Determination of a New Fatigue Rupture Criterion for Bituminous Mixes

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ABSTRACT: The fatigue failure is defined as being the reduction or the loss of the pavement mechanical properties under repeated traffic loads and its bearing capacity progressive reduction. Because of the complex determination of the pavement cracking evolution as well as the laboratory bituminous mixes fatigue behaviour, some problems and questions are still irresolute. The difficult resolution of these problems makes that a universal testing method with a clear failure criterion approaching the pavement reality was not established yet. There are today different types of testing methods associated with different failure criteria, which lead to different results that are sometimes contradictory. In order to develop and to look further into the study of the bituminous deterioration process, nine different bituminous mixes at three different temperatures were analysed. Their stress/strain evolution and their dynamic modulus evolution were analysed by using a new fatigue test and the standardised three-point bending beam test. The analysis of these dynamic characteristics of the mixes have shown that there is a failure deformation value that can be considered as constant for each mix. That means that whatever could be the value of the initial imposed solicitation, there is an irreversible deformation level that is constant for all the specimens of one single mix. This phenomenon could be observed through the study and analysis of an amount of 231 fatigue test results.

KEY WORDS: Bituminous mix, fatigue, rupture criterion.

1 INTRODUCTION

The fatigue phenomenon in bituminous mixtures is the damage accumulation under a repeated loading. The damage accumulation leads to the development of cracking that is one of the most important damage in flexible pavements. The development of the failure mechanism of bituminous pavements with time and in function of the number of load applications depends on external factors like the temperature, the material type, the laboratory sample size, etc. Three steps are usually considered in the fatigue process until the total failure of the material (van Dijk, 1975) (Di Benedetto et al., 1996, 1997). The first one is characterized by the development of microcracks, the second one by the stable evolution of these microcracks in macrocracks, and the last one by the development of macrocracks inducing the total failure of the material (see figure 1).

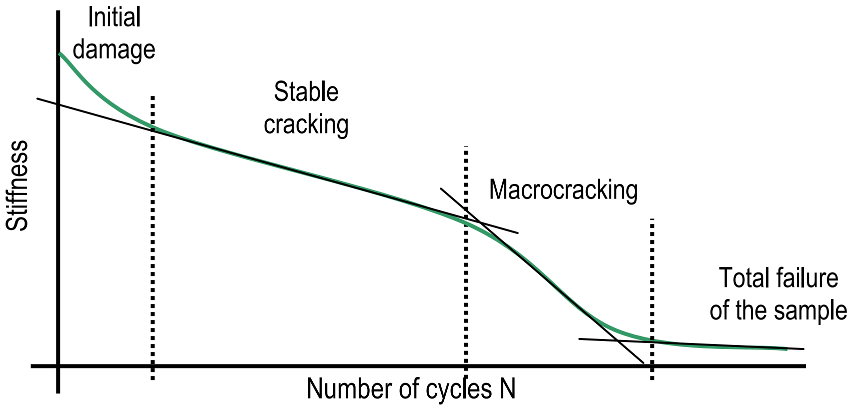

Figure 1: Crack evolution and failure mechanism of bituminous mixes.

2 CHARACTERISATION OF THE FATIGUE DAMAGE

The determination of the material failure and the resistance limits during a fatigue test has always been an arbitrary choice of a fixed criterion. The most commonly used failure criterion is the reduction of 50% of the initial stiffness. There are also some processes that use the dissipated energy, the damage accumulation or the fracture mechanics.

2.1 The Wöhler approach (classical method)

The Wöhler approach is the most commonly used for the characterisation of the fatigue behaviour of laboratory bituminous mixes. This approach considers that the failure occurs when the stiffness of the mix reaches 50% of its initial stiffness. If the test is stress-controlled, the failure will occur when the condition (1) is true. If the test is strain-controlled, the failure will occur when the condition (2) is observed.

$$D = 2 \cdot D_0 \tag{1}$$

$$F = \frac{1}{2} \cdot F_0 \tag{2}$$

where D, F: final deformation, force
D_0, F_0: initial deformation, initial force

