FATIGUE PERFORMANCE OF BITUMINOUS MIXTURES MADE WITH RECYCLED CONCRETE AGGREGATES AND WASTE TIRE RUBBER

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Abstract

Fatigue cracking is one of the main hot-mix asphalt (HMA) failure modes. The current laboratory investigation analyses the fatigue performance of HMA made with recycled concrete aggregates (RCA). An HMA type AC 22 bin S made with 0%, 35% and 42% of RCA was tested in the indirect tensile fatigue test (ITFT) device. Three constant stress levels, ranging from 150 kPa to 350 kPa were used. Mixtures were manufactured at the optimum bitumen content using two types of bitumen: a B35/50 penetration grade bitumen and a 10% waste tire rubber modified bitumen, BC35/50. This investigation demonstrates the beneficial effect on fatigue life of the incorporation of RCA. Additionally, the use of crumb rubber could lead to RCA bituminous mixtures with higher fatigue life in medium traffic roads.

Keywords: fatigue life; hot-mix asphalt; recycled concrete aggregates; indirect tensile fatigue test; waste tire rubber

1. Introduction

Hot-mix asphalt (HMA) is a widely used road pavement material. Of the more than 5.2 million km of the European road and highway network, it is estimated that over 90% are paved with HMA or other bituminous materials [1]. Similarly, more than 92% of the more than 4 million km of U.S. highways and roads are paved with asphalt [1].

Transport infrastructures enhance the economic and social development of a region, increase accessibility and help to mitigate territorial imbalances. For all of these reasons, the quality and durability of highways and road networks must be ensured. It is very important to analyse HMA properties and weaknesses carefully.

Fatigue cracking is one of the main HMA failure modes along with rutting and low temperature cracking [2]. Fatigue cracking results in the shortening of pavement life [3] and is directly related to the quality of road asphalt pavements [4]. Fatigue cracking occurs when the asphalt pavement is subjected to repeated traffic loading [5], as a consequence of the passage of vehicle wheels with a loading level lower than the tensile strength of the material [4]. Despite this low loading level, the cumulative effect of repeated traffic loading over time leads to the appearance of fissures. This phenomenon usually occurs in two stages. In the first stage, called “initiation phase”, the appearance of micro-cracks (not visible to the naked eye) that reduce the stiffness of the HMA occurs [6]. Later, in a second stage called “propagation”, as traffic loads continue, the coalescence of micro-cracks gives way to the formation and growth of macro-cracks [7]. The growth of these macro-cracks begins with stable crack growth and continues with unstable crack growth [8] that finally, at the end of the second phase, leads to the structural failure of the mixture.

It is necessary to take into account that other mechanisms, such as self-heating or bitumen tixotropy, which are acting in parallel to cause fatigue, can reduce stiffness [6]. These mechanisms are predominant at the beginning of the "initiation" phase [6].

The fatigue structural failure manifests itself at the flexible pavement surface in two main cracking forms:

- When the bituminous layer is thin or medium, the highest tensile stress is at the bottom of the HMA as a result of bending of the bituminous layer when vehicles pass. In this case, fatigue cracking is usually visible as interconnected cracks, known as "alligator" cracking [9] because of the appearance (figure 1a). These cracks may allow water infiltration to reach the base course or the subgrade [4] and lead to the subsequent appearance of other pavement distress, such as potholes. When "alligator" cracking occurs, the classical fatigue approach, that is, bottom-up fatigue cracking, is prevalent: as a consequence of the horizontal tensile strains or stresses induced by the traffic at the bottom of HMA layers, cracks are originated and propagate upward to the surface course [10]. As a result, the loss of stiffness originated by the appearance of cracks finally leads to increased tensile strains at the bottom of the asphalt layers and increased surface deflections [11].
- When the thickness of the bituminous layer is sufficiently high, the most prejudicial stresses are shear stresses originating at the top of the HMA, which are the consequence of the complex contact pressure distribution under the vehicle tire [11]. This causes fatigue of HMA in the form of longitudinal cracking along the wheel path [10] together with small transverse cracks [11] (figure 1b). In this case, the prevalent fatigue mechanism is top-down fatigue cracking: cracks initiate at the HMA surface and progress downwards through

the bituminous layer. Environmental factors, such as thermal stresses and the existence of damage zones, may accelerate top-down fatigue cracking [12].

