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Investigation of Fatigue Life by Four Point Bending Test of Recycled Asphalt Pavements

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Abstract. The performance of added 50% reclaimed asphalt (RAP) mixtures was investigated by four-point bending fatigue tests (FPBT). Mixtures with 50% RAP were modified with SBS polymer, diatomite (D) and hydrated lime (HL). Ten specimens were produced and fatigue of specimens was evaluated with FPBT. Some samples give the fatigue breaking cycle compatible with each other. In some samples, the number of cycles is much higher than the average breaking load. Some samples may deteriorate in a short time before the end of test. Although the briquettes are mixed homogeneously for longer mixing times and produced with great care, inconsistent results can be obtained. If water damage is applied to briquettes due to the presence of HL, more compatible results can be obtained. The use of SBS-HL and rejuvenating oil at high RAP ratios will provide more compatible results. As a result of 50% stiffness reduction, the difference in the remaining stiffness values is usually 2-3 times, while there are huge differences between the cycle numbers that cause this. In terms of sustainable and long-term performance, the homogeneity of the pavement composition appears to be essential, having a much more pronounced effect than the number of loadings.

1. Introduction

The main variables that are effective in the formation of fatigue in asphalt pavements are evaluated. The complexity of mathematical modeling is expressed. It is emphasized that the difficulty of calibration of the models is mainly due to the fact that the fatigue resistance of the asphalt mixtures of the mathematical equations depends on the load mode (stress-controlled or strain-controlled), the type of load (haversine or sinusoidal), and the rest periods to which the laboratory samples are subjected. Also, the subject of fatigue calibration; both on-site and in the laboratory; It varies according to stiffness, volumetric composition (type and content of asphalt and aggregate), geometry of samples, mixture durability and environmental conditions, test type, border conditions and support layers (base, subbase, subgrade). If these physical parameters are not taken into account, the mathematical equations lose reliability [1].

Examination of fatigue performance are divided into two categories as the asphalt binder characterization and mixing properties. Fatigue crack initiation and propagation usually occurs in the binder or mastic phase of asphalt mixtures. Therefore, improving the fatigue resistance of the asphalt binder has a significant effect on the fatigue performance of the asphalt mixture [2-3].

The rapidly increasing cost of pavement materials and the increasing awareness of the damage to the environment have led researchers to a more economical and environmentally friendly pavement construction technology. One approach is to recycle materials used in road construction. Recycling pavement reduces raw material consumption, which reduces the cost and energy associated with road construction. In addition, these excavated pavements can be recycled, saving valuable landfill space needed for unloading materials. In the last few years, a number of governments and private organizations have turned to research into checking the feasibility of recycled materials and improving their quality in pavement construction [4].

Laboratory and field evaluations were conducted on mixes containing high levels of RAP, and it was noted that the structural performance of recycled mixtures was equal to, and in some cases better than, conventional ones. In addition, it is emphasized that RAP stocks have less variability than unused aggregate stockpiles and the use of higher RAP percentages does not lead to increased variability of produced asphalt mixes. Several management best practices have also been developed to assist producers in supplying high quality asphalt mixes containing RAP [5].

The use of RAP in pavement preventive maintenance (PPM) processes and the repeated recycling of RAP-ACPs (i.e. RnAP) were evaluated. It is envisaged that by promoting these two practices, the implementation and benefits of RAP can be further maximized to improve sustainability. The long-term behavior of RAP-ACP was evaluated. Research on RAP-PPM has shown that virgin PPM processes can successfully accommodate RAP materials by adjusting blend designs. Until now, research on RnAP has been limited to how multiple recycling affects the performance characteristics of blends; showed improvements in rutting resistance and moisture sensitivity, but had little effect on linear viscoelasticity and cracking. Overall, the lack of adequate research is the biggest challenge in facilitating the implementation of these two sustainable RAP technologies. Little or nothing is known about the binding mechanisms between RAP and fresh PPM binders, the molecular and chemical changes in RnAP binders, or the functional performance characteristics, actual pavement performance, and long-term performance of both RAP-PPM and RnAP blends. Understanding these aspects is crucial to maximize and sustain the beneficial reuse of RAP in ACPs while protecting human and environmental health [6].

Fatigue resistance is highly affected by aging. The use of high proportions of RAP raises concerns that the blends produced become more prone to fatigue cracking due to the aged binder in the RAP. Therefore, adding a real rejuvenator to improve the chemical and rheological properties of the recycled binder has been a prominent solution to prevent fatigue crack degradation [7-8].