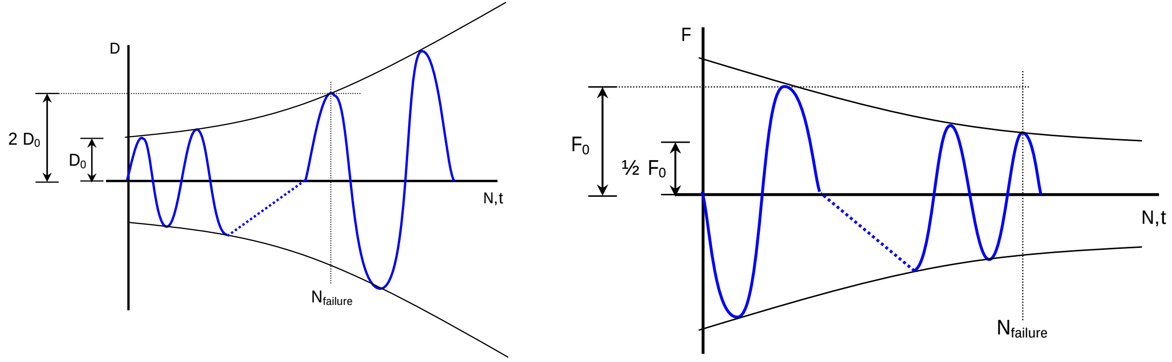

Figure 2: Failure criterion in the classical approach for a stress- and strain-controlled test.

2.2 The dissipated energy approach

Some authors (Tayebali et al. 1992, Baburamani, 1992) mentioned the existence of a relation between the fatigue life and the total dissipated energy until failure. The produced energy by the viscous dissipation during a cycle is done by (3):

$$W_i = \pi \cdot \varepsilon_i \cdot \sigma_i \cdot \sin(\varphi_i) \qquad (3)$$

where W_i,: dissipated energy until cycle i
ε_i, σ_i: strain and stress amplitude in cycle i
φ_i: phase angle between stress and strain in cycle i

For some authors (Hopman et al. 1989, Rowe, 1993, Thom et al. 2002) the dissipated energy is the result of the damage that occurs in the material. For others (Di Benedetto et al. 1996, De La Roche et al. 1996), the dissipated energy is the result of the heating within the mix. The dissipated energy approach allows the fatigue characterization of a bituminous mix independently of the type of test, i.e. stress- or strain-controlled.

2.3 The fracture mechanics approach

In 1963, the "Paris law" (4) was developed (Paris et al., 1963) evidencing the importance of the sample dimensions in the fatigue characterization of a bituminous mix. The Paris law defines the percentage of crack propagation (dc/dN) where K is the stress intensity factor and the variables A and n are parameters depending on the material and the experimental conditions like the type of dynamic solicitation, the temperature and frequency.

$$\frac{dc}{dN} = A \cdot K^n \qquad (4)$$

In the three phases of the damage evolution described in figure 1, the parameter K has its own value. In the initial damage, there is a K-value under which the crack does not initiate. In the stable cracking phase, K describes the stable process of crack development. In the failure phase, the crack growing percentage dc/dN is infinite and K which represents the fracture toughness of the mix is independent of the type of the imposed solicitation and of the sample dimensions. Some authors (Schapery,1973, Molenaar, 1984) developed and found values of these parameters for the specific and local conditions of their countries.

2.4 The damage accumulation approach

To characterize the damage, a parameter ρ is used, which equals zero when the material is not damaged. Assuming that the material does not totally heal with time and that the damage increases, $d\rho/dt \geq 0$ is true. To describe the damage and to modelise its effects, it is important to know the parameters that influence the damage process like the material forces, the initial load and its evolution, the initial damage, the material type, the geometry and the local characteristics.

The first studies about damage accumulation were done by Miner (Miner, 1945) who admitted that the crack evolution through the different phases was linear and that the dissipated energy was important to characterize the fatigue damage (5).

$$D=\sum_{i=1}^{n}\left(\frac{W_i}{W_{N,i}}\right)^{x_i} \tag{5}$$

where $W_{i,}$: dissipated energy until cycle i
$W_{N,\,i}$: dissipated energy permitted in cycle i until failure

3 EXPERIMENTAL STUDY

Nine different bituminous mixes at three different temperatures (5°C, 20°C and 35°C) and at a frequency of 10 Hz were analysed with the three-point bending beam test and a new direct tensile test developed at Barcelona Tech for the purpose of this study and the related doctoral thesis. Their stress/strain evolution and their dynamic modulus evolution were analysed by using a new fatigue test and the standardised three-point bending beam test. The analysis of these dynamic characteristics of the mixes have shown that there is a failure deformation level that can be considered as constant for each mix. That means that whatever could be the value of the initial imposed solicitation, there is an irreversible deformation level that is constant for all the specimens of one single mix. This phenomenon could be observed through the study and analysis of an amount of 231 fatigue test results.