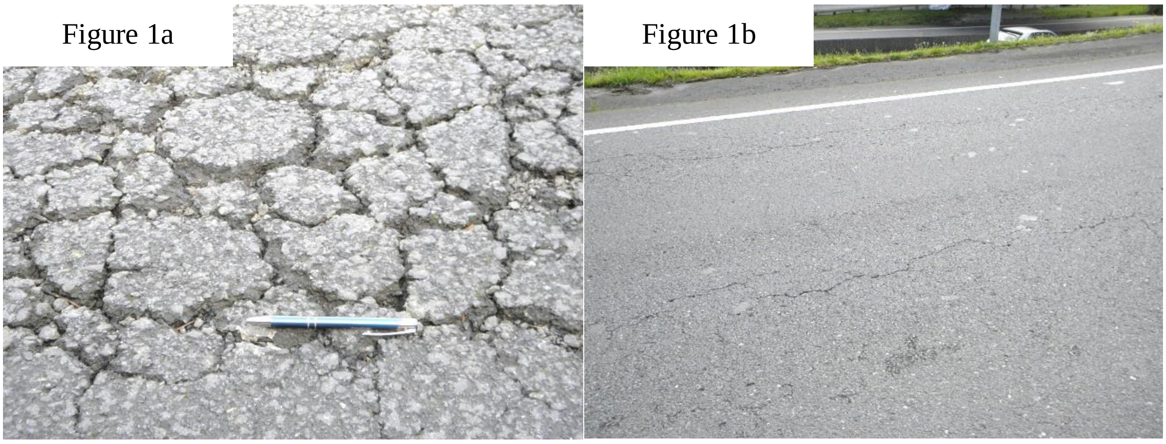

Figure 1. Cracking due to HMA fatigue: a) “Alligator” cracking and b) Longitudinal cracks along the wheel pad.

HMA is typically composed of approximately 95 percent mineral aggregates mixed with 5 percent of bituminous binder [1]. In some cases, the addition of small amounts of other materials such as fibres, may improve some of the bituminous mixture’s properties [10].

In view of these percentages, it is clear that the substitution of virgin mineral aggregates with recycled aggregates will have economic and environmental advantages. For these reasons, the use of residues and industrial by-products as recycled aggregates has been an excellent choice over the last few decades. Some of these residues are still being studied. This is the case with recycled concrete aggregates (RCA) from construction and demolition waste (C&DW).

Some authors have investigated the use of RCA on HMA, with encouraging results [13]. The fatigue resistance of HMA made with RCA is one of the less studied properties. In this regard Chen et al. [14] followed the AASHTO T-321 to analyse the four-point bending fatigue life, concluding that the use of RCA as mineral filler in HMA produced mixtures with higher fatigue resistance. Pérez et al. [15, 16] followed Spanish NLT-350 standard to analyse the three-points bending fatigue life of HMA made with RCA up to 60%, concluding that these mixtures behave similar to conventional ones. Arabani and Azarhoosh [17] used the Nottingham Asphalt Tester to analyse the fatigue life of mixtures made with RCA. They concluded that when RCA is used in the fine fraction, the fatigue life of the mixtures increases, while when RCA is used in the coarse fraction, the fatigue life decreases. Moghadas Nejad et al. [18] used the indirect tensile fatigue test and concluded that the use of up to 100% RCA improved the fatigue life of the bituminous mixtures. Pasandín and Pérez [19] concluded that mixtures up to 20% of RCA perform similar to conventional ones, while higher percentages of RCA lead to mixtures with poor fatigue life. Also Pasandín and Pérez [20] stated that mixtures made with RCA coated with bitumen emulsion perform similar to conventional mixtures in terms of fatigue life.

The aim of this investigation is

- Determine whether the use of RCA affects the fatigue resistance of HMA.
- Evaluate whether there is any trend in fatigue life as the RCA percentage in HMA is increased.
- Reach a better understanding of the performance of HMA made with RCA.

To fulfil these objectives, an experimental laboratory investigation was conducted that focused on the fatigue resistance of HMA made with RCA. In the study, an AC 22 bin S made with 0%, 35% and 42% RCA was tested in the indirect tensile fatigue test (ITFT) device at a constant temperature of 20°C at the optimum bitumen content with two types of bitumen: B35/50, penetration grade bitumen, and BC35/50, a waste tire rubber modified bitumen.

2. Materials and Methods

2.1. Basic Materials

2.1.1. Aggregates

Two aggregates were used in this investigation: natural aggregates and recycled concrete aggregates (RCA) from construction and demolition waste (C&DW).

The natural aggregates were crushed limestone from a local quarry in Madrid (Spain). RCA were obtained from the demolition of residential buildings and were supplied by a C&DW recycling plant in Madrid (Spain).

As shown in table 1, RCA display lower bulk specific gravity (ρa) than the limestone as well as higher water absorption (W_{24}). The cement mortar adhering to the RCA surface, which is more porous and less dense than the aggregates [21], is mainly responsible of this characteristic. This phenomenon is more pronounced in the finest fractions due to the higher percentage of mortar included in this fraction [21].

The sand equivalent (SE) values of the RCA (67%) and the limestone (59%) obtained according to UNE-EN 933-8 complied with the Spanish General Technical Specifications for Roads (PG-3) [22], for HMA as a base course material for all heavy traffic categories (SE > 55%).

The flakiness index (FI) of RCA (8%) and limestone (15%) obtained according to UNE-EN 933-3 also complies with the PG-3 for all heavy traffic categories (FI ≤ 20%).