With rejuvenators, the fatigue resistance of recycled blends was higher than that of the unused mixes [9]. It is recommended to use biobinders or modifiers to reduce the fatigue sensitivity of mixtures containing high RAP [10-11]. The effect of prolonged aging did not significantly alter the fatigue properties of the high RAP mixture with and without rejuvenator [12]. Therefore, it has become very important to develop a new test method to characterize the true cracking resistance of rejuvenator-containing high RAP mixtures.

With certain modifications, it has been found possible to maximize the application of RAP on ACP surface layers without sacrificing performance. Common techniques that allow the use of high RAP are the use of soft binders, the addition of rejuvenators or emollients, or the use of WMA additives. Softening agents generally reduce the viscosity of the aged binder, while rejuvenators facilitate the rebalancing of the chemical composition in the aged binder that has lost its light molecular weight fraction during manufacture and use. In any case, the type and amount of additive chosen should be carefully selected and its effectiveness evaluated by binder and mixture tests [13].

The inclusion of RAP raises concerns about the long-term fatigue and cracking resistance of the resulting mixture due to the presence of an old binder. Using a rejuvenator additive is one way to extend the aging time for initial cracking and ensure higher RAP content is included. There are many inconsistencies in the literature regarding the effectiveness of rejuvenators in improving the fatigue performance of the RAP binder and mixture. These vague and contradictory findings are attributed to the use of different rejuvenator types and dosages, RAP origins and percentages, binders, and blend fatigue testing approaches. In addition, rigorous laboratory studies should be performed to determine the sensitivity of performance indicators to confound composition and variability. It was concluded that the inclusion of rejuvenators in RAP binders and blends may not bring their fatigue and cracking performances to the same level as untreated materials. However, by using polymer modification, the bond between materials is significantly increased, resulting in better fatigue performance of rejuvenated RAP materials. Despite the positive effect of rejuvenators on RAP blend fatigue performance, comparison of different test results does not provide a consistent indicator for determining fatigue resistance. Therefore, future research with reasonable test methods, more complex analytical techniques, service life characterization models and climate-identical test conditions is recommended to clarify the durability index. Also, a complete assessment of field performance using RAP and rejuvenator is considered valuable [14].

The aim of this study is to examine the variation of fatigue test results on a large number of identical cylindrical beam samples in the selected additive formulation with four-point bending fatigue test in 50% RAP modified asphalt mixtures. SBS additive, diatomite (D) and hydrated lime (HL) additives were used in the production of 50%RAP added asphalt mixtures. While evaluating the use of SBS as a rejuvenating approach, D and HL additives were used in order to manage aging processes and to produce more qualified plant mixtures. For D and HL, the low usage ratio option was preferred in common usage rates. The four-point bending test, one of the accepted test methods, was chosen to investigate the complexity of fatigue and the degree of RAP compliance. In our previous studies, higher performance values were obtained for similar additive types and RAP ratio compared to conventional mixtures in terms of water damage and rutting. In this study, the change in the results of the additive usage type specified at the point of fatigue complexity in terms of fatigue test of RAP added mixtures is discussed for modified mixtures.

2.Materials and Method

In this study; aggregate, bitumen, diatomite, HL, SBS polymer materials and RAP material obtained from the field were used. Sieve analysis grain size distribution data are in Table 1; coarse aggregate physical properties are given in Table 2, and fine aggregate physical properties are given in Table 3. The RAP gradation is given in Table 1 and the bitumen percentage was calculated as 3.85% from the extraction experiment.

Table 1. Particle Size Distribution
(Experimental Method-ASTM C136 /117)

Sieve No (inç)	Sieve No (mm)	12-19 mm	5-12 mm	0-5 mm	RAP
3/4"	19	100,0	100,0		100
1/2"	12,5	15,6	97,1		100
3/8"	9,5	4,9	73,3	100,0	99,4
No 4	4,75	3,9	15,4	98,4	83,4
No 10	2,0	3,9	5,2	61,3	53,4
No 40	0,425	3,9	5,0	24,4	25,1
No 80	0,180	3,9	4,4	12,5	18
No 200	0,075	2,0	3,0	5,6	12