3.1 The three-point bending beam test

The three-point bending beam tests have been realised following the Spanish standard NLT-350/90 where prismatic samples are submitted to a continuous sinusoidal deformation.

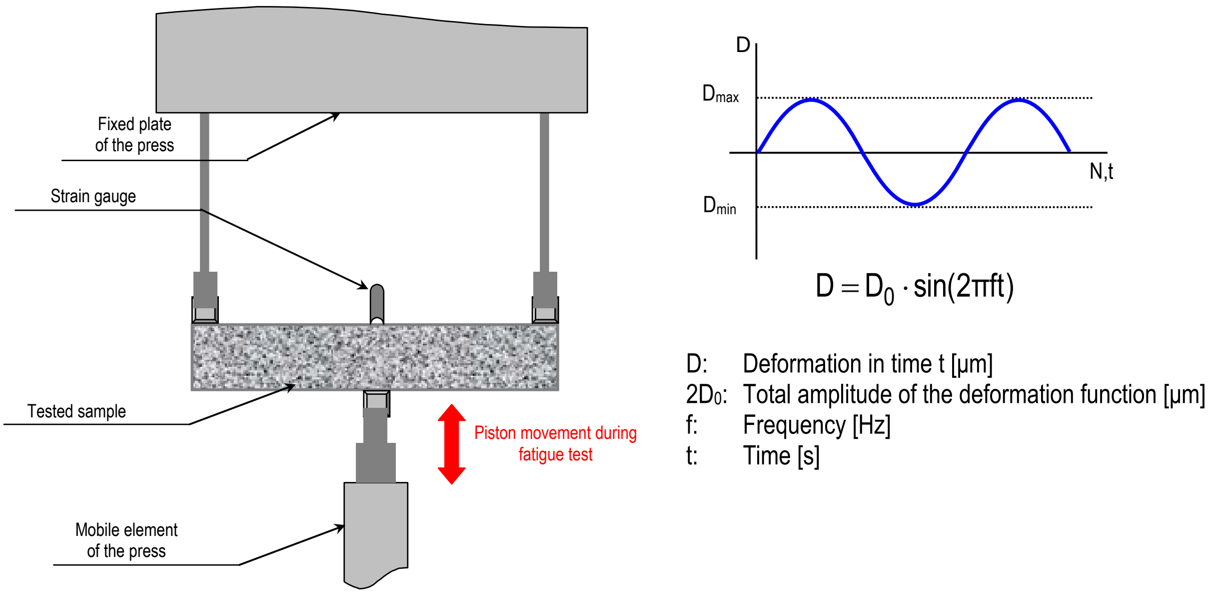

Figure 3: Three-point bending beam test (strain-controlled).

3.2 The direct tensile test

The direct tensile test used in this study was developed to have a more homogeneous repartition of the forces and to eliminate the bending stresses inside the bituminous samples. The notched prismatic samples were submitted to a continuous positive sinusoidal stress to permit, in a reasonable time, the realisation of a great amount of fatigue tests and the analysis of the damage evolution until total failure.

The decision to develop a stress-controlled test was made after the observation that the technical installation of the sample in the three-point bending beam test does not allow the tested specimen to reach physically the total failure. With the direct tensile test, the whole deformation needed to reach the total physical failure of the sample is permitted. In addition, the samples were notched in two opposite faces to control the location of the rupture section. Two strain gauges were placed on the non-notched opposite faces.