The Los Angeles (LA) abrasion coefficient obtained according to UNE-EN 1097-2 for the limestone (15%) also complies with PG-3 (LA ≤ 25%) for all heavy traffic categories. The LA for the RCA (32%) is too high and only complies with the PG-3

(LA ≤ 35%) for medium and light heavy traffic categories (Annual Average Daily Heavy Traffic < 200 vehicles per day).

Table 1. Bulk specific gravity and water absorption of RCA and limestone obtained according to UNE-EN 1097-6.

Aggregate		RCA	Limestone
ρa (g/cm^3)	0/2 mm	2.693	2.720
	2/4 mm	2.675	2.709
	4/8 mm	2.645	2.686
	8/16 mm	2.630	2.688
	16/22.4 mm	2.605	2.686
WA_{24} (%)	0/2 mm	7.467	1.404
	2/4 mm	5.772	2.351
	4/8 mm	5.065	1.473
	8/16 mm	4.376	1.671
	16/22.4 mm	4.088	1.631

2.1.2. Bitumen

The asphalt binder used in this investigation was a penetration grade bitumen B35/50 typically used in HMA manufacture in Spain. The same bitumen, modified with 10% by weight waste tire rubber, BC35/50, was also used. Its main properties are summarized in Table 2.

Table 2. Basic properties of bitumen.

Test	Standard	B35/50	BC35/50	Specification [23]
Penetration (100 g, 5 s, 25℃), 0.1 mm	UNE-EN 1426	41	38	35-50
Softening point, ℃	UNE-EN 1427	53	64	50-58 for B35/50 ≥ 58 for BC35/50

2.2. Specimen Preparation

A hot-mix asphalt type AC 22 bin S has been selected for this investigation. Figure 2 shows the grain size distribution of the mixture that is included and the limits specified by the PG-3 [22].

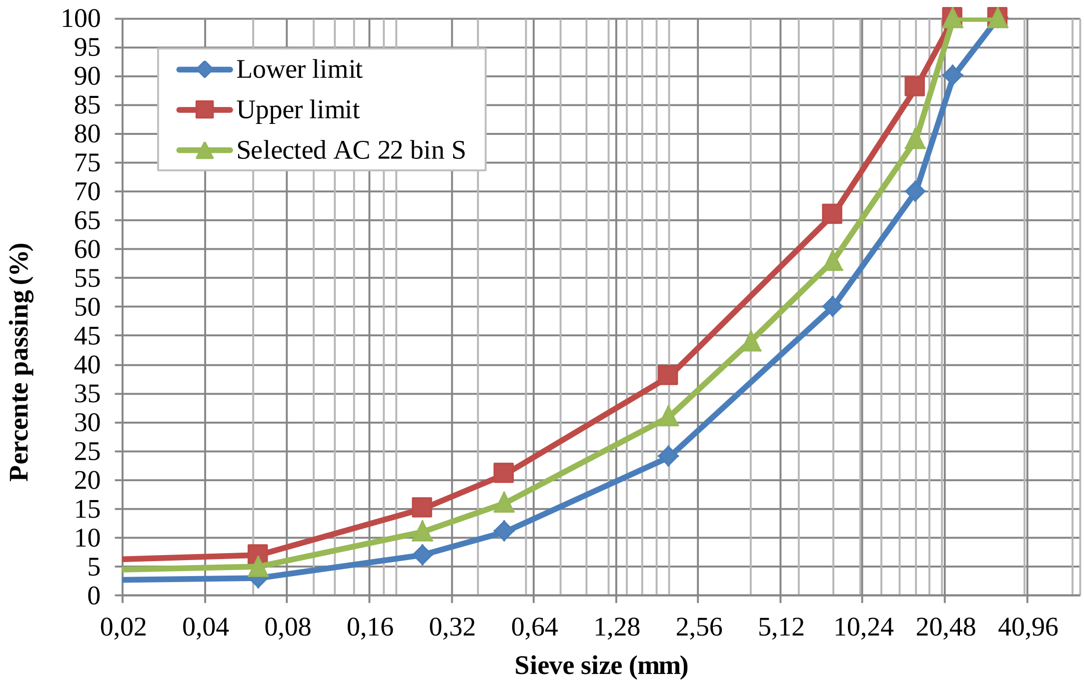

Figure 2. Grain size distribution of AC 22 bin S.

Specimens with 0%, 35% and 42% of RCA were studied. The specimens were manufactured at their optimum bitumen content. To obtain this optimum bitumen content, volumetric properties according to UNE-EN 12697-8 and water sensitivity according to UNE-EN 12697-12 were analysed. The optimum bitumen content for each bitumen type and each RCA percentage is the minimum that displays air voids ranging from 4% to 7% and achieves a minimum indirect tensile stress ratio of 80%, according to the PG-3 [22]. Also, according to the PG-3, the optimum bitumen content must be equal or higher than 4.0%.

