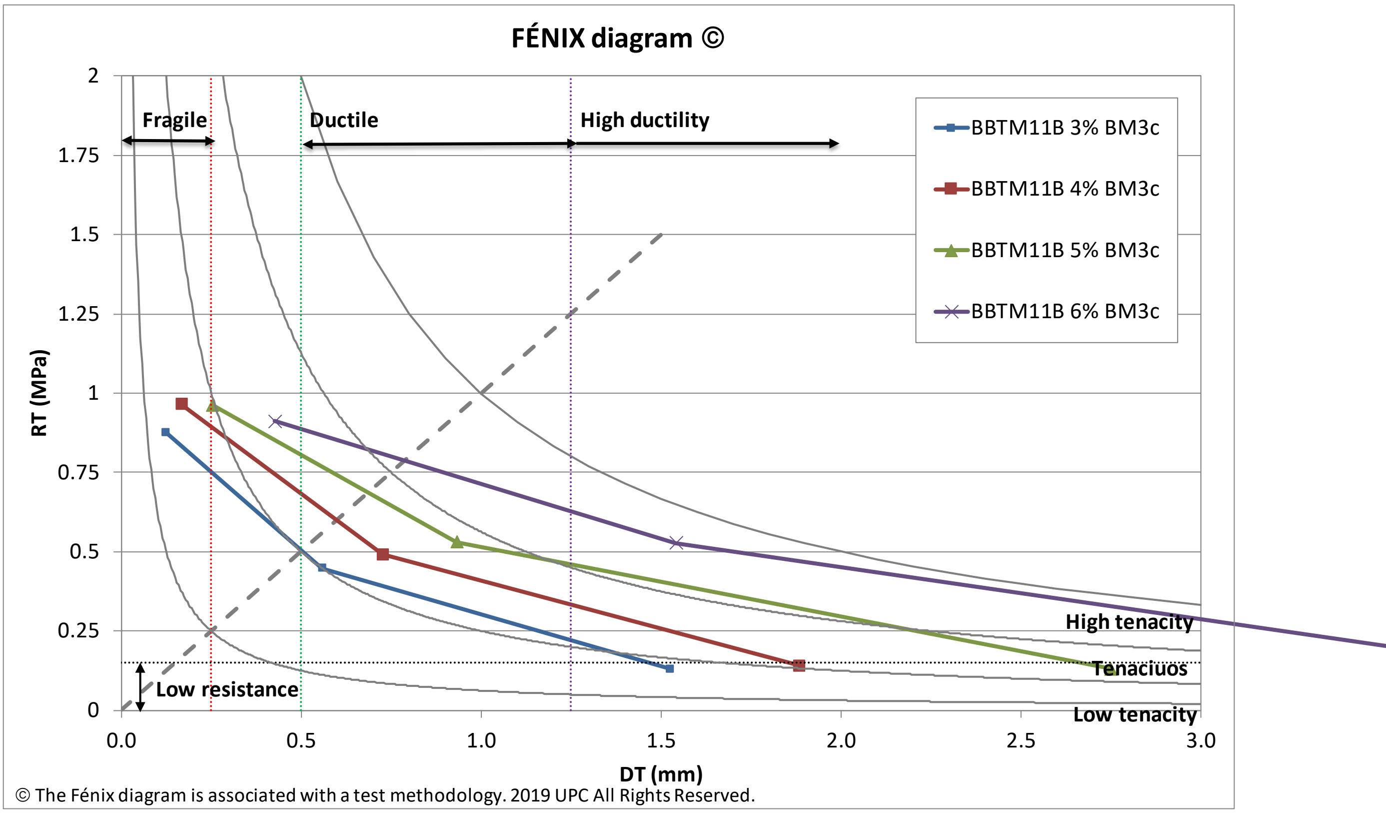


Figure 9: Bituminous mixtures BBTM11B with different BM3c bitumen contents

The observation of all these characteristic curves, both for AC and BBTM mixtures, shows the importance of testing the mixture at a wide range of temperatures, as the difference between mixtures and the advantages of one over the other may become more evident as the temperature varies. It is therefore advisable to analyse the curves in the presented way. However, in the case of testing only at 20ºC, for BBTM mixtures, a minimum deformation should be requested, DT ≥ 1.5 mm and the result (RT*DT) should be above the curve known as tenacious, 0.5^2 MPa.mm.

