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Fatigue Resistance of Bituminous Layers Incorporating Reclaimed Asphalt Pavement

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Abstract:
This paper presents the results of an investigation into the fatigue performance of a 20 mm Binder Course Asphalt Pavement Mix incorporating Recycled Asphalt Pavement (RAP). For the study, a series of binder course mixes were designed containing varying percentages of RAP. A mix made only from virgin material, was selected as the control mix for the investigation. A Circular Wheel Tracker (CWT) was developed in order to simulate the dynamic loading conditions of a rolling wheel and to study the initiation and growth of fatigue cracks in an asphalt pavement mix. The CWT was commissioned within a temperature-controlled room with a customised data acquisition system. The test specimens were subjected to dynamic loading in the CWT and the dynamic strain on the underside of the slab was monitored throughout the test. A digital image processing technique was also used to measure the crack area and crack length at the underside of the test specimen. Parallel to this a separate testing programme was undertaken, whereby the fatigue resistance of bituminous mixtures incorporating same RAP contents was assessed using the indirect tensile fatigue test as described in BS DD ABF:1997. The results from these parallel strands are compared, and the performance of the various mixes incorporating RAP is assessed.

Key words: Recycled Asphalt Pavement (RAP), Binder Course (BC), Fatigue, Circular Wheel Track (CWT), Dynamic Strain

Introduction

The increase in traffic volume and loads requires that road materials withstand additional stability and durability. In recent decades alternative mixes have also been developed where recycled materials are implemented into the bituminous mixtures (Public Roads, 2005; Fitzsimons & Gibney, 2004; Khalaf, 2004; Woodward, 2004; Perez Jimenez et al, 2004; Hossain et al, 1993; Emery, 1993; Gerardu & Hendriks, 1985). For bituminous mixtures the fatigue cracking and the permanent deformations are two primary structural modes of failure (Gibney 2001, Hartman 2000). The increasing costs of road maintenance and rehabilitation led the road industry to develop alternative methods for evaluating asphalt pavement mixture performance under simulated road traffic loading. These test methods include: the four point bending fatigue test (Hartman, 2000; Hartman & Gilchrist, 2004), the three point

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bending fatigue test (Petit et al, 2002), the indirect tensile fatigue test (Read et al, 1997) and the wheel tracking test fixture (Gibney, 2001; Hartman, 2000; Hartman et al, 2001a). Simple fixture tests are the most commonly used to obtain fatigue damage of the asphalt pavement mixture. During such a loading method, a state of predominantly uniaxial tensile bending is created within the specimen. As a result, this is one of the most appropriate methods for simulating the fatigue damage that originates at the bottom of the asphalt layers.

Recent publications reported the use of digital image technology to investigate fatigue behaviour in asphalt mixtures (Hartman, 2000; Hartman et al, 2001a; Hartman & Gilchrist, 2004). Hartman and Gilchrist (2004) detailed a digital image technique to measure reflective crack in asphalt beam specimens. The digital image technique, allows the increase of crack length propagation in the test specimen to be monitored and as such determine the total length of the crack to be determined.

A Circular Wheel Track test rig was developed to evaluate the fatigue performance of asphalt pavement mixtures submitted to a dynamic wheel loading. The CWT system was commissioned within a temperature controlled room and a data acquisition system was developed monitor the dynamic strain at the underside of the test specimens. The digital image technique was employed in order to monitor fatigue crack propagation within the test slab specimens. The ITFT is generally regarded as a reliable laboratory fatigue test method (Read et al, 1997), and it was therefore selected as a fatigue test method which could verify the performance of the CWT. The influence of RAP on to the fatigue performance of the 20mm binder course mix was studied. The results from two test methods are analysed, compared and presented in the paper.

Materials Investigated

The bituminous mixture investigated was the standard Irish 20mm binder course mix (BS 4987: Part1: 1993). Different percentages of RAP were included in the binder course mix, in order to investigate the influence of RAP on the fatigue performance 20mm binder course mix.