Table 3 shows the optimum bitumen content used in this investigation for each mixture, their air voids (Va) and their indirect tensile stress ratio (TSR).

Table 3. Volumetric properties and TSR at the optimum bitumen content.

RCA (%)		HMA with B35/50	HMA with BC35/50	PG-3 limits [22]
0%	Va (%)	4.49	6.09	4-7
	TSR (%)	80.24	80.09	≥ 80
	Optimum bitumen content (%)	4.75	5.0	minimum: 4.0%
35%	Va (%)	4.76	6.42	4-7
	TSR (%)	83.23	85.85	≥ 80
	Optimum bitumen content (%)	5.25	5.50	minimum: 4.0%
42%	Va (%)	5.13	4.19	4-7
	TSR (%)	80.95	80.30	≥ 80
	Optimum bitumen content (%)	5.75	6.0	minimum: 4.0%

2.3. Experimental Procedure

Indirect Tensile Fatigue Test (ITFT) according to UNE-EN 12697-24 controlled stress procedure was conducted. The controlled procedure is preferred to the controlled strain method because of its better correspondence with field conditions [24]. In this test, pulse repetition simulates traffic passing on the bituminous mixture.

The Marshall specimens required for the test (Figure 3a) were manufactured in accordance with Spanish NLT-159/86 [25], compacting them with 75 blows per side of the Marshall hammer. These cylindrical Marshall specimens were manufactured at the optimum bitumen content (table 3) for each RCA percentage (0%, 35% and 42%).

In Cooper's pneumatic press NU14 (figure 3b), each of these series were tested in a temperature controlled cabinet at a reference temperature of 20° C. Three constant stress levels, typically ranging from 150 kPa to 350 kPa were used. A minimum of three samples for each of the three stress levels were tested, so that a minimum of 10 samples were tested for each RCA content. Each cylindrical Marshall sample was subjected to repeated haversine loads along a vertical diameter until reaching failure. The load time was 0.1 s and the rest time was 0.4 s. During the 10 first cycles, the initial deformation must range between 100 to 400 με. If the initial deformation is out of this range, the load must be adjusted.