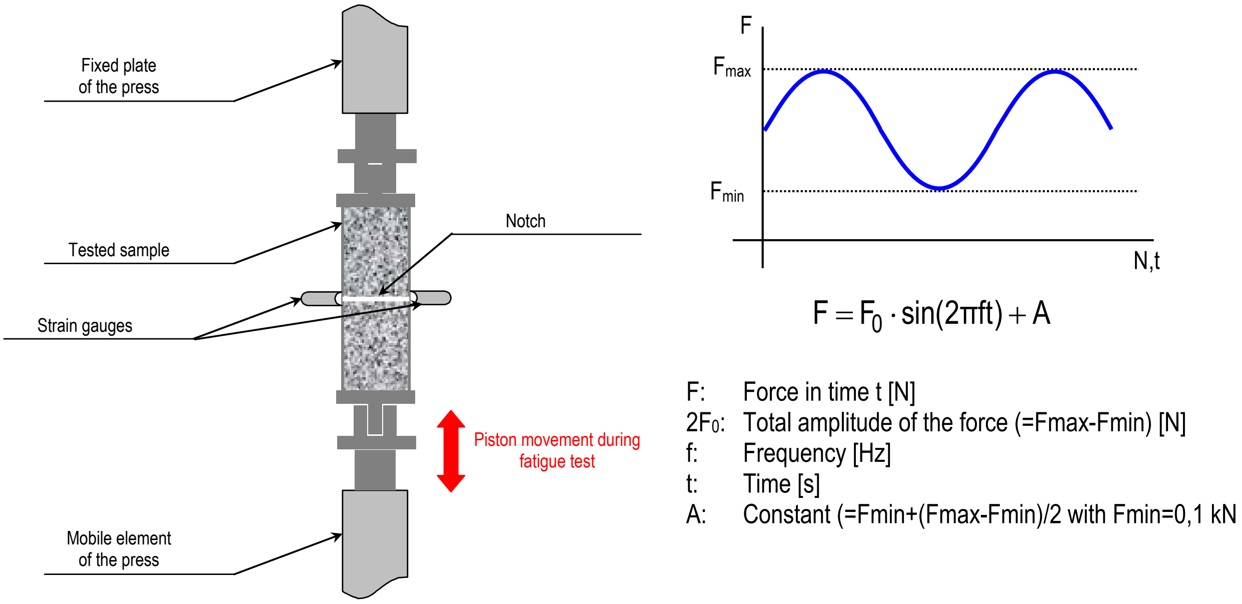

Figure 4: Direct tensile test (stress-controlled).

3.3 Validation of the new direct tensile test

The first step was to validate the new direct tensile test. The first observation was that the total failure was actually reached, which was not the case with the 3-point bending beam test. The cracking occurs within the notch until the complete separation of both parts of the sample. The second observation was that the deformation and the dynamic modulus evolution with the number of cycles follow the same trend observed by other authors (van Dijk, 1975, Di Benedetto et al. 1996, 1997). The third observation was that the signals transmitted by both the strain gauges were similar. This is a primary information because it shows that there are not bending stresses within the tested material and that the sticking device is adequate to perfectly stick the plates on both ends of the sample. The fourth observation, which is important too is about the tests that did not work as expected. Among all the realized tests, only 1.4% of them did not proceed as expected (0.7% due to a mechanical problem in the press and 0.7% due to material or sticking defaults). This observations were good for a first validation.

Nevertheless, the validation process continued by comparing the initial dynamic modulus $|E^*|_{ini}$ obtained with the three-point bending beam test and the direct tensile test. The figure 5 shows the $|E^*|_{ini}$ average value (of all tests for each mix) and the standard deviation in the abscissa (3-point bending beam test) and the ordinate (direct tensile test). The observations that can be done regarding the comparison between both test methods are that, on one hand, the mean variability of $|E^*|_{ini}$ values in both test methods (12% and 14%) shows a good repeatability within each type of mix. On the other hand, the linear regression linking the drawn points shows a very good determination coefficient (R^2=0.9433).

These findings allow us to consider this new fatigue test as appropriate for the realisation of fatigue tests and the analysis of the deterioration process.