The primary concern in using RAP as an aggregate within the mix, is that RAP contains a variety of materials such as stone aggregates and binder and it may also contain some contaminants. The binder and surface courses from the old roadway could be mixed together in a single stockpile in addition to the RAP from several sources. If the RAP varies widely in terms of properties such as gradation or binder content, the resulting binder course may also be variable. Good stockpile management is necessary to control material variability. For this project the RAP material was provided by Roadstone Ireland Ltd. The material was not analysed prior to extraction from the road and it's specific origins are unknown.

The particle size distribution for the mix designs is presented in table 2. Four representative samples of RAP were used to determine the relative density of the RAP, which was calculated to be 2626.0 kg/m^3. Further set of four samples were taken in order to determine the aggregate gradation according to the British standard; BS 812: Part 103.1: 1985, and the results are presented in table 1. Comparing the gradation of the RAP to the virgin aggregates, it can be observed that RAP is a continuously graded material. This meant that RAP could be used to replace a proportion of each constituent in the mix.

Table 1. Percentage by weight passing

Sieve size (mm)	20mm	14mm	10mm	CRF	Sand	RAP
28	100	100	100	100	100	100
20	92.46	100	100	100	100	95.80
14	23.10	94.65	100	100	100	85.85
10	2.80	32.01	98.73	100	100	75.41
6.3	0.87	2.23	33.41	99.37	100	58.38
3.35	0.75	1.00	1.65	90.83	100	43.73
0.300	0.74	0.70	0.85	23.46	58.32	25.64
0.075	0.66	0.62	0.77	13.62	6.53	17.34

Following BS 4987: Part 1: 1993 - Table 15, three mixes containing 10%, 20% and 30% RAP were designed. The mixture compositions are presented in table 2. Figure 1 illustrates the aggregate grading. Using the standard limitations, the maximum RAP content that can be included in the mix is 30%. Although several studies have used higher RAP content within the asphalt pavement mix (Khalaf, 2004; Perez Jimenez et al, 2004; Public Roads, 2005). In this work, the material mixture grading abided by the standard. A mix made only of virgin material was used as a control mix.

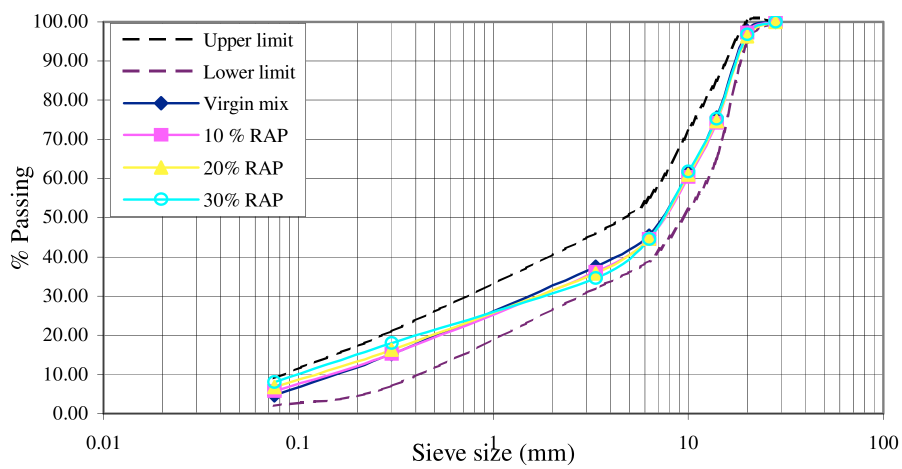

Figure 1. Particle size distribution percentage passing

Table 2. Particle size distribution for mix designs

Sieve size (mm)	Virgin Mix	10% RAP	20% RAP	30% RAP	Lower limit	Upper limit
28	100.00	100.00	100.00	100.00	100.00	100.00
20	97.66	97.24	96.32	96.78	95.00	100.00
14	75.52	74.21	74.67	75.33	65.00	85.00
10	61.48	60.41	61.03	61.73	52.00	72.00
6.3	45.41	44.55	44.67	44.52	39.00	55.00
3.35	37.54	36.13	35.79	34.52	32.00	46.00
0.300	15.19	15.27	16.24	17.91	7.00	21.00
0.075	4.60	5.70	6.77	8.03	2.00	9.00

During investigation the RAP evaluation mixes were submitted to the Marshal test, BS 598: Part 107: 1990. This test was conducted in order to ascertain the optimum binder content for each mix. The Marshal test showed that increasing the RAP in the mix, reduces the binder content.

