Fatigue life of asphalt concrete with rubber grains

A. D’Andrea, N. Fiore

Department of Hydraulics, Transportation and Roads, “La Sapienza” University of Rome, Italy

Abstract

This paper presents some results achieved in a wide research carried out in the road material laboratory of the Rome University “La Sapienza” to assess the suitability of a new hot mix asphalt (HMA), containing crumb rubber (particle size 2-5 mm), as sub-ballast in railways or base layer in road pavements. This material could be effective in the reduction of vehicular traffic vibrations; however, crumb rubber is responsible for reducing mechanical characteristics of the asphalt concrete. The aim of this step of the program here discussed is to evaluate the influence of kind and content of crumb rubber on bituminous mixes, regarding fatigue life. The experimental analysis was directed to detect the initial modulus value, above which this bituminous material will remain structurally serviceable for a considerable period. The tests were conducted on cylindrical specimens, using a servo-hydraulic loading system and operating in a loaded-controlled fashion (tension-compression), at a frequency of 10 Hz and a temperature of 20° C. The adopted failure criterion, considering an assigned constant stress amplitude, was the number of load repetition that causes a decrease in modulus to half the initial value or, depending on the progress of the test, the fracture of the specimen due to macro-cracking. The tests were performed with various stress levels, related to the stiffness of the mix. This study documents the relationship between stiffness, as characterized by dynamic (complex) modulus, and fatigue life. Four mixes, different in kind and content of rubber, were checked and compared with a traditional HMA. The interpretation of experimental results demonstrates that mixes, containing a certain kind and a weight content up to 3% of crumb rubber, show a fatigue life comparable with traditional HMA.
1 Introduction

With the increase in the number of waste tires accumulating around the world, more nations are looking for ways to make use of them evenly within railway and road constructions. In this field, at now, the most common uses of waste tires are:

- tire shred as a lightweight fill material in embankments [1], [2], [3];
- powdered rubber as additive to modify bituminous binder properties (wet process) [2], [3];
- crumb rubber as aggregate in bituminous mixes (dry process) [2], [3].

The idea of using ground crumb rubber to make anti-vibrating layers leads to an added value for waste tires. This concerns the augment of people life conditions and the protection of ancient monuments and places against the vibrations induced by vehicular traffic. With regard of this issue several studies has been carried out with powdered rubber [4]. They have demonstrated the effectiveness of rubber-modified asphalt concrete towards vibrations, but crumb rubber used in dry process could supply a more cost-effective and simple system.

The aim of this part of the research is to assess the suitability of asphalt concrete containing crumb rubber (dry process) with regard to fatigue life. This study documents the relationship between stiffness, as characterized by dynamic (complex) modulus, and fatigue life. It is easy to envisage that the presence of crumb rubber may result in a reduction of the mechanical properties of such a particular hot mix asphalt (HMA) [3], this appears clearly considering the results of the traditional mechanical strength tests (Marshall stability, indirect tensile stress test etc.) [5]. Therefore a similar decrease could be presumed with regard to fatigue resistance. In the end this paper will present the evaluation of the appropriate type and content of rubber to guarantee the asphalt pavement to be serviceable for a considerable period, or at least comparable with traditional asphalt concrete.

2 Asphalt concrete with rubber grains

The inert materials used in the project were common calcareous aggregates coming from quarries nearby Rome. The gravel and sand were all crushed materials distributed in three fractions, resulting in the final grading suitable to be used in bitumen concrete normally used in Italian railways as sub-ballast layer. Portland cement was also provided as filler. The gradation curve is presented in figure 1. The binder was bitumen with the following characteristics:

- penetration grade: 55 dmm;
- ring and ball softening point: 48.5°C.

Two types of crumb rubber were introduced in the mixes, coming from different production processes. The first, named CN, is obtained by simple mechanical shredding of tires in pieces of the desired dimension; the second one, named FR, is obtained with a system of hammers and sieves after freezing tires at very low temperature, about -100°C. The steel belt fragments are
removed by a magnetic separator. Fibers are separated from finer rubber particles by an air separator. Table 1 shows some of the physical properties of the two types of crumb rubber used. The introduction of crumb rubber within the mixes was made by substitution of the corresponding aggregate fraction. Due to the great difference in density between crumb rubber and calcareous materials the substitution was made by volume [3].