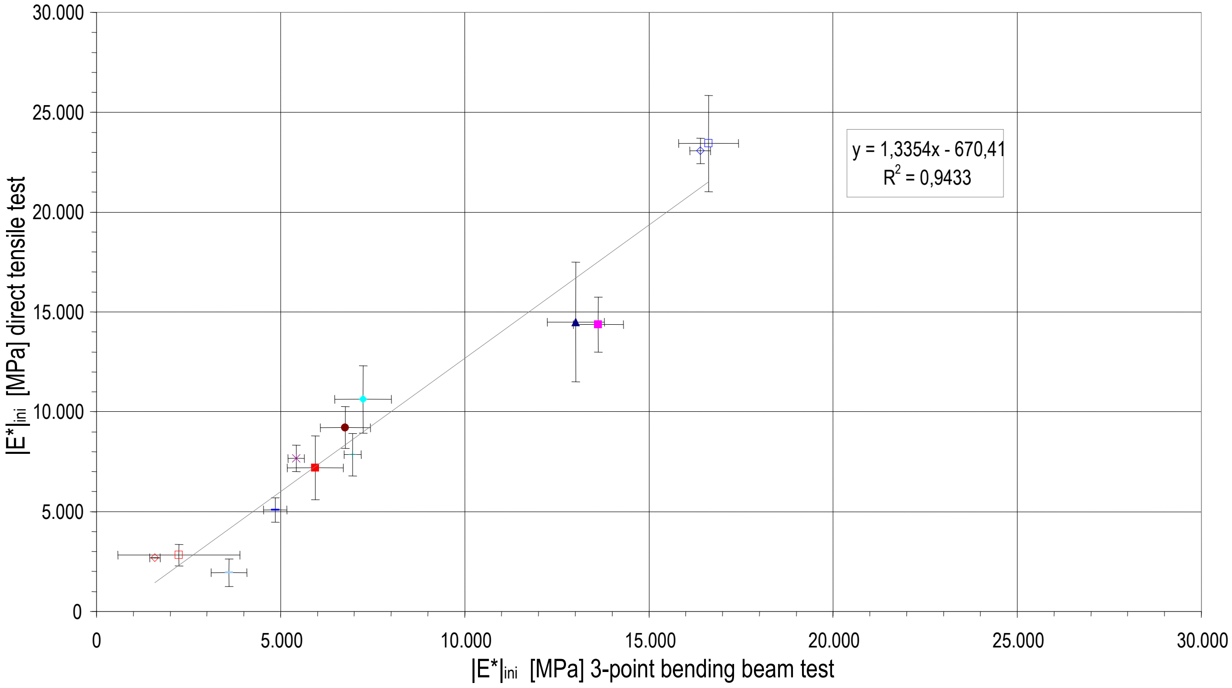

Figure 5: Comparison between $|E^*|_{ini}$ 3-point bending beam test and direct tensile test.

4 ANALYSIS OF THE DETERIORATION PROCESS

For all the mixes tested using the standardised three-point bending beam test and the new direct tensile test, the stress/strain evolution and the dynamic modulus evolution were analysed.

4.1 Three-point bending beam test

Different aspects can be observed in the analysis of the deformation evolution. The slope of the stable cracking phase is linked with the stiffness of the mixture. When the stiffness is higher, the slope is lower and the duration of the fatigue test shorter. The figure 6 also show some samples with an initial strain amplitude of ε_{ini}=0,0003 that did not fail and did not show any sign of failure even after 600'000 cycles. At this moment, it is not possible to admit that the material has reached its resistance limit. There is no graphical nor physical sign that could show the sample failure. Besides, according to the standard, the stress evolution show that the sample is supposed to have failed but the reality shows that there is still a certain resistance in the material.