In discussion with industry with regard it was suggested that binder content less than 4.5 % would not be considered at this point. With some detailed knowledge regarding the binder content in the RAP this research shows that it will be feasible to reduce the added binder accordingly.

Circular Wheel Track (CWT)

To study the dynamic effects of a rolling wheel travelling over an asphalt pavement and in order to better understand the initiation and growth of fatigue cracks, a Circular Wheel Track (CWT) was developed (Hartman et al, 2001a, Hartman, 2000). A schematic diagram of the CWT is shown in Figure 2.

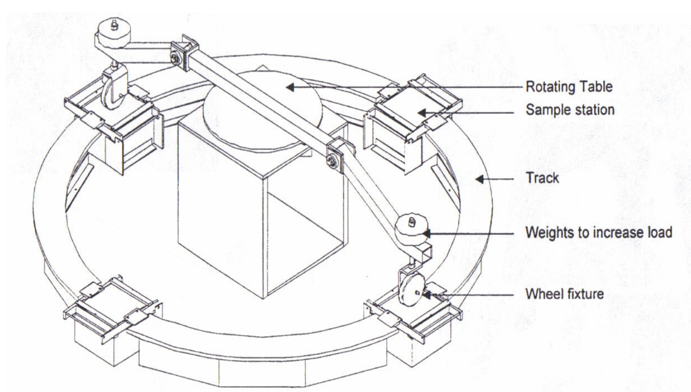

Figure 2. Schematic diagram of the Circular Wheel Track (Hartman et al, 2001a)

The testing facility permitted the testing of large slab specimens (305x305x50mm) using dynamic wheel loading. The slab specimens were supported on a soft elastomeric foundation, which represents a weak foundation and also prevented gravitational bending of the slabs. In additions to the original CWT (Hartman et al, 2001a, Hartman, 2000) was housed in a temperature controlled room and a Data Acquisition System (DAQ) was also developed in order to measure the dynamic strain at the bottom of the test slabs. Using this system, all four mixtures were evaluated under identical loading conditions, ie. at a temperature of 20^{o}C and with a vertical constant loading of 80kg per wheel, which resulted in a tyre pressure of approximately 695kPa per wheel. The diameter of the working circle is 3m, and the large arc of the track reduces the effect of cornering on the specimen, while centrifugal forces are minimised by the relatively slow operational speed of the CWT, of approximately 3km/h or 7 rpm.

Four test specimens per mix, 16 specimens in total, were compacted using the standard Cooper Research Technology Roller Compactor (2005), at dimensions noted above, with each specimen containing roughly 11kg of aggregate mix. After the specimens were compacted, they were left to cure for 24 hours at room temperature, approximately 20^{o}C. Prior to testing, the bases of the test specimens were cleaned and painted white, in order to facilitate the study of crack propagation, (Hartman & Gilchrist 2004). A 100x100mm square area was marked underneath the wheel path in the centre of each slab, see Figure 3. All crack monitoring was concentrated in this area. The fatigue damage (cracks) that occurred during the test were monitored using two image capturing methods, digital photography and hand traced images, which were later digitised (Hartman, 2000; Hartman et al, 2001a,). At certain intervals, the test was paused, the specimens were turned and the damage recorded. Digital images were captured by an Olympus C840L digital camera, a transparent sheet was then placed over monitoring area and the cracks traced manually.

The digital images were imported in to Adobe Image Photoshop 7.0.1 for further image processing. The monitoring area was cropped from the original image and the image converted to greyscale. The dimensions of monitoring area were calibrated against pixel size in order to maintain the direct dimensional measurements (100x100mm or 283x283 pixels) and a binary format (consisting only of black and white pixels) was applied to the best threshold value, as illustrated in figure 3.