Table 2. Physical Properties of Coarse Aggregate

Test Name	Method	Unit	Result	Limit
Los Angeles Abrasion	TS EN 1097-2	%	17	Max. 27
Flatness Index, 5-12 mm	TS EN 933-3	%	13	Max. 20
Flatness Index, 12-19 mm	TS EN 933-3	%	11	Max 20
Stripping Strength	TS EN 12697-11	%	70	Min. 60
Clay and Friable Grains	ASTM C142	%	0	Max.0,3
Dry Grain Density	TS EN 1097-6	Mg/m^3	2,72	-
Apparent Grain Density	TS EN 1097-6	Mg/m^3	2,77	-
Saturated Dry Density	TS EN 1097-6	Mg/m^3	2,74	-
Water Absorption	TS EN 1097-6	%	0,8	Max. 2,0

Table 4 gives the bitumen properties. In the design, aggregates (12–19), (5–12) and (0 –5) mm grain size and B50/70 bitumen were used. In the preparation of the gradation, the sieve averages in Table 5 were taken. The proportions, gradation and tolerance limits of the aggregates are given. As a result of the Wearing Type 1 design with the sandstone aggregates taken from the İSFALT AŞ Factory from the Akdağlar Quarry and delivered to the laboratory, the samples compressed with 2x75 blows at 135-140°C according to the "Asphalt Institute MS-2 Marshall Method; It was found as 5.3±0.2% by weight (100g dry aggregate + 5.3gr B50/70 bitumen) compared to dry aggregate. Marshall charts were used to calculate the optimum bitumen, and the bitumen value corresponding to 4% void value was taken. The results are given below.

Table 3. Physical Properties of Fine Aggregate

Experiment Name	Test Method	Unit	Result	Spec. 2013
Plasticity Index	TS 1900-1	%	NP	NP
Methylene blue	TS EN 933-9+A1	MB	1,3	Max.1,5
Dried Grain Density	TS EN 1097-6	Mg/m^3	2,66	-
Apparent Grain Density	TS EN 1097-6	Mg/m^3	2,79	-
Saturated Dry Density	TS EN 1097-6	Mg/m^3	2,71	-
Water Absorption	TS EN 1097-6	%	1,7	Max. 2,0
Filler Grain Density	TS EN 1097-7	Mg/m^3	2,75	-

Table 4. Bituminous Binder Properties (B50/70)

Experiment Name	Test Method	Unit	Result	Spec. 2013
Penetration 25°C	TS EN 1426	0,01mm	60	50-70
Specific Gravity d25/25	TS EN 15326 +A1	-	1,014	-
Density @25°C		Kg/m^3	1011	-
Softening Point	TS EN 1427	°C	50	46-54
Flash Point	TS EN ISO 2592	°C	306	Min.230
Solubility	TS EN 12592	%	100	Min.99

Table 5. Aggregate usage ratios and mix gradation

Ratio		5%	52%	43%	Mix Grad.	Spec. 2013 Wearing Type 1 Spec		Job Mix Formula	
Aperture Size (Inch)	(mm)	12-19 mm	5-12 mm	0-5 mm					
¾”	19,0	5,0	52,0	43,0	100,0	100		100	
½”	12,5	0,8	50,5	43,0	94,3	88	100	90	98
3/8”	9,5	0,2	38,1	43,0	81,4	72	90	77	85
No 4	4,75	0,2	8,0	42,3	50,5	42	52	47	52
No 10	2,00	0,2	2,7	26,4	29,3	25	35	26	32
No 40	0,425	0,2	2,6	10,5	13,3	10	20	10	16
No 80	0,180	0,2	2,3	5,4	7,9	7	14	7	11
No 200	0,075	0,1	1,6	2,4	4,1	3	8	3	6
Effective Spec. Gravity (G_{ef}) of Aggregate Mixture: 2,736 gr/cm^3 Volume Spec. Gravity (G_{sb}) of Aggregate Mixture: 2,692 gr/cm^3									

The Job Mixture Formula covers the determination of the physical properties of the produced mixture and the density for compaction control, after the plant is adjusted according to the laboratory design. The design is for Wearing Type 1 mixture prepared with aggregates taken from Akdağlar Quarry and delivered to the laboratory and is essential to the operation of the plant. SBS polymer was used. HL is hydrated limestone of S-KK-80-T type. SBS Kraton 1192 was added to the 5% to 50/70 Penetration bitumen. The modified bitumen was prepared in a 3000-rpm high shear mixer at 180 °C for 4 hours. Diatomite coded as D2 and supplied from Bentaş Bentonit company was used. Diatomite XRF main oxide results are given in Table 7 and its granulometry is given in Figure 1. Diatomite was used in 5% of bitumen. HL is 0.5% of the dry mix. Diatomite and HL were added to the dry mix.