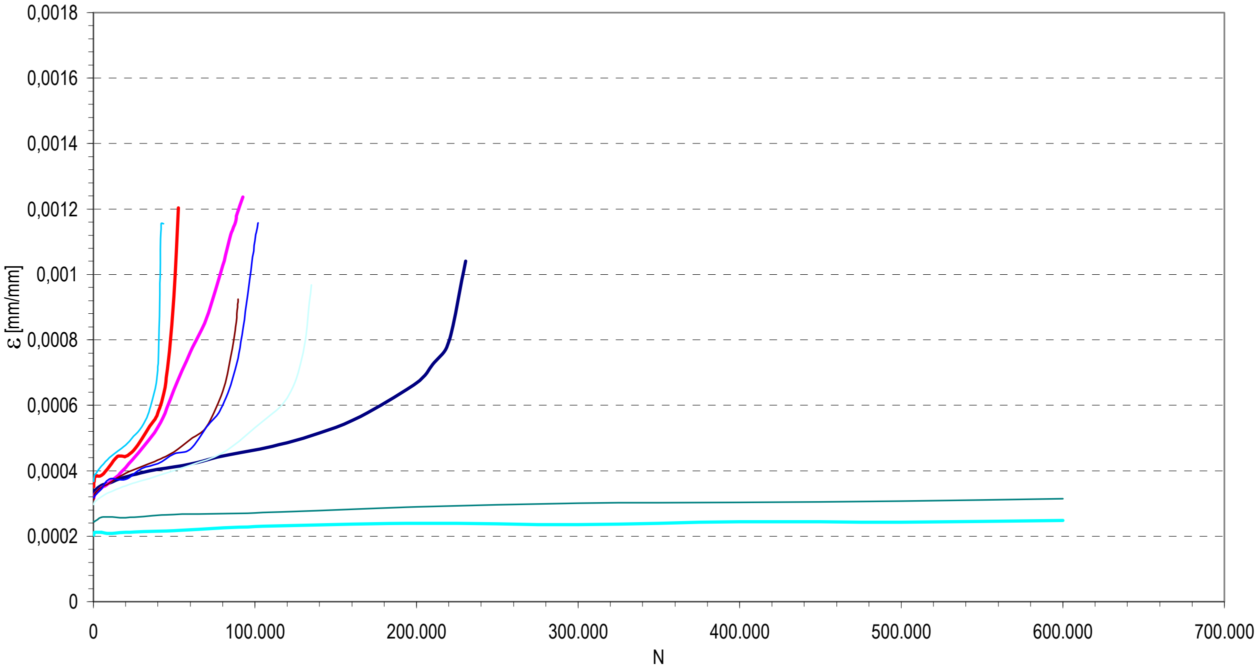

Figure 6: Evolution of the deformation in the three point bending beam test.

4.2 Direct tensile test

The figure 7 shows the evolution of the deformation of the mix 9 tested at 20°C. The three cracking phases described before can be clearly observed. The slope of the stable cracking phase is dependent from the stiffness of the mix. The greater the stiffness the lower the slope.

The graphs from the different mixes show that there is a point from which the failure is inevitable. This point is characterized by a deformation level ε_D that represents the highest deformation supported by the material. When this deformation level is reached by the sample, it leaves the stable cracking phase and enters the failure phase where the deformation increases suddenly until imminent physical failure.

An important finding is that the failure deformation level ε_D is very similar from one sample to another within the same mixture. Whatever the amplitude of the initial imposed solicitation and the duration of the test, the failure deformation level is always the same. This phenomenon led to the conclusion that this deformation value is a material characteristic which is totally independent of the initial imposed solicitation.

The figure 8 shows the values of ε_D for the tested mixes. Besides, the standard deviations of the test results within each mix were calculated. The average standard deviation for all mixes is 17.2% (with a range from 0 to 35%). For the test temperatures of 5°C and 20°C, the values of ε_D are very similar among all samples tested for each bituminous mix. For the test temperature of 35°C, these values increase slightly with the number of cycles until failure. Nevertheless, the lower values of ε_D appear for the more rigid mixes.