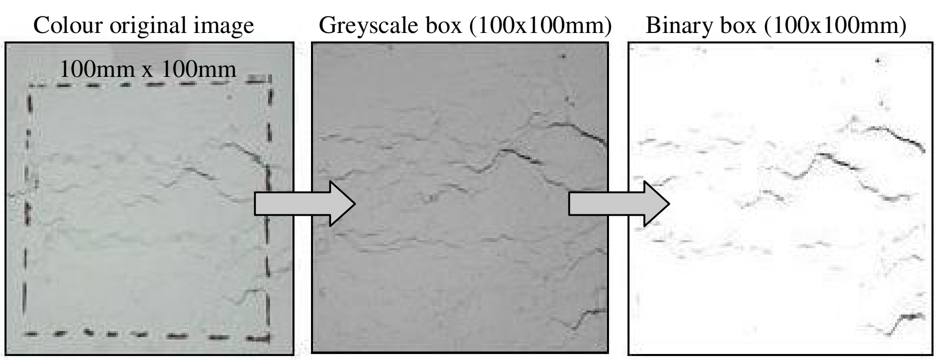

Figure 3. Manipulation of the original image to select monitoring area, convert the image to greyscale, apply a threshold value to obtain a binary image for crack analysis

A Matlab program was developed to calculate the crack area. The program measured the number of black and white pixels and the special calibration of this data allowed the area of crack to be given in mm^2, (see figure 4). The images obtained from the manually traced transparencies were used to determine crack length, and visible defects were recorded with a marker of standard width. A further analysis involved analysing the images for crack length. For this analysis, images were imported into UTHSCSA Image Tool. This method involved using an algorithm that reduces a crack to a single pixel width. The number of pixels thus related directly to a physical crack length, (see figure 5).

Measurements of crack direction were also performed on the crack network pattern. Using the UTHSCSA Image Tool software functions, the cracks were identified as objects. A line was drawn through the crack, then a horizontal line was drawn representing the major axis and the angle between two lines represented the crack direction. The orientation of the final crack pattern with reference to the direction of the wheel loading was determined and the results are presented in table 3.

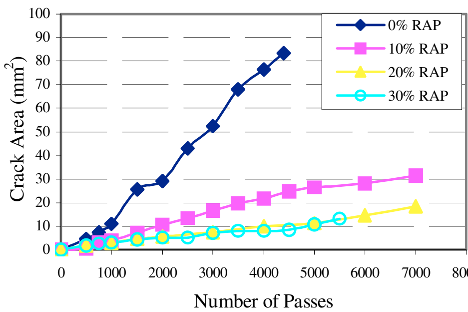

Figure 4. Crack Area Measurements

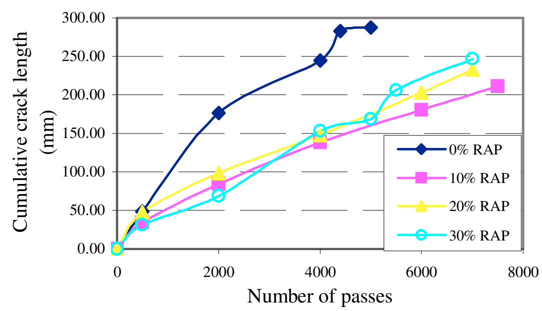

Figure 5. Cumulative crack length

Table 3. Effective crack direction measurements

Mix	Average effective crack direction, C_D^{eff}(^{o})
Virgin Mix	26.80
10% RAP	26.80
20%RAP	27.51
30% RAP	24.42

As the slabs were clamped parallel to the direction of the wheel travel, it allowed the test specimens to bend in the same direction as the wheel travel and as a result, the cracking primarily occurred in the direction of the wheel travel. Figure 5 demonstrates that the crack length increases sharply initially, and then after some 1000 passes, increases gradually. The crack area gradually increased as the test progressed. The measurements of crack length and crack area at the bottom of the slab successfully characterised the first stage of initial crack formation, (stage I). On the other hand, in the permanent deflection and dynamic strain test results two stages of the fatigue damage evolution were identifies, ie. initiation and propagation, figure 6 and 8, similar crack formation was observed by Hartman (2000) in his study.