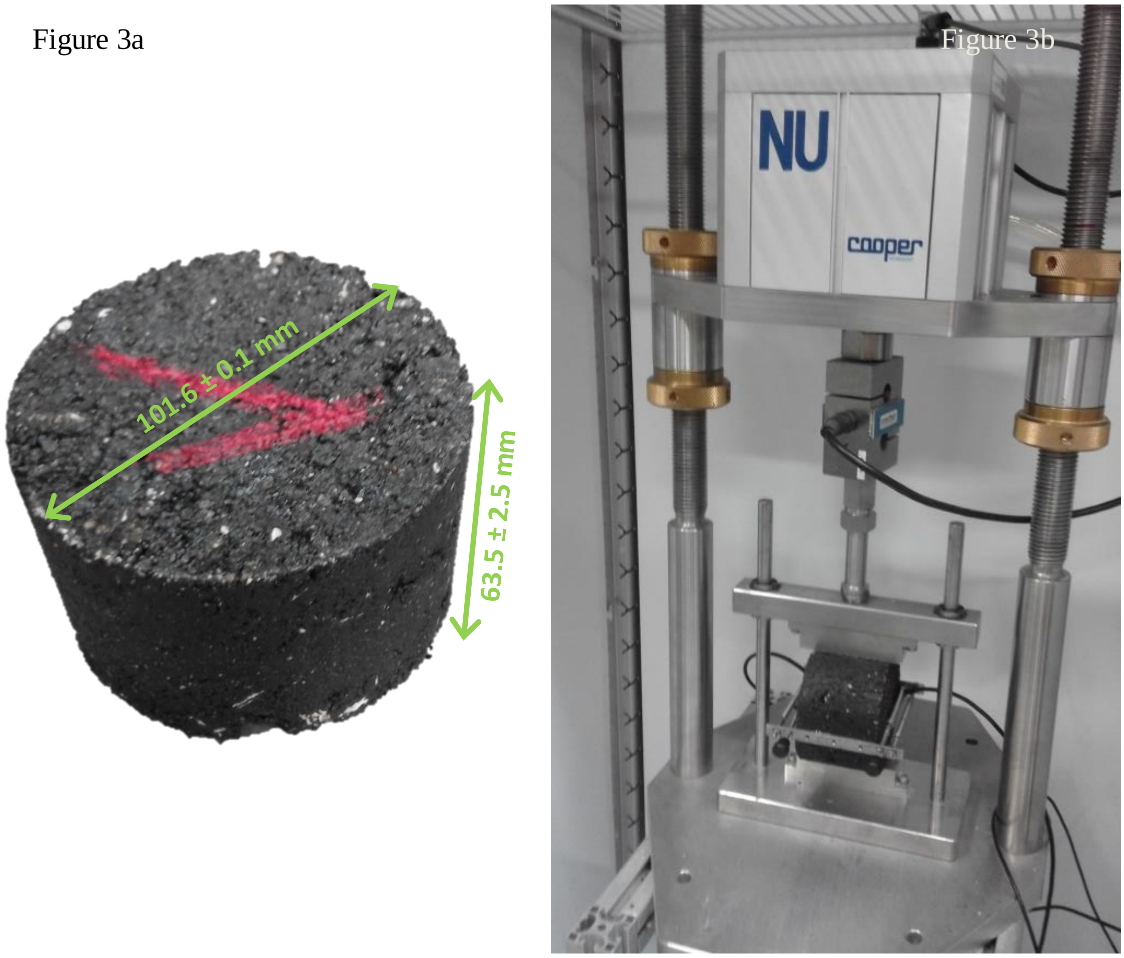

Figure 3: a) Marshall cylindrical specimen and b) Cooper NU14 servo-pneumatic machine.

To obtain the fatigue laws for fatigue life prediction, the Whöler equation was used:

$$\varepsilon_0 = k.Nf^{-n} \quad (1)$$

where Nf = the number of load cycles until fatigue failure; k and n = material constants obtained from the ITFT and ε_0 = the initial tensile horizontal strain at the centre of the sample in $\mu\varepsilon$.

As a result of ITFT the stiffness of the bituminous mixture can be obtained, as follows:

$$S_{mix} = \frac{\sigma_S}{\varepsilon_S}.(1+3\upsilon) \tag{2}$$

where Smix = stiffness module of the bituminous mixture (MPa); σ_s = maximun horizontal stress at the centre of the sample (MPa); ε_s = maximum horizontal strain at the centre of the sample (μm/m); ν = Poisson coefficient (a constant value of 0.35 was assumed).

3. Results and Discussion

3.1. Fatigue failure characteristics

During ITFT, a combination of fatigue and permanent deformation mechanisms may occur [26]. In controlled stress tests, two failure criteria are usually employed in ITFT in order to determine fatigue life [27]:

- The total number of load cycles to complete splitting of the specimen (Figure 4). In this case, the fatigue mechanism is prevalent and the tensile stress acting perpendicular to the loaded plane is mainly responsible of the failure [28].
- The total number of cycles to reach the 10% vertical deformation of the specimen along the vertical plane. In this case, the permanent deformation mechanism is prevalent.

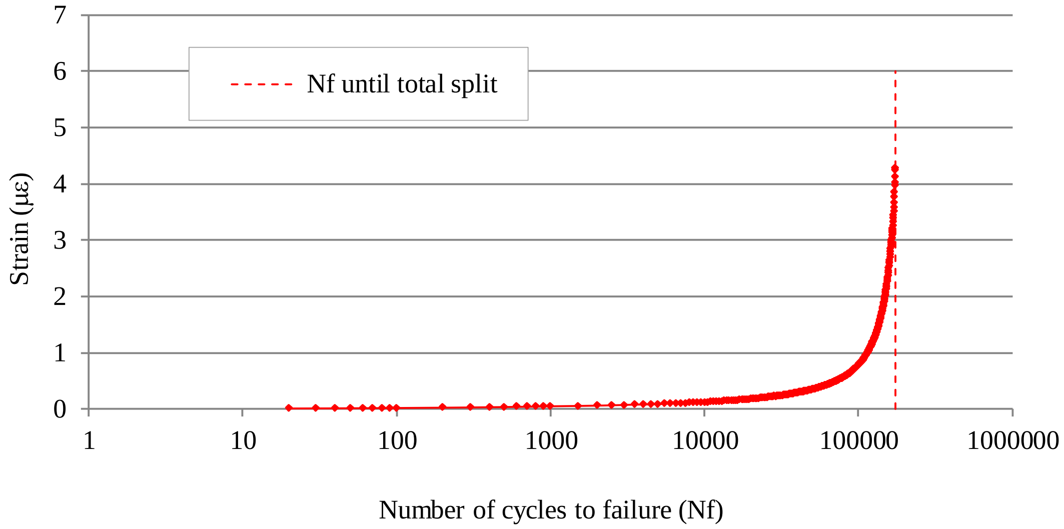

Figure 4. Number of cycles to total structural failure. Mixture made with 0% RCA and BC35/50.

Of the two failure mechanisms considered, the first has always been given in the present investigation (Figure 5), independently of the RCA percentage and whether the bitumen was B35/50 or BC35/50. Therefore, the mechanism of fatigue prevails over that of permanent deformation.

In addition, this kind of failure can cause different split patterns such as ideal strip, localized crushing failure, double cleft failure, single cleft failure and triple cleft failure [28]. As shown in Figure 5, the single cleft failure pattern was produced in all tested samples.

