False Failure in Flexural Fatigue Tests

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ABSTRACT: Flexural fatigue tests are typically run under displacement or in a strain-controlled mode. In these tests, either the oscillatory displacement amplitude or strain amplitude applied to the bottom of the specimen is kept constant. The evolution of loading required to cause fatigue is then measured. Load amplitude decreases with the number of cycles, and the specimen is considered to have failed when the load is half its initial value. This failure criterion may be erroneous when non-fragile fracture mixtures prepared with high bitumen contents or modified binders are tested. In these cases, mixtures exhibit a visco-plastic behaviour and increasingly less stress is necessary to cause strain without cracking. Mixtures are hardly deteriorated when the fatigue failure is determined, and may be subjected to a larger number of load repetitions. It is then recommended to control the evolution of loading more effectively and regard as valid only tests where load decreases sharply to very low levels, making sure that the three stages in the fatigue process have occurred.

1 INTRODUCTION

Fatigue cracking is considered one of the most important and frequent distresses in a bituminous mixture. Among the several ways to analyse this phenomenon, three different concepts are the most usually considered: the classical criterion, the fracture mechanics based method and the energy approach.

The classical criterion consists in relating the stress or strain in the bituminous mixture to the number of load repetitions to failure. Based on the traditional fatigue analysis (Wöhler curves), many researchers studied fatigue process through this method: Pell (1962), Pronk and Hopman (1990), Tayebali et al. (1996), Van Dijk and Visser (1977), and was taken by AASTHO as a fatigue failure criterion in 1994.

The fracture mechanics approach consists in studying the crack propagation in a bituminous mixture specimen subjected to a repetitive loading. Majidzadeh et al. (1971), Roque et al. (1999, 2002), Zhang et al. (2001) used this approach to analyse fatigue process.

Another way of studying fatigue failure is the damage-energy approach, which may be analysed with the constitutive damage model or the dissipated energy concept. The first alternative is based on the constitutive model developed by Kim and Little (1990), that takes into account linear viscoelasticity, healing due to a rest period and time dependence of the material. Van Dijk (1975) and Carpenter (1997) used the dissipated energy concept that defines fatigue life as a function of the dissipated energy accumulated on each loading cycle. Derived from this approach, the Dissipated Energy Ratio (DER) concept was developed by Ghuzlan and Carpenter (2000) and also used by many other researchers, such as Khalid et al. (2005).
Other researchers, Breysse et al. (2003, 2004) have also studied and modelled the influence of rest time on damage during fatigue tests and have shown the potential precariousness of the healing.

The fatigue failure process of bituminous mixes has been studied in the Road Research Laboratory of the Technical University of Catalonia through the classical theory of fatigue failure and special attention has been paid to the strain evolution in the fatigue fracture region.

Flexural and direct tensile fatigue tests were conducted to determine the strain evolution during the fatigue process of a series of bituminous mixtures with the aim of determining whether there is or not a certain level of permanent strain at which the mix fails due to fatigue process, irrespective of the stress or strain level applied.

2 MATERIALS AND METHODS

Different semidense bituminous mixtures with a maximum aggregate size of 20 mm have been tested through three and four point bending beam tests and direct tensile fatigue test. Although they have been prepared with different RAP contents and different bitumen types, the grading was kept constant (Table 1), as well as total bitumen content (4.5% by mass of aggregate). Mixtures with 30%RAP used 80/100 penetration bitumen, mixtures with 50%RAP used 150/200 penetration bitumen and mixture without RAP were fabricated with 60/70 penetration bitumen. The average grading of the aggregates is summarised in Table 1.

Table 1. Average grading for the bituminous mixtures studied

<table>
<thead>
<tr>
<th>Sieve Size (mm)</th>
<th>Passing (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>100</td>
</tr>
<tr>
<td>20</td>
<td>91.8</td>
</tr>
<tr>
<td>12.5</td>
<td>71.3</td>
</tr>
<tr>
<td>8</td>
<td>59.6</td>
</tr>
<tr>
<td>4</td>
<td>41.8</td>
</tr>
<tr>
<td>2</td>
<td>28.8</td>
</tr>
<tr>
<td>0.5</td>
<td>14.4</td>
</tr>
<tr>
<td>0.25</td>
<td>10.3</td>
</tr>
<tr>
<td>0.125</td>
<td>7.1</td>
</tr>
<tr>
<td>0.063</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Two flexural fatigue tests have been used: four and three-point bending beam tests (the last one standardized in Spain), and also a dynamic direct tensile test developed in the Road Research Laboratory of the Technical University of Catalonia, with the objective of comparing the results obtained with the bending beam tests and another fatigue test type.

The tests have been carried out at different temperatures: 5, 20 and 35°C, in order to analyse different mixture performances: stiff and fragile behaviour at low temperatures, flexible and ductile behaviour at high temperatures.