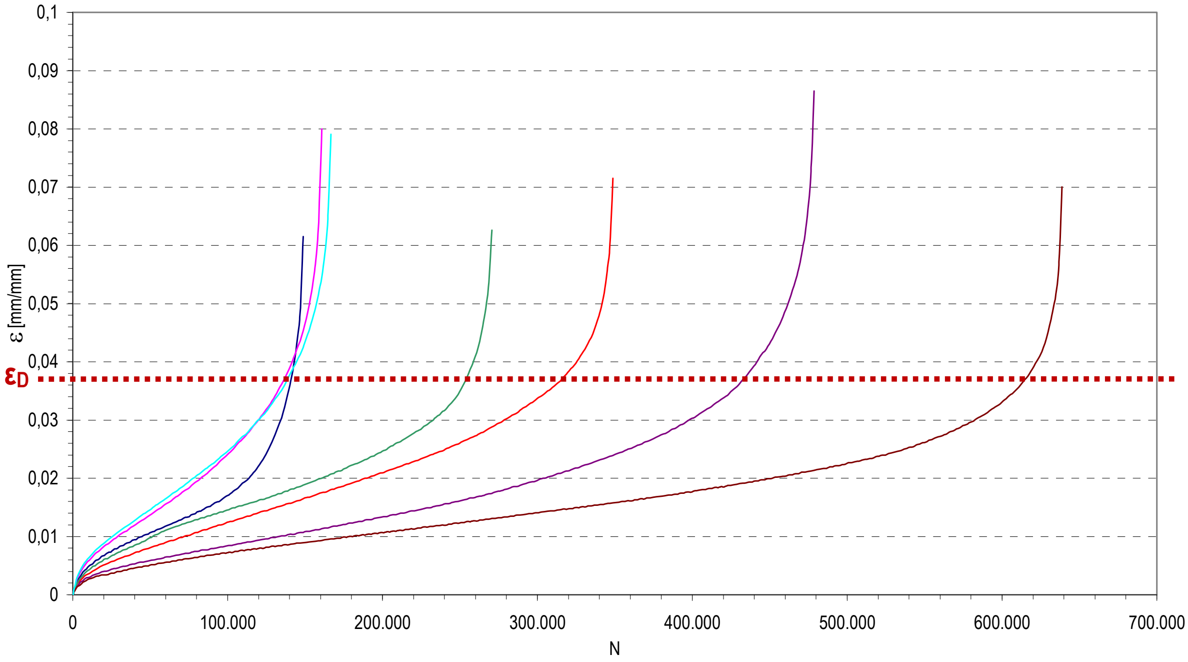

Figure 7: Evolution of the deformation in the direct tensile test for the samples of the mix 9.

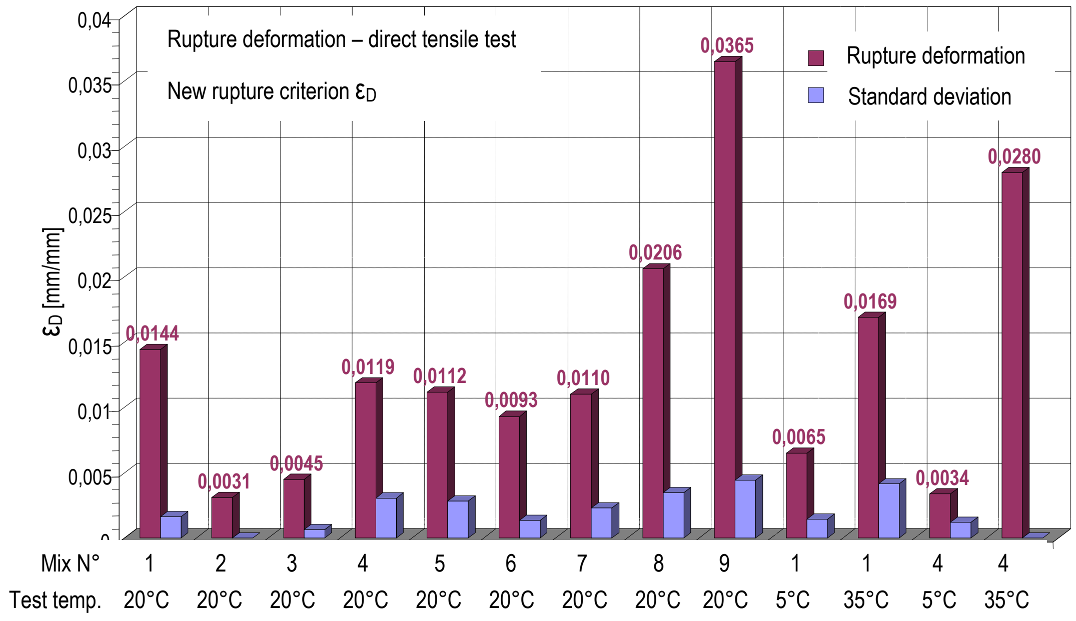

Figure 8: ε_D values for the tested bituminous mixtures.

4.3 Deterioration level of non failed samples during the dynamic direct tensile test

Some samples did not reach failure during the dynamic direct tensile test and after more than 2 million cycles. These samples were then tested in the same press under a quasi static solicitation at a speed of 0.1 mm/min. In parallel other new samples of the same mix where tested under the same conditions. The purpose of that was to observe which was the behaviour of samples already tested and new untested samples.

The figure 9 shows the behaviour of one of those samples tested twice (red line) in comparison with the untested samples (grey lines). It can be observed that unless the operator says that one sample has been tested twice, no one can detect that the red sample already supported more that 2 million cycles during almost 3 days. In this case, its behaviour is even better than the one from the untested samples.