Figure 5a

Figure 5b

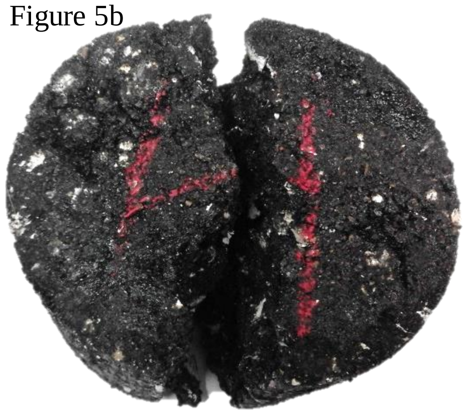

Figure 5c

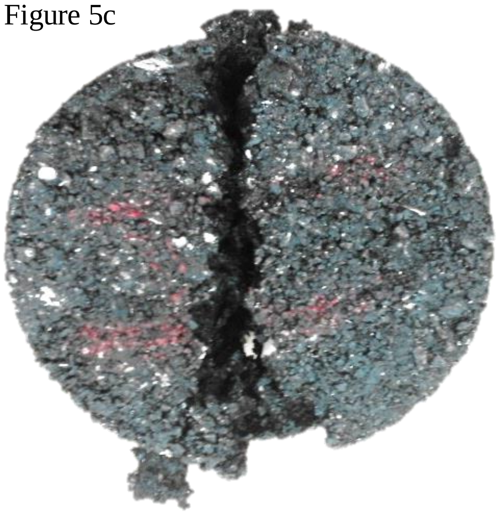

Figure 5d

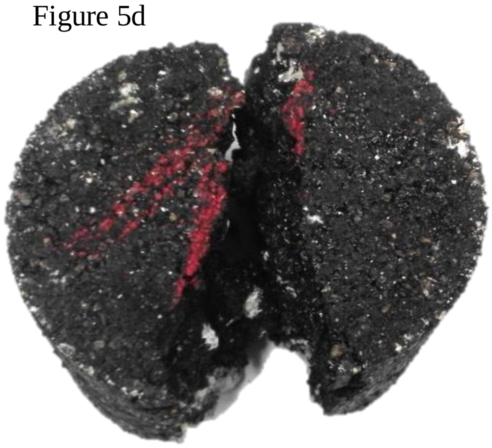

Figure 5: a) 35% RCA with B35/50, b) 42% RCA with B35/50, c) 35% of RCA with BC35/50 and d) 42% of RCA with BC35/50.

No different split patterns were observed due to the RCA percentage or the type of bitumen. This conclusion is consistent with that stated in the technical literature, since the type of loading strip is primarily responsible for the split pattern [28].

3.2. Stiffness

Figure 6 shows the initial stiffness of the mixture (at 100th cycle) versus the initial micro-strain (at 10^{th} cycle) [27] for all the tested mixtures.

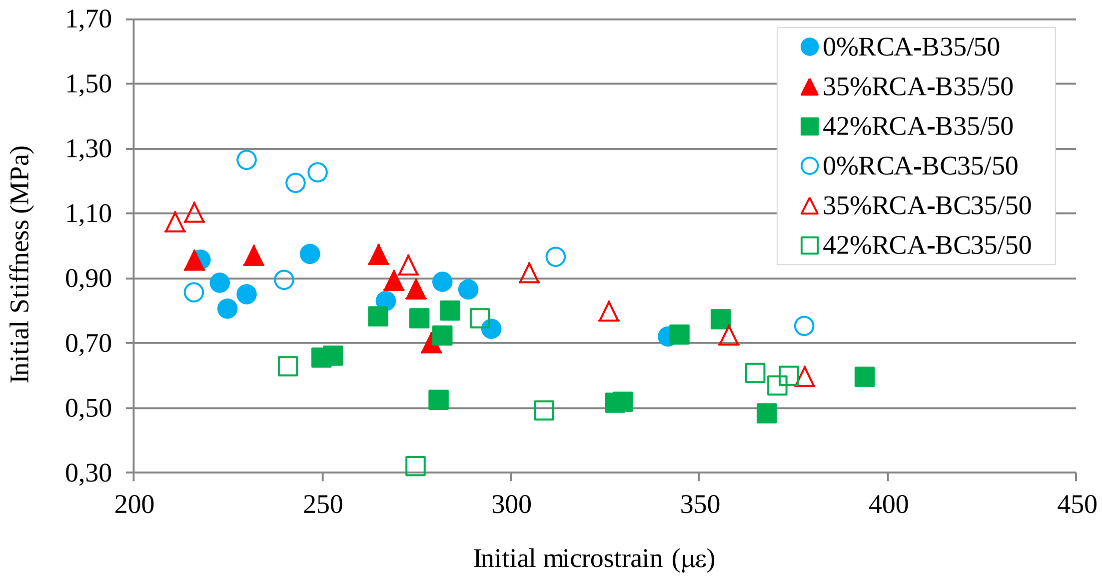

Figure 6. Initial stiffness of the mixture vs initial micro-strain for mixtures made with 0%, 35% and 42% RCA with B35/50 and BC35/50.