Four point bending beam was carried out according to UNE-EN 12697-24, Annex D. Figure 1 shows the four point bending equipment, composed of two inner and two outer clamps symmetrically placed. The two outer clamps keep the beam fixed and the two inner clamps are loaded to create a constant moment.
Three point bending beam was carried out according to Spanish Standard NLT-350 (or UNE-EN 12697-24, Annex C), with a prismatic specimen laid on its ends and fixed in its centre. Figure 2 shows the anchoring devices for the specimen testing.

The dynamic bending beam tests (both three and four point beam tests) consist in subjecting a prismatic specimen to a time-variable displacement according to the following law:

\[ D = D_0 \cdot \sin(2\pi ft) \]  

where \( D \) = displacement at moment \( t \); \( 2D_0 \) = total amplitude of the displacement function; \( f \) = wave frequency; and \( t \) = time.
Direct tensile test was developed at the Road Research Laboratory of the Technical University of Catalonia and consists in subjecting a prismatic specimen to tensile stress.

Prismatic specimens can be obtained from laboratory-made prismatic or cylindrical specimens of different sizes depending on the compaction equipment used. They must be properly sawn to achieve approximate dimensions of 150x50x50 mm. Alternatively, they can be obtained by sawing cylindrical cores extracted directly from the pavement layer.

In both cases, a small 5 mm indentation is made at both sides of the central section of the specimen. A metallic support is stuck on the bases of the specimen so that clamps placed on each of the press pistons are fixed to the specimen. In this way, tensile stress can be applied to the specimen, Figure 3a.

During the specimen testing, the variation of strain produced in the mixture is recorded with one or two extensometers placed on one or both indented sides of the specimen, respectively, Figure 3b.

Figure 3. Direct Tensile Test, (a) photo, (b) scheme.

Under stress controlled mode, tests were carried out at a frequency of 10 Hz and a cyclic loading is applied according to a sinusoidal function expressed in equation (2). During the test, strain evolution with the load applications is registered.

\[ F = F_0 \sin(2\pi f t) + A \]  
\[ 2F_0 = F_{\text{max}} - F_{\text{min}} \]  
\[ A = F_{\text{min}} + (F_{\text{max}} - F_{\text{min}}) / 2 \]

where \( F \) = load at moment \( t \); \( 2F_0 \) = total amplitude of the load function; \( F_{\text{max}} \) = maximum load; \( F_{\text{min}} \) = minimum load; \( f \) = wave frequency; and \( t \) = time.

3. RESULTS AND DISCUSSION

When the beam is subjected to a four point bending test, its modulus decreases with the increase of the number of cycles applied. The value of the initial modulus is calculated from the measured values of force, displacement and phase lag after the hundredth cycle. According to the classical fatigue failure criterion, the fatigue test continues until the modulus drops to half its initial value or until the specimen breaks. However, if the test is stopped at that moment of 50% modulus reduction (and the specimen is not broken), and the strain amplitude is increased, the specimen will behave as if it is not broken, since the modulus turns to be high and the test will continue until the modulus reaches half its initial value. Figure 4 shows the load evolution,
directly related to modulus evolution, where the specimen was tested according to the above mentioned procedure.

Figure 4. Load evolution with the number of cycles. Four-point Bending Beam Test at 20°C, semidense bituminous mixture.

So, the authors put forward that a mistake can be made if the specimen failure is considered when its modulus is reduced to a 50% of its initial value and the strain evolution is not taken into account, since the specimen may be considered to have failed much before it actually has.

Flexural bending beam tests present this problem when they are performed at displacement-controlled mode, especially when deformable mixtures containing polymer-modified bitumens or high bitumen contents are tested.

In order to show this fact, and considering that the four point bending beam test does not allow registering the strain evolution at the bottom of the specimen, the authors use the three point bending beam test, where an extensometer can be fixed to the face of the beam, Figure 5.

Figure 5. Three-point Bending Beam Test. Extensometer placed to measure the strain evolution.

The results obtained from the test conducted in the dynamic mode reveal that, for each mixture type, there is a strain from which the fatigue process proceeds very rapidly. This strain, which we have called “critical strain”, is independent of the stress state to which specimens are subjected during the fatigue process. That is, if a high stress is applied, the initial strain will be greater and will increase with each load application until the critical strain level is reached. At this point, the fatigue process will speed up and the strain level produced in each cycle will increase until the material cracks. The initial strain will be lower if a smaller load is applied,
but it will increase with each load application until reaching the critical strain and the final situation will be similar.

Figures 6 and 7 show some of the results obtained with the three-point bending beam, including the critical strain level for each test, Alonso (2006) and Rodriguez (2009). Each specimen was tested at the displacement amplitude indicated in the legend of the figures.

Critical strain is a parameter which depends on the type of test and tested mixture. Although test results exhibit some dispersion, a feature common to all fatigue tests, critical strain is noticeable.