5. ANALYSIS OF THE EFFECT OF BITUMEN TYPE AND CONTENT

The effect of the bitumen type and content in an AC type mixture is shown in Figures 9 and 10. Two conventional penetration bitumens, B50/70 and B15/25, and a crumb rubber modified bitumen, BC50/70, were used, being the percentages of binder studied 6 and 4%. The effect of penetration and binder content is clearly observed when analysing the corresponding results. With the highest binder content (6%), the mixture manufactured with hard bitumen, B12/25, shows little ductile behaviour: at 5 and -5ºC its response is fragile and only at 20ºC it can be considered ductile. The two mixtures manufactured with the bitumens with the highest penetrations, B50/70 and BC50/70, present a ductile break at 5ºC and a very ductile break at 20ºC. On the other hand, these two mixtures have a lower resistance at 20ºC, although at 5 and -5ºC their resistance is similar to that of the mixture with the hard bitumen, B15/25.

By lowering the bitumen content (4%), the mixtures maintained their resistant characteristics, but decreased their ductility and tenacity. Now the tenacity of these mixtures is very low at 5ºC.

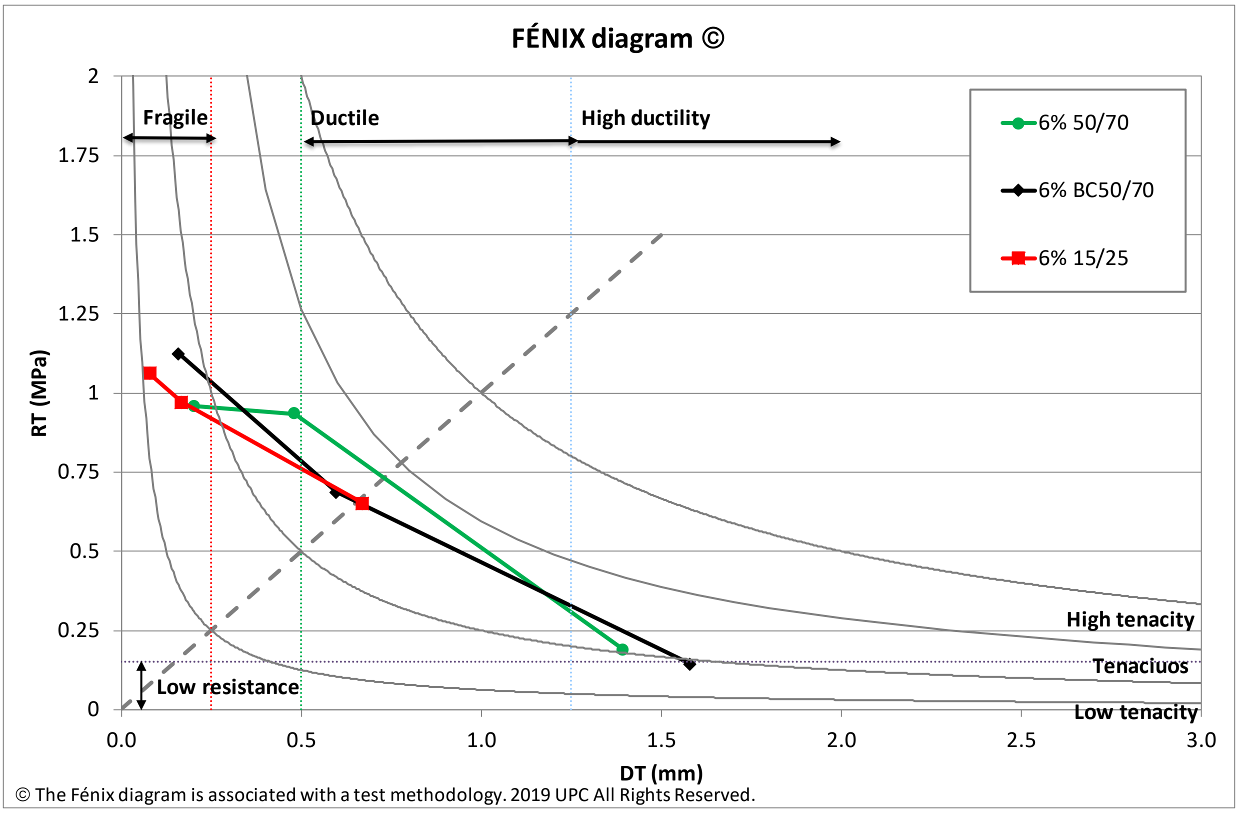


Figure 9: Mixtures AC with different bitumen types (6% bitumen content)