Figure 6 shows that as the initial micro-strain increases, the initial stiffness slightly decreases in all cases. It was an expected result because the ITFT was conducted with the controlled stress procedure.

Figure 6, shows the influence of the type of bitumen, that is, whether the bitumen is modified with waste tire rubber or not. Bituminous mixtures made with 0% RCA and BC35/50 display higher initial stiffness than mixtures made with 0% RCA and B35/50. It can be clearly stated that the bitumen modified with waste tire rubber leads to bituminous mixtures with higher stiffness. This is probably due to the increased stiffness of the binders modified with waste tire rubber [29].

When RCA is added to the mixtures (35% RCA and 42% RCA) there is almost no difference between the mixtures made with B35/50 and those made with BC35/50. Thus, it can be stated that the RCA influence on the stiffness is higher than the influence of the use of waste tire rubber.

Additionally, in figure 6, it can be seen that a higher RCA percentage leads to lower initial stiffness for all initial micro-strain levels and for all kinds of tested bitumen. The mortar attached to the RCA surface, which is porous and weak, could explain this behaviour. The higher bitumen consumption as the RCA percentage grows, could also explain this trend. There is only one exception to this performance, mixtures made with 0% RCA and B35/50 display similar initial stiffness results as those obtained by the mixtures made with 35% RCA and B35/50 or BC35/50. As above, when no RCA is added to the mixtures, the influence of the bitumen is more noticeable. The absorptive nature of RCA, which is more porous and weak than natural aggregate, may be responsible of this performance.

In addition, in Figure 6, when the mixtures are made with BC35/50, the initial stiffness differences between mixtures with 0%, 35% and 42% RCA for all of the initial micro-strain ranges are higher than the initial stiffness differences for mixtures made with B35/50. This finding is probably observed because the B35/50 is more easily absorbed by the pores of the RCA than the BC35/50, which has higher viscosity.

3.3. Fatigue life

Fatigue life is defined as the number of load cycles until failure occurs (Nf) in bituminous mixtures and represents the ability of the mixture to withstand the traffic cyclical loads [30]. Fatigue life is related to service life in such a way that higher fatigue life leads to higher service life [31].

Figure 7 shows the initial horizontal strain versus the number of cycles to failure (total split of the sample) at 20°C on a logarithmic scale for the tested mixtures (N-S plot). This figure also includes the fatigue life law equations and the correlation coefficient (R^2). As seen in Figure 7, this coefficient ranges from 0.8516 to 0.9546 which indicates a good statistical relationship between the results obtained to determine each fatigue law.

As can be clearly seen in Figure 7, the higher the percentage of RCA is, the longer the fatigue life of the bituminous mixture is. It was an expected result because, as said above, as RCA percentage grows the stiffness of the mixture decreases. Thus, it can be clearly stated that RCA is beneficial for the fatigue life of the bituminous mixtures.

Also, figure 7 shows that bituminous mixtures made with B35/50 displayed similar slopes in their fatigue life laws regardless of the RCA percentage used. The same applies to mixtures made with BC35/50. This shows the strong influence of the type of bitumen in the fatigue life of hot-mix asphalt.

In this regard, mixtures made with BC35/50 displayed more pronounced slopes than mixtures made with B35/50. For this reason, for lower initial micro-strains, mixtures made with BC35/50 have lower fatigue life than mixtures made with B35/50. For higher initial micro-strain, mixtures made with BC35/50 present higher fatigue life.

The initial micro-strain from which this change of behaviour occurs varies depending on the RCA percentage. For 0% RCA, the initial micro-strain of 303.1 μm, is the limit for this change of performance. However, for 35% RCA the initial micro-strain is 226,6 μm and in the case of 42% RCA the initial micro-strain is 264,7 μm. As seen, there is no correlation between the initial micro-strain limit and the RCA percentage.