Figure 6 illustrates the development of the permanent central deflection with fatigue loading (wheel passes) for all tests. The initial rate of deformation is high, but as the tracking continues, the rate of deformation reduces, as illustrated in figure 6. The virgin material mix demonstrated the highest rate of deformation until the pre-set deflection limit of 5mm. The reason for this is that mixes with RAP content contain a higher content of bitumen and are therefore, more resilient to deformation.

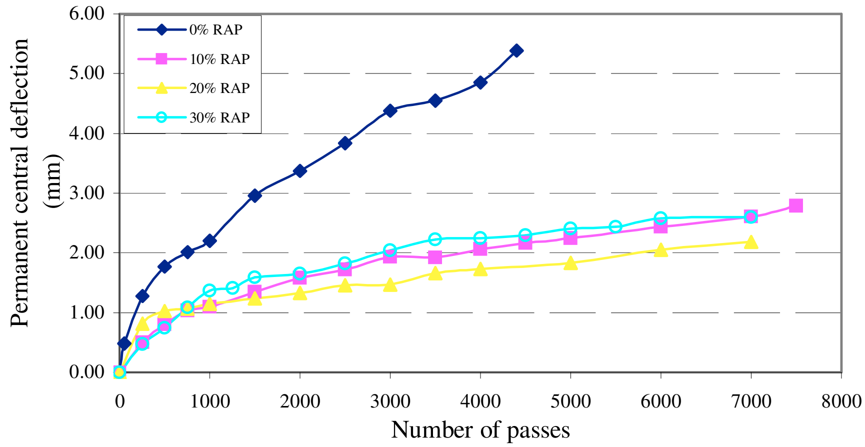

Figure 6. Permanent central deflection

The CWT was designed primarily to measure dynamic strain at the base of test specimens. Due to the intensive effort required for conducting this test, only four specimens were used, one specimen of each mix. In order to monitor the dynamic strain, a DAQ system was developed. The National Instruments (2005) LabVew 7.0 software was used to create a program to collect data from the strain gauges, placed on the underside of the slab specimens, as shown in figure 7. The horizontal tensile strain was monitored using a 120 ohm strain gauge with 10mm gauge length. In order to eliminate the influence of aggregates, the strain gauges were glued to a thin (0.3mm) brass foil strip (12.5x40mm). A brass sheet was used because brass has a similar stiffness value to the bituminous mixtures, approximately 2000MPa, this procedure was also used by Hartman (2000). Two gauges were fixed for each slab, 50mm apart and 25mm from the centre of the test specimen. They were positioned perpendicular to the direction of the wheel travel, and as a result the strain gauges measure strain in the transverse direction to the direction of tracking.

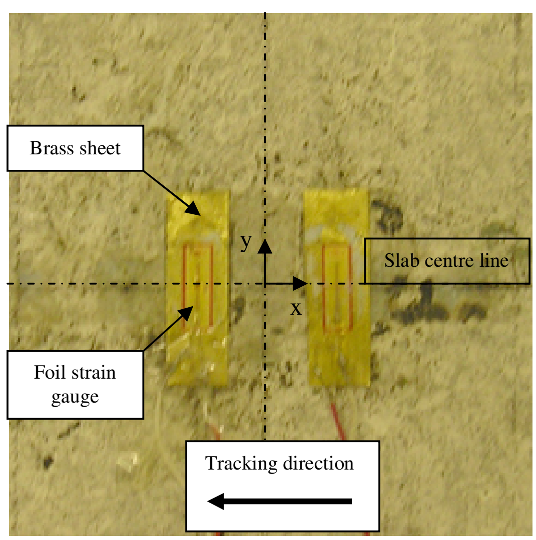

Figure 7. Position of strain gauges on test specimen

During the test the dynamic tensile strain was monitored and the total strain calculated. When the test sample reached a permanent deflection limit of 5mm, it was removed from the test rig. Figure 8 illustrates the typical manner in which the dynamic strain varied during loading intervals for all binder course mixes.