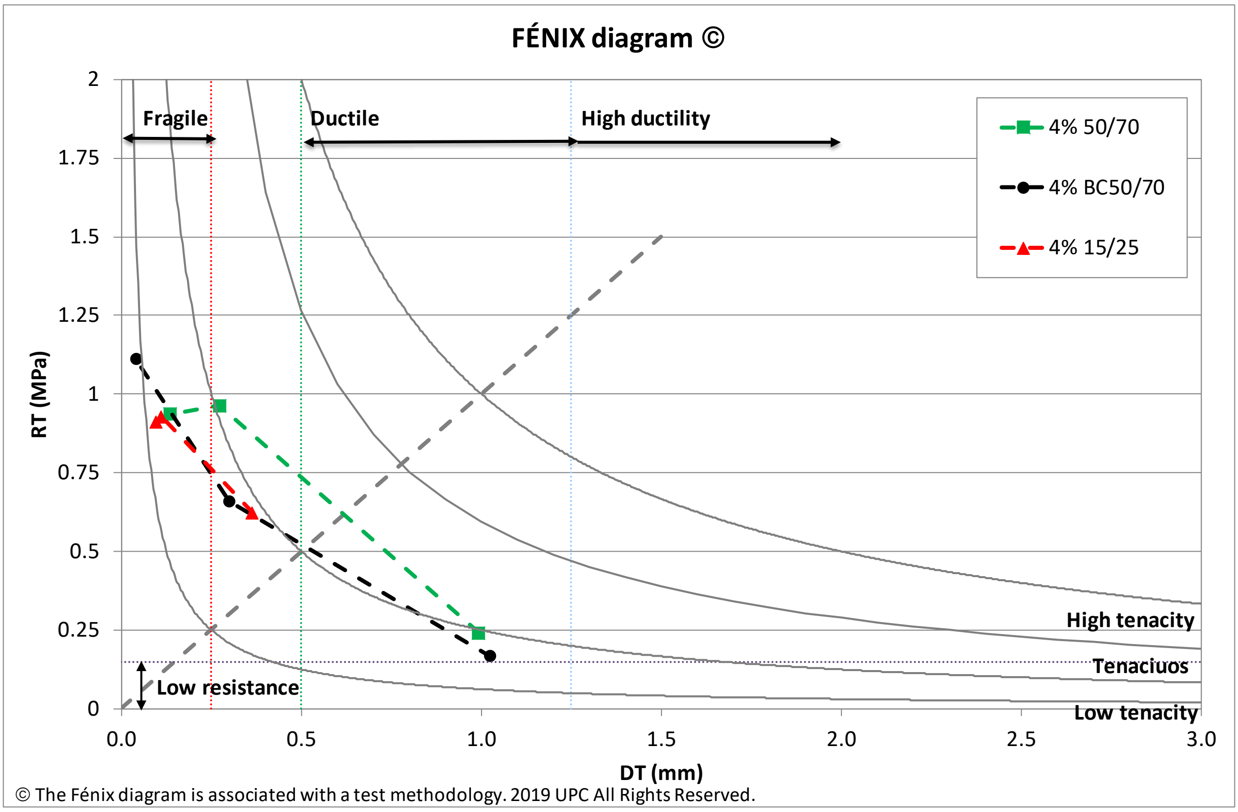


Figure 10: Mixtures AC with different bitumen types (4% bitumen content)

6. ANALYSIS OF BITUMINOUS MIXTURES WITH RECLAIMED ASPHALT PAVEMENT (RAP)

The use of characteristic curves also shows the effect of introducing the milling of asphalt pavements (RAP) and rejuvenators in the manufacture of bituminous mixtures. Figure 11 shows with continuous lines the curves of mixes manufactured with 0, 20, 40 and 60% RAP. A 50/70 penetration bitumen was used for the control mixture without RAP and a 70/100 penetration bitumen was added to the recycled mixtures [11].

The reference mixture with 0% RAP and B50/70 is the one with the highest ductility and tenacity. Its response is ductile at 20ºC and fragile at -5ºC. The characteristic curve barely changes with the addition of 20% RAP, although the mixture becomes slightly more fragile and less ductile at 5 and -5ºC.

This increase of fragility and loss of tenacity becomes more evident as the percentage of milled material increases to 40 and 60%. The addition of a rejuvenating product in the manufacture of the mixture by 5 or 10% by weight of RAP binder hardly affects the mixture response.