This phenomenon confirms the fact that if a sample, even already tested, does not reach the deformation level characterising the mix, the material never fails and can behave like any other intact material.

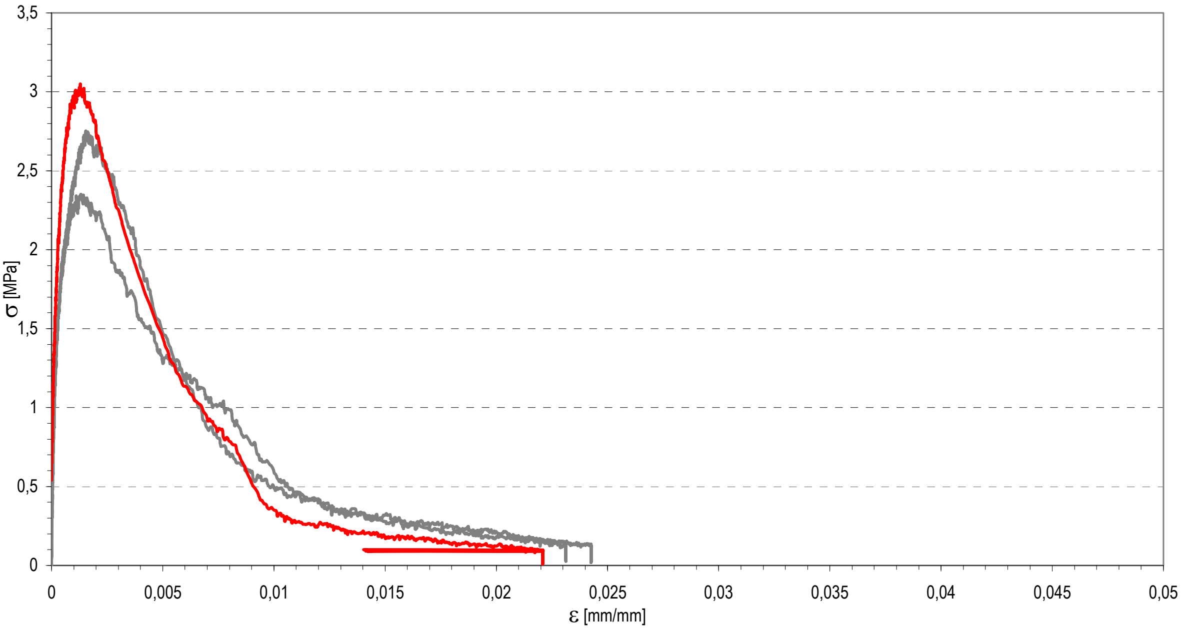

Figure 9: Resistance of already tested (dynamic direct tensile test) and non tested samples.

5 CONCLUSION

In the 3-point bending beam test, the analysis of the deformation evolution highlighted that the whole resistance of the material is not considered when, according to the standard, the tested material is supposed to have failed. There is no graphical nor physical element permitting to state that the sample has clearly failed and reached its resistance limit.

For the purpose of studying the damage evolution and to establish a clear failure criterion, a new direct tensile test was developed and validated. With this new direct tensile test, it has been possible to observe the crack propagation initiated on the notched faces and to establish that there is a progressive crack propagation in the material and a deformation level ε_D from which the initiated crack propagates in the material until the complete failure of the sample. The deformation level ε_D can be considered as a constant for each different type of bituminous mix. Indeed, whatever the initial imposed force at the beginning of the test, the failure deformation level (when the material inevitably fails) is practically constant for all the samples of the same bituminous mix. Thus, the deformation level ε_D characterizes each type of mix and is independent of the amplitude of the initial imposed solicitation. If the material does not reach the ε_D threshold, it does not fail. This phenomenon was confirmed by additional quasi-static tests that showed that if a sample, even already tested, does not reach the deformation level characterising the mix, the material never fails and can behave like any other intact material.

The analysis of the deformation evolution with the number of cycles also showed that the higher the initial dynamic modulus $|E^*|_{ini}$, the lower the deformation increment in each solicitation cycle. These elements ($|E^*|_{ini}$ and ε_D) have a strong influence on the fatigue behaviour. The higher $|E^*|_{ini}$ and ε_D, the higher the fatigue resistance.

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