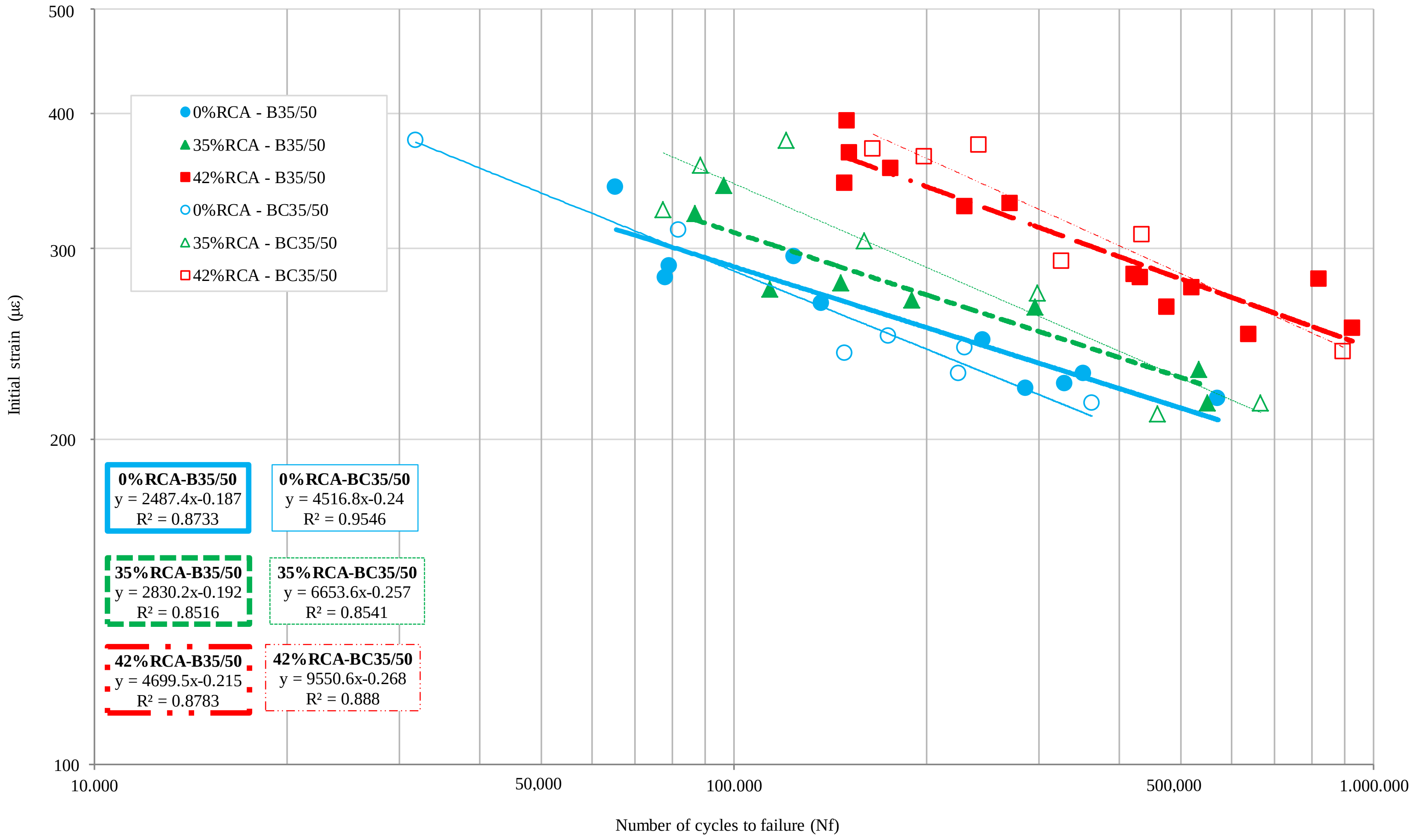

Figure 7. N-S plot and fatigue life laws for mixtures made with 0%, 35% and 42% RCA with B35/50 and BC35/50.

As said before, Figure 7 shows that the differences between fatigue law equations are mainly due to the RCA percentage used and to the use of B35/50 or BC35/50. Nevertheless, it must be noted that the RCA percentage produces more pronounced changes in fatigue laws than the type of bitumen used. It was an expected result as seen in section 3.2.

4. Conclusions

This paper analyses fatigue performance of HMA made with RCA. The research focused on the fatigue resistance of an AC 22 bin S manufactured with 0%, 35% and 42% RCA in place of natural limestone aggregates. In addition, two types of bitumen, B35/50 and BC35/50, were used since waste tire rubber could affect the fatigue life of such mixtures. From the investigation the following conclusions were drawn:

- In this type of mixture, during the ITFT, the fatigue mechanism is prevalent versus the permanent deformation mechanism, independent of the RCA percentage and the use of waste tire rubber as bitumen modifier.
- The higher the percentage of RCA is (up to 42%), the longer the fatigue life of the bituminous mixture is. Thus, the introduction of this waste material not only is not detrimental to the fatigue performance of HMA but is beneficial. The lower stiffness displayed by mixtures made with higher RCA percentage, could explain this trend.
- The use of waste tire rubber as a bitumen modifier clearly affects the fatigue performance of HMA made with RCA.
- For lower initial micro-strains, mixtures made with BC35/50 have lower fatigue life than mixtures made with B35/50. For higher initial micro-strains, mixtures made with BC35/50 have higher fatigue life.

- HMA made with RCA are only suitable for light and medium traffic categories due to the low resistance to the fragmentation of RCA.
- Taking into account the two previous conclusions, it can be stated that for medium traffic roads, the use of waste tire rubber could improve the fatigue resistance of HMA made with RCA. In contrast, for light traffic categories, the fatigue life of mixtures made with RCA could be shortened if waste tire rubber is used as bitumen modifier.

In view of the results, the use of RCA and waste tire rubber in HMA is encouraging, particularly when used in medium traffic roads. Nevertheless, further investigation is warranted.

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