Table 6. Design Criteria

	Result	Spec.
Bitumen % (by weight, to 100)	5,3 ± 0,2	4,0 -7,0
Practical Specific Gravity, gr/cm^3 (Mg/m^3)	2,422	
Marshall Stability, kg	1200	Min.900
Flow, mm	3,8	2- 4
Filler / Bitumen Ratio	0,8	Max. 1,5
Void, %	4,0	3- 5
Void filled with asphalt (bitumen), %	73,0	65- 75
VMA %	14,6	14- 16

Table 7. Diatomite additive main oxide analysis results

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
Unit	%	%	%	%	%	%	%	%	PPM	%
D_2	74.099	8.437	2.839	3.049	1.852	0.109	1.002	0.46	0.139	0.054
	SO_3	Cl	BaO	CuO	NiO	SrO	V_2O_5	ZnO	ZrO_2	
Unit	%	PPM	%	%	%	%	%	%	%	
D_2	0.016	83	0.017	0.319	ND	0.029	0.077	ND	0.018	

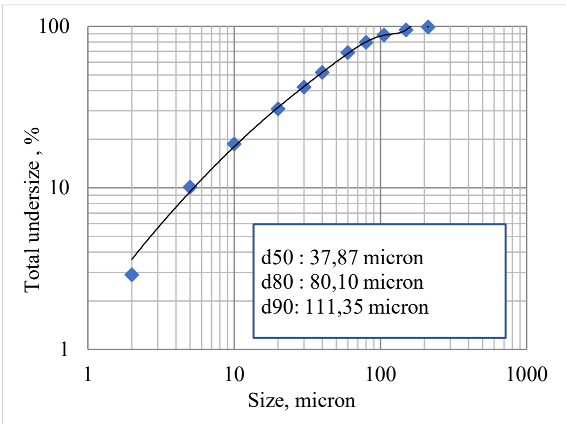

Fig. 1. D2 Coded Diatomite Granulometry Curve
(d50-%50, d80-%80, d90-%90- Grain diameters corresponding to the percentage amount)

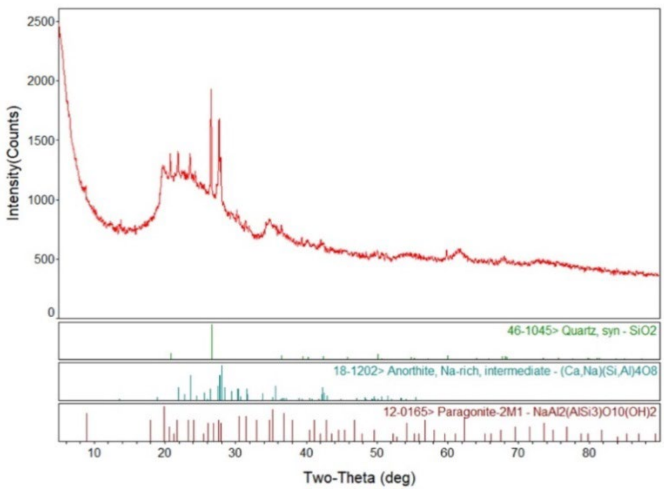

Fig. 2. XRD Analysis of D2 Coded Sample

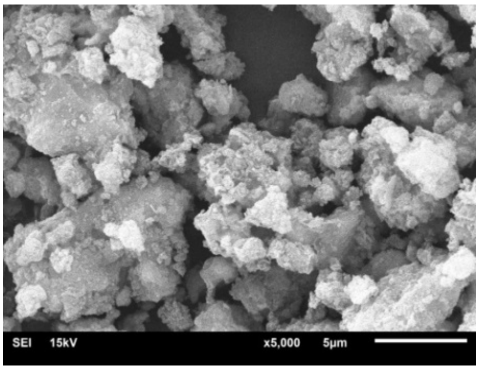

Fig. 3. D2 SEM Image

3.Four Point Bending Test

Asphalt pavement is known to be subject to multiple repetitions of bending loads that lead to fatigue damage during its lifetime. Four-point bending tests, which can be performed at different temperatures and loading frequencies, are used to determine the fatigue life of materials under bending forces. Four-point bending can also be used to determine the stiffness of asphalt mixes. The results are the fatigue and stiffness characteristics of asphalt concrete as a function of temperature and frequency (master curves) [15].

During the test, the load and displacement are measured continuously. In this way, flexural stiffness, tensile stress, tensile strain, phase angle, dissipated energy etc. parameters such as can be easily calculated. The fatigue life is defined as the number of cycles where the stiffness is half the initial value [16].