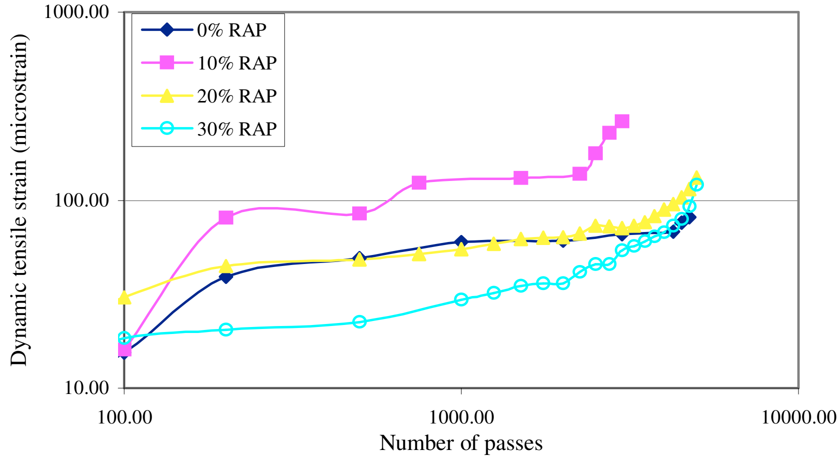

Figure 8. Development of dynamic tensile strain under fatigue loading

The dynamic strain results, as well as crack length and permanent central deflection results, illustrate initially sharp strain increases until the slab settled (for some 1000 passes). After this stage the strain stayed relatively constant until small cracks begins to form at the underside of the test specimen. From about the 3000 passes the dynamic strain begins to increase sharply which indicates that the cracks are propagating underneath the strain gauges.

Comparing the results from the dynamic strain test and the crack monitoring test, it was expected that the mix which contained only the virgin material would show higher dynamic strain values than those containing RAP. The exact reason for the virgin mix behaviour is unknown. Nevertheless the mixes containing the RAP had demonstrated repeatedly, similar response through out the testing.

Fatigue Strength Test (ITFT)

To evaluate the dynamic strain results from the CWT, the ITFT was identified as a suitable method of fatigue testing.

The Indirect Tensile Fatigue Test (ITFT) was carried out according to the procedure described by the British standard, BS DD ABF:1997. The Coopers Research Technology (2005) NU-10 testing apparatus was used to determine the resistance of the mixtures to failure under repeated loading. Six specimens of each mix, 100mm diameter and 70mm high, were prepared using the gyratory compactor in accordance with EN 12697-31 test standard. The specimens were subjected to a repeated constant load with 124ms ± 4ms loading time and pulse repetition time of 1.5 ± 0.1 sec. at a temperature of 20^{o}C. Prior to the ITFT test, the indirect tensile stiffness modulus parameter was obtained for specimens, at the fatigue test stress level. Readings were taken for two diameters at 90^{o} to each other and the average value was calculated.

The pulse repetition in the ITFT test simulates traffic passing over the pavement, which resulted in the repeated applications of tensile stress and strain within the test sample. The fatigue life was defined as the total number of load pulses that caused the total structural failure of the test specimen. The strain was calculated from the direct computation of maximum tensile stress at the centre of the specimen using the indirect tensile stiffness at the maximum tensile stress.