Figure 6. Strain evolution with the number of load cycles. Three-point Bending Beam Test at 5°C, semidense bituminous mixture with 30% RAP.

Figure 7. Strain evolution with the number of load cycles. Three-point Bending Beam Test at 5°C, semidense bituminous mixture with 50% RAP.
Therefore, fatigue critical strain may be regarded as a mixture characteristic irrespective of the stress state to which specimens are subjected in the test.

Three-point bending beam tests have also shown that mixtures not reaching the critical strain level, Figure 8, are not broken despite having attained the level of conventional failure, i.e. a 50% reduction of the load applied at the beginning of the test, cycle 200, Figure 9.

The specimen is highly deformable because the test temperature is 35°C. If the test results for strains and stresses are analyzed, it is observed that the initial load is reduced to half after 200,000 applications. According to the classical criterion, the specimen would have failed. However, observation of the strain evolution shows that it does not increase but rather remains stable. It would appear that the outer fibres have cracked whereas the inner fibres remain intact since the displacement necessary to make them crack is not significant enough, Figure 10.

![Figure 8. Strain evolution with the number of cycles. Three-point Bending Beam Test at 35°C.](image1)

![Figure 9. Load evolution with the number of cycles. Three-point Bending Beam Test at 35°C.](image2)
Kim et al. (2006) found a transition point for asphalt matrix mixtures with a new type of fatigue testing apparatus when assessing the decrease of dynamic modulus with the number of loading cycles. Two different rates of change in stiffness were observed, which were possibly indicating the limit between microcracking and macrocracking. So, this point was proposed as a failure criterion by the authors, Kim et al. (2008). It is possible that critical strain indicates the same situation, although more analysis should be done to confirm this hypothesis.

This critical strain in fatigue tests can also be observed in direct tensile fatigue tests under controlled stress, Figure 11.

Under controlled strain, this type of testing shows that, if the strain level is low, the specimen behaves almost elastically and the necessary load for each cycle varies very little. If the strain level is increased, the process is similar until there is a strain value under which load decreases quickly and fatigue failure takes place, Figure 12.
Fatigue critical strain is a mixture constant which varies with mixture type and test temperature. Moreover, the analysis of the strain evolution with the number of cycles shows that the higher the mixture modulus, the smaller the increase in strain for each load application, Figure 13. It seems that critical strain and mixture modulus determine the fatigue behaviour of the mixture. It can therefore be deduced that the higher the mixture modulus and critical strain, the better its fatigue behaviour.

The fatigue law is expressed by the following equation:

\[ \varepsilon = aN^b \]  

where \( N \) = number of load applications to failure; \( \varepsilon \) = strain; and \( a \) and \( b \) are experimentally determined coefficients.

Table 2 shows the modulus, the critical strain and the fatigue laws obtained for the studied mixtures considering the classical criterion and the proposed critical strain criterion for the mixtures A, B, C, and D.
extreme temperatures studied: 5 and 35°C. Critical strain was determined with the bisecting line of the tangents to the strain evolution curve where the slope changes remarkably.

Table 2. Modulus, critical strain and fatigue laws for mixtures with 30%RAP tested at 5 and 35°C.

<table>
<thead>
<tr>
<th>Temperature Testing (ºC)</th>
<th>Modulus (MPa)</th>
<th>Critical Strain (mm/mm)</th>
<th>Fatigue Law Classical Criterion</th>
<th>Fatigue Law Critical Strain Criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>16616</td>
<td>0.0004</td>
<td>$\varepsilon = 0.0007N^{0.1327}$</td>
<td>$\varepsilon = 0.0006N^{0.1285}$</td>
</tr>
<tr>
<td>35</td>
<td>2007</td>
<td>0.0016</td>
<td>$\varepsilon = 0.0008N^{0.0874}$</td>
<td>$\varepsilon = 0.0044N^{0.2052}$</td>
</tr>
</tbody>
</table>

Fatigue laws at 5ºC are very similar, but the results obtained at 35ºC show higher fatigue life when it is calculated with the Critical Strain criterion (this life comparison is valid for a number of cycles less than 1,000,000), Figure 14.

![Figure 14. Fatigue laws for the mixtures with 30%RAP tested at 5 and 35°C.](image)

4. CONCLUSIONS

The results of this study reveal that fatigue cracking of mixtures takes place when a certain strain level is reached, here named fatigue critical strain, for each test type and temperature, independently of the applied stress.

Mixtures with the same critical strain level but different modulus exhibit different fatigue behaviour. It can therefore be deduced that the higher the mixture modulus and critical strain, the better its fatigue behaviour.

The results have also shown that, when performed at controlled strain rate, flexural bending beam tests may yield false results when highly deformable mixtures are tested, as is the case of mixtures prepared with polymer-modified bitumens.

5. REFERENCES