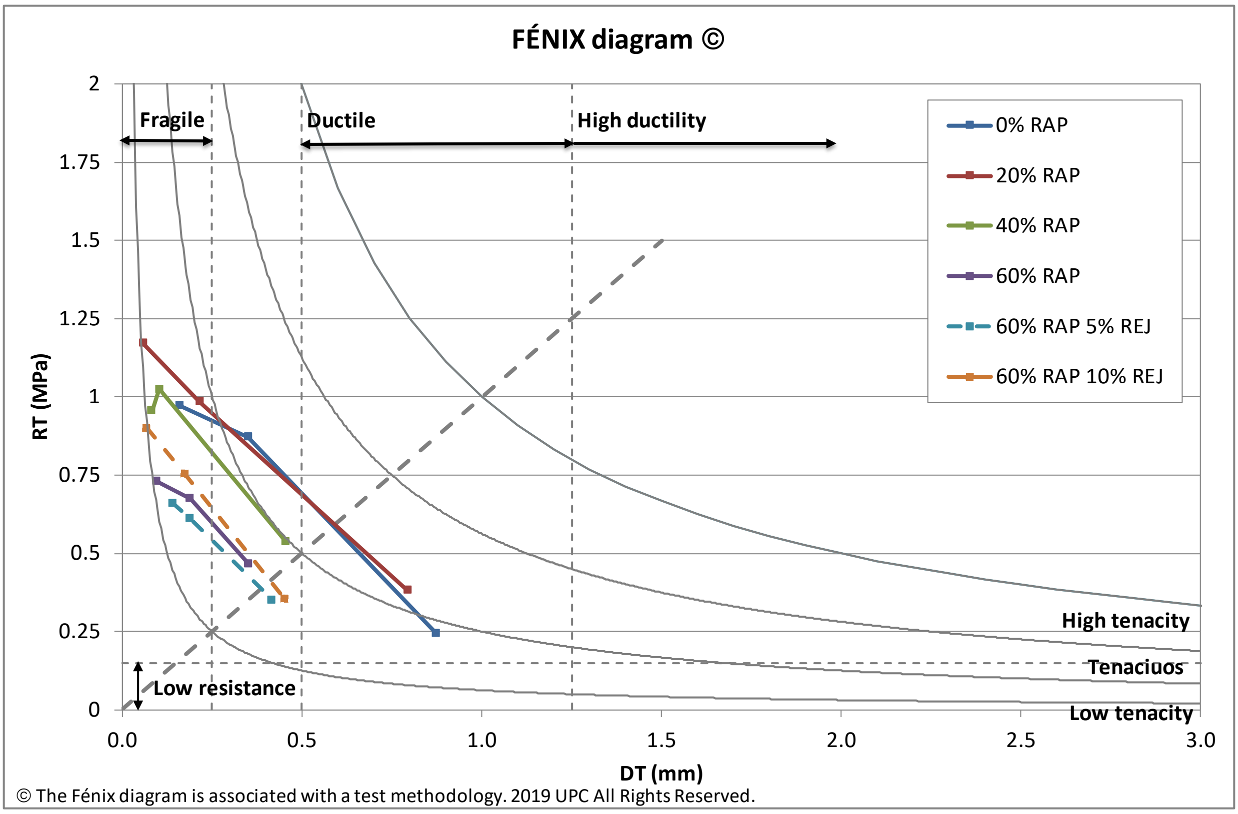


Figure 11: Recycled bituminous mixtures with different RAP contents

These curves allow to differentiate the response of recycled mixes with different RAP contents and to evaluate the effect of rejuvenator.

7. CONCLUSIONS

The implementation of a specific test to evaluate the cracking resistance of bituminous mixtures, the Fénix test, makes it easier and more effective to assess the strength, ductility and tenacity of the mixture. The test can be performed at different temperatures, which allows to observe the evolution of the mixture from a ductile and tenacious response to a fragile one. The representation of the calculated parameters (RT and DT) in the Fénix Diagram© allows the characteristic curve of each mixture to be obtained. This characteristic curve makes it possible to assess the response of each mixture to cracking failure and to compare the response of different mixtures with each other.

In this paper, the Fénix test was applied to the analysis of two different mixtures: a dense mixture (AC16S) with different bitumen types and a gap-graded mixture (BBTM11B) with a polymer modified bitumen. Different binder contents were used to evaluate and compare the results. The observation of the characteristic curves in the Fénix Diagram© allowed showing the response of the mixtures at a wide range of temperatures with the help of the proposed iso-tenacity thresholds. This methodology was also applied to the analysis of recycled mixtures with different RAP contents. In this case, the curves revealed the increase of fragility and loss of tenacity of the recycled mixtures as RAP content increased. Moreover, the use of a rejuvenating agent was unable to counteract completely the effect of the aged bitumen provided by RAP.

In conclusion, an easy and simple methodology is presented for the dosage and design of bituminous mixtures from the use of the Fénix test and Diagram©.

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