![Figure 1: gradation curve before substitution with crumb rubber, mixture suitable to be used as HMA subballast in railway track.](image)

<table>
<thead>
<tr>
<th>type of crumb rubber</th>
<th>treatment</th>
<th>density (g/cm³)</th>
<th>particle size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CN</td>
<td>mechanical</td>
<td>1.18</td>
<td>2-5</td>
</tr>
<tr>
<td>FR</td>
<td>cryogenic</td>
<td>1.17</td>
<td>0.4-5</td>
</tr>
</tbody>
</table>

A total of five mixes were studied using the Marshall mix design. Samples were categorized by their rubber type and rubber content. Table 2 summarizes the characteristics of the different asphalt mixtures. A laboratory study program was undertaken in order to investigate the effects of rubber content. The tests included Marshall stability and indirect tensile stress test. The decrease of mechanical properties of mixes containing crumb rubber towards traditional hot mix asphalt is shown in table 3.
Table 2: bituminous mixes.

<table>
<thead>
<tr>
<th>Mix</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber type</td>
<td>-</td>
<td>CN</td>
<td>CN</td>
<td>FR</td>
<td>FR</td>
</tr>
<tr>
<td>Rubber content by weight of dry aggregates (%)</td>
<td>0</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Rubber content by volume of dry aggregates (%)</td>
<td>0</td>
<td>6.7</td>
<td>10.8</td>
<td>6.8</td>
<td>10.9</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>2.54</td>
<td>2.25</td>
<td>2.14</td>
<td>2.22</td>
<td>2.09</td>
</tr>
<tr>
<td>Bitumen content by weight of dry aggregates (%)</td>
<td>4.1</td>
<td>4.7</td>
<td>4.9</td>
<td>4.4</td>
<td>4.5</td>
</tr>
<tr>
<td>Bitumen content by volume of dry aggregates (%)</td>
<td>10.8</td>
<td>12.2</td>
<td>12.3</td>
<td>11.3</td>
<td>11.4</td>
</tr>
<tr>
<td>Air voids (%)</td>
<td>4.0</td>
<td>7.6</td>
<td>10.3</td>
<td>9.9</td>
<td>12.9</td>
</tr>
</tbody>
</table>

Table 3: mechanical properties decay of asphalt mixes containing crumb rubber related to traditional hot mix asphalt.

<table>
<thead>
<tr>
<th>Mix</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability [daN]</td>
<td>1307</td>
<td>677</td>
<td>571</td>
<td>798</td>
<td>604</td>
</tr>
<tr>
<td>Rigidity [daN/mm]</td>
<td>388</td>
<td>101</td>
<td>67</td>
<td>118</td>
<td>76</td>
</tr>
<tr>
<td>Indirect tensile [daN/cm²]</td>
<td>14.3</td>
<td>7.1</td>
<td>7.6</td>
<td>9.5</td>
<td>4.8</td>
</tr>
</tbody>
</table>

3 Fatigue test and setup

In order to address fatigue distress in mixture and pavement design procedures, it is necessary to describe the behaviour of asphalt mixes under repeated load stress. Axial tensile and compressive loading, applied on cylindrical specimens using a servo-controlled electro-hydraulic machine, has been preferred in this experimental tests. Such test method was considered by SHRP [6]; its advantages include the following:
- it is possible to simulate the loading pulse observed in the field (compression-tension-compression);
the results can be used to evaluate mixtures effects and, with field correlation factors, to design pavements to control the fatigue cracking. Disadvantages include the following:

- the test does not represent well the field conditions except the form of the loading pulse;
- when compared with direct tensile test, reversed-stress tests require more time, are more costly, and require more specialized equipment.

However, advantages seemed to overcome disadvantages, for the test method was also developed and validated as European standard to determine dynamic complex modulus of asphalt mixtures (pr EN 12697-26) [7]. Furthermore, Read and Brown found a good correlation between indirect tensile and tension compression fatigue test [8]. Last but not least the test method chosen ensures an homogeneous state of stress and strain inside the sample: this allows to obtain directly the material behaviour, e.g. complex modulus; whereas flexion of beam test or indirect tensile test creates a non homogeneous state of stress: this require to fix in advance a behaviour law of the material that could lead to remarkable errors [9], [10].

Experimental tests have been carried out on cylindrical specimens with a diameter of 100 mm and a height of approximately 200 mm. The top and the bottom of the specimen have been glued to rigid steel plates that could be fixed to the servo-controlled electro-hydraulic machine. A tension-compression stress was applied cyclically under stress controlled conditions. The equipment had a computer-based operation system and an automated data acquisition system. A computer program was used to calculate the dynamic complex modulus of the tested material. The climatic testing chamber was set at a temperature of 20°C and the sinusoidal loading frequency was 10 Hz.

The test was interrupted overnight both to simulate the healing that occurs to the asphalt concrete, during the low traffic periods, and for our laboratories are placed in the city centre, nearby Colosseum, so all testing machine have to be turned off during the night.