According to the specifications, the stiffness at the 50th loading cycle is considered the initial stiffness (E0), and the number of load repetitions required to reduce the initial stiffness of a sample to 50% is traditionally used as the fatigue breaking point [17].

In this study; Cooper Research Technology four-point fatigue test was applied (Test Standard: EN 12697-24) such as Effective Length: 355.5mm, Mid-Span Length: 118.50mm, Control Method as Constant Strain, Frequency: 10.0Hz, Target Amplitude: 150.0 (micro strain), temperature: 0.0°C, Test End Value: 50.0%. During the rutting mold preparation, the mass M of the bituminous mixture to be prepared in the mold; It is a function of the maximum density ρ_m of the bituminous mixture, the internal dimensions L and ℓ, the thickness e of the sample, and the expected or unexpected v content (compression under controlled energy). Here; M is the mass of asphalt mix in kilograms (kg), L is the inner length of the mold in millimeters (mm), ℓ is the inner width of the mold in millimeters (mm), e is the final thickness of the asphalt mix in millimeters (mm), ρ_m is the maximum density of the bituminous mix in kg per cubic meter (kg/m^3) and v is the void content in the asphalt mix in percent (%). The mass M is calculated with the help of the formula.

$$M = 10^{-6} x L x l x e x \rho_m x (\frac{100-v}{100}) \quad (1)$$

The mold filling process is carried out. Bituminous mixture is prepared according to TS EN 12697-35:2004+A1 standard or samples brought from asphalt plant are used. Special paper that does not stick with asphalt is placed on the bottom of the mold. If possible, the mold is filled by reducing the mass of the bituminous mixture (M ± 0.1%), taking care to distribute the mixture evenly in the mold with a shovel, avoiding any splitting. In order to obtain as flat a surface as possible, the mixture is compressed by pressing, including the corners, before starting the compaction. Compaction temperatures should be as specified in the TS EN 12697-35:2004+A1 standard. 150°C temperature value was used.

Compaction is done with Controlled Compression Energy. The load is handled by a compression management consisting of preload and displacement that controls the load. Preload and load are applied step by step, increasing the load after each roller pass. When Compressing for Mold Removal is complete, the mixture is cooled to room temperature before removing the mold.

Fatigue experiments were performed for identical samples in two groups. For various numbers of cycles values are given in Table 8-17. The number of load repetitions required to reduce the stiffness value of a beam sample by 50% at the 50th loading was interpreted as the fatigue fracture point of that briquette.

Fig. 4. Some Images of the Four Point Fatigue Test Process

Table 8. Four-point bending fatigue test results for various cycles (Sample 1)

Cycle	Initial Stiffness	Stiffness	Micro Strain	stress	Deformation	Dissipated Energy	Cumulative Dissipated Energy
[-]	[%]	[MPa]		[kPa]	[μe]	[MJ/m^3]	[MJ/m^3]
50	100,0	18600	142,000	2630,00	0,075600	4,34E-05	2,73E-02
100	100,0	18400	151,000	2770,00	0,080300	5,08E-05	2,97E-02
500	98,3	18000	151,000	2720,00	0,080300	5,45E-05	5,10E-02
1000	96,8	17800	151,000	2680,00	0,080400	5,60E-05	7,87E-02
5000	90,7	16700	151,000	2510,00	0,080300	5,49E-05	2,99E-01
10000	88,2	16200	150,000	2430,00	0,080200	5,40E-05	5,67E-01
20000	85,4	15700	150,000	2360,00	0,080100	5,04E-05	1,09E+00
30000	81,9	15000	150,000	2260,00	0,080000	4,83E-05	1,58E+00
40000	78,4	14400	150,000	2160,00	0,080100	4,58E-05	2,04E+00
50000	76,0	13900	150,000	2100,00	0,080200	4,36E-05	2,49E+00
100000	62,8	11500	150,000	1730,00	0,079800	3,56E-05	4,55E+00
181000	49,9	9160	150,000	1380,00	0,080100	2,12E-05	6,85E+00

Table 9. Four-point bending fatigue test results for various cycles (Sample 2)

Cycle	Initial Stiffness	Stiffness	Micro Strain	stress	Deformation	Dissipated Energy	Cumulative Dissipated Energy
[-]	[%]	[MPa]		[kPa]	[µe]	[MJ/m^3]	[MJ/m^3]
50	100,0	2140	135,000	288,00	0,071900	2,87E-05	1,26E-03
100	100,0	2200	150,000	330,00	0,079900	3,06E-05	2,74E-03
500	143,0	3150	2,390	7,52	0,001270	3,98E-08	1,43E-02
811	48,8	1070	2680,000	2880,00	1,430000	9,98E-06	1,94E-02