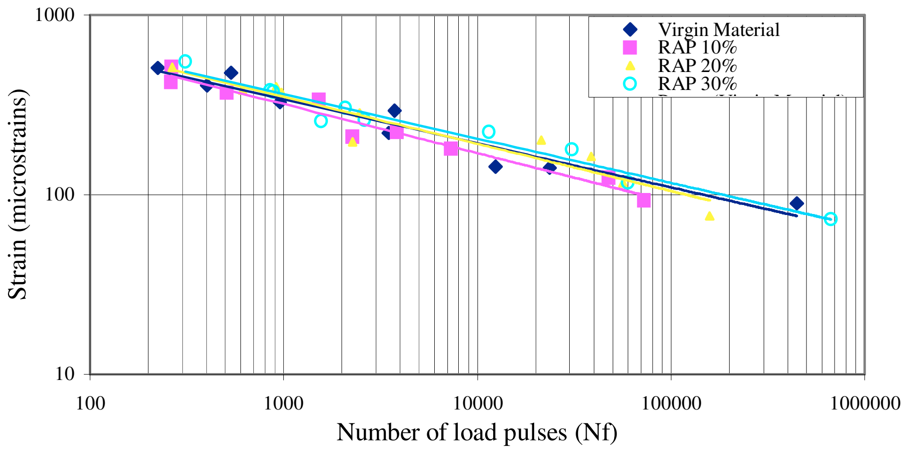

Figure 9. Tensile strain Vs Number of load pulses (Nf)

An empirical growth relationship was used during the regression analysis:

$$Nf = k_1(\varepsilon_T)^{k_2}$$

where Nf is the number of strain applications to failure; ε_T is the initial tensile strain (μstrain); and k_1,k_2 are the fatigue growth rate coefficients listed in table 4.

Table 4. Summary of empirical growth regression data

Mix	Coefficients		R^2	Cycles at 100 μstrain
	k_1	k_2		
0% RAP	5.0E+12	-3.8234	0.9370	112,763
10% RAP	7.0E+11	-3.5142	0.9602	65,569
20% RAP	1.7E+12	-3.6098	0.9172	104,869
30% RAP	1.0E+13	-3.8876	0.9598	167,803

The fatigue results are presented in Figure 9. From the results it is apparent that the mix with a lower amount of RAP (10%) demonstrated the lowest resistance to fatigue. However, an increase in the amount of the RAP in the mix improved the fatigue life of the mix. Of the mixes tested, the binder course mix containing 30% RAP demonstrated the best resistance to repeated tensile stress loading. However with such close results it is hard to conclude which mix performs the best. Nevertheless, RAP has proven that can be an ideal alternative material for natural aggregates in the 20mm binder course mix.

Results comparison

The comparison was conducted in respect to the dynamic tensile strain at bottom of the CWT test slabs and the fatigue dynamic strain in the ITFT test specimens. The graph of the dynamic strain results exhibit a similar behaviour to that observed in the ITFT results, see figure 8 and figure 9. The mix improves its resistance to failure with an increase of RAP content in the mix. However results to the crack investigation and permanent central defection test contradicted the dynamic tensile strain tests. The difference is within the virgin material mix behaviour. The crack length, crack area and permanent central deflection measurements showed that mixes which include RAP, have a very distinct advantage over the mix containing only virgin material, as illustrated in figures 4,5and 6. The dynamic tensile strain results showed conflicting results where mix containing virgin material, responded relatively well to the fatigue loading, see figure 8 and 9.

While, the reason for such behaviour is unknown, one of suggestions is that for the dynamic strain tests only one specimen was tested per mix and four specimens were used per mix in the crack investigation, thus results obtained for the virgin material in the dynamic strain test could be unreliable. Therefore the CWT dynamic tensile strain results will be repeated, four specimens will be tested for each mix. It is hoped that the repeated tests will clarify the problems that arose.

Conclusions

The CWT test facility, was purposely designed and constructed in order to simulate the dynamic loading of a wheel travelling over the bituminous test specimens. In accord to this study the CWD was housed in a temperature room and a data acquisition system was developed in order to record growth of dynamic tensile strain at the bottom of the test slabs throughout the test. The image processing technique was employed within the test procedure in order to measure the crack area and crack length underside the test slab. The ITFT standard laboratory fatigue test was employed to evaluate the results from the CWT test. The dynamic tensile strain results, from both tests confirmed similar material behaviour for all the binder course mixtures. The CWT crack test results and the dynamic tensile strain results showed some discrepancies. Further testing will be required in order to clarify current discrepancies between test results. The 20mm Binder course mixtures containing the RAP demonstrated that it can perform as well as mix containing virgin material only.

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