It is known that the performance of HMA pavement structure depends on the interaction between pavement responses and the strength and modulus of the different layers. In this view, in order to match the real stress conditions, a fatigue protocol has been developed to define the stress levels the specimens should be subjected to. A multilayer elastic model has been implemented to work out the real tensile stress experienced at the bottom of the bound layer placed as sub-ballast in the railway track modelled. The initial stiffness of each mixture has been detected after a few load cycles. The stress ($\sigma_i$) related to the mixtures stiffness has been calculated with the CIRCLY computer program using an ordinary railway load (ETR 500). The stress ($\sigma$) the specimens have been subjected to has been chosen as a multiple of the calculated stress. In this way the tests were performed at different stress levels ($\sigma/\sigma_i$), all related to the stiffness of the mix. The initial moduli and the related stresses are summarized in Table 4. Failure was defined as the number of load repetition, recorded under an assigned stress level, where the material stiffness become half its initial value or, depending on the progress of the test, the fracture of the specimen due to
macro-cracking. Figures 2 to 4 show the tests progress, with regard to the resulting modulus and the trend of the phase angle of mixes without crumb rubber and containing rubber named CN, at stress level 2 (i.e.: $\sigma/\sigma_t=2$). A second set of specimens have been tested, trying to find out a fatigue behaviour. The results and the suggested slope of fatigue behaviour are collected in Figures 5 and 6.

Table 4: real stress related to initial elastic modulus of asphalt mixes

<table>
<thead>
<tr>
<th>Mix</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial stiffness E (daN/cm²)</td>
<td>50000</td>
<td>24000</td>
<td>18000</td>
<td>16000</td>
<td>15000</td>
</tr>
<tr>
<td>initial stress $\sigma_i$ (daN/cm²)</td>
<td>1</td>
<td>0.6</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Figure 2: mix A - modulus of the complex modulus and phase angle, $\sigma/\sigma_t=2$. 

Figure 3: mix B - modulus of the complex modulus and phase angle, $\sigma/\sigma_f=2$.

Figure 4: mix C - modulus of the complex modulus and phase angle, $\sigma/\sigma_f=2$. 
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Figure 5: Summary review of the fatigue tests results with regard to stress levels.

Figure 6: Summary review of the fatigue tests results with regard to stress absolute value.

4 Discussion

The low number of load repetitions at failure has to be related to the high level of stress applied and with the known observation that laboratory fatigue tests
generally under-estimate the fatigue resistance of bituminous mixes. In figures 2 to 4 we can see the decay of the stiffness under cyclic loading and its subsequent substantial recovery during the rest periods. This could depend on the visco-elasticity of the matrix that causes hysteretic behaviour of the material. Previous studies have already demonstrated that a remarkable part of the dissipated energy turns into heat [9]. Actually during the tests the climatic cell can’t completely compensate the increase in temperature inside the specimen. However, the temperature raise can partly explain the observed decrease in stiffness modulus. A secondary role is probably acted by initial micro-cracking that doesn’t lead to macro-cracking at lower stress levels. Micro-cracking could also be repaired during the rest period. At higher stress levels micro-cracking propagates rapidly to macro-cracking and then to failure.

If we compare the several mixes considering the absolute values of stress amplitude applied, it can be noted the great difference between traditional asphalt concrete and crumb rubber mixes; this is due in some measure:
- to the higher void content that characterizes them, for this factor affects largely the mechanical properties [11], [12] and fatigue behaviour of the asphalt mixtures [13];
- to the type of crumb rubber.

Vice versa, we can accept that the stress levels have to be related to the material stiffness, in fact the higher the stiffness the higher the stress experienced at the bottom of subballast. On these terms we can observe that asphalt mixes B and C showed a fatigue resistance comparable with asphalt concrete without crumb rubber, despite of the higher voids content and the lower mechanical properties. It is interesting to note that both mixes B and C contain crumb rubber named CN, coming from mechanical treatment, but different content (3% and 5% by weight, 6.7% and 10.8% by volume of dry aggregates). Fatigue behaviour of mixes D and E is definitely worse than all the other tested mixes.

5 Final result

A new hot mix asphalt containing crumb rubber, addressed to be used as anti-vibrating subballast in railway constructions, has been tested in order to assess its fatigue resistance. Four mixes different in type and content of crumb rubber have been compared with traditional hot mix asphalt. A multilayer elastic model has been implemented with the view of relate the test stress with the stress experienced at the bottom of subballast. To accelerate the response, stress levels multiple of the real stress, have been applied to laboratory specimens. Despite the small deal of experimental data, it seems to be extremely interesting to note the substantial alignment of the fatigue curves outlined. With regard to fatigue life, the mixture with 3% by weight of crumb rubber shredded mechanically, appears the most suitable to be used as subballast and to be tested in the second step of the research concerning damping vibrations.
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6 References