Table 10. Four-point bending fatigue test results for various cycles (Sample 3)

Cycle	Initial Stiffness	Stiffness	Micro Strain	stress	Deformation	Dissipated Energy	Cumulative Dissipated Energy
[-]	[%]	[MPa]		[kPa]	[µe]	[MJ/m^3]	[MJ/m^3]
50	100,0	15700	148,000	2320,00	0,078600	5,12E-05	1,54E-03
100	100,0	15600	149,000	2330,00	0,079000	4,80E-05	3,71E-03
500	99,4	15500	150,000	2340,00	0,079900	5,11E-05	2,38E-02
1000	98,9	15500	150,000	2320,00	0,079700	4,91E-05	4,88E-02
5000	95,8	15000	150,000	2240,00	0,079500	5,01E-05	2,51E-01
10000	93,0	14600	150,000	2180,00	0,079600	5,18E-05	5,07E-01
50000	63,7	9970	150,000	1500,00	0,079900	4,42E-05	2,37E+00
62051	50,0	7820	150,000	1170,00	0,079600	3,91E-05	2,87E+00

In fatigue tests, it is generally considered that the deviations are high depending on the ratio height in RAP mixtures. The large number of variables complicates the assessment of the subject. Mixing time is kept for a minimum of 4 minutes in mixtures with RAP. For mixtures without RAP, the mixing time is generally 2-2.5 minutes. All mixtures were mixed in a large mixer. Separate mixing was not done. This created an advantage in terms of the sameness and homogeneity of the mixtures (in terms of production). It is evaluated that a homogeneous mixture is formed as an image. Mixing was not done separately; the same large mixer was used.

Pavement life predictions based is using a fatigue relationship that can be obtained by four point bending tests was proposed. Fatigue is such test is defined as the number of constant strain applications until the specimen reaches half of its initial stiffness [18-19].

Table 11. Four-point bending fatigue test results for various cycles (Sample 4)

Cycle	Initial Stiffness	Stiffness	Micro Strain	stress	Deformation	Dissipated Energy	Cumulative Dissipated Energy
[-]	[%]	[MPa]		[kPa]	[µe]	[MJ/m^3]	[MJ/m^3]
50	100,0	14700	143,000	2110,00	0,077100	2,56E-05	6,87E-04
100	100,0	14600	149,000	2170,00	0,080500	3,26E-05	2,19E-03
500	97,5	14200	150,000	2130,00	0,081100	3,88E-05	1,78E-02
1000	95,9	14000	150,000	2100,00	0,081200	4,08E-05	3,82E-02
5000	92,0	13400	150,000	2010,00	0,081000	4,18E-05	2,06E-01
10000	89,7	13000	150,000	1950,00	0,080800	4,02E-05	4,13E-01
20000	86,8	12600	149,000	1890,00	0,080600	3,89E-05	8,19E-01
30000	85,3	12400	150,000	1860,00	0,080900	3,81E-05	1,20E+00
40000	84,2	12300	150,000	1840,00	0,080900	3,76E-05	1,58E+00
50000	83,0	12100	150,000	1810,00	0,080700	3,70E-05	1,96E+00
100000	77,5	11300	149,000	1680,00	0,080500	3,68E-05	3,79E+00
150000	73,3	10700	150,000	1600,00	0,080800	3,57E-05	5,57E+00
200000	69,3	10100	150,000	1510,00	0,080800	3,34E-05	7,35E+00
300000	63,9	9300	149,000	1390,00	0,080500	3,06E-05	1,06E+01
400000	59,6	8670	150,000	1300,00	0,080600	2,99E-05	1,37E+01
500000	54,9	7990	151,000	1200,00	0,081300	2,95E-05	1,67E+01
600000	50,6	7360	150,000	1110,00	0,081100	2,87E-05	1,96E+01
613000	50,0	7270	150,000	1090,00	0,081000	2,87E-05	1,99E+01

Table 12. Four-point bending fatigue test results for various cycles (Sample 5)

Cycle	Initial Stiffness	Stiffness	Micro Strain	stress	Deformation	Dissipated Energy	Cumulative Dissipated Energy
[-]	[%]	[MPa]		[kPa]	[µe]	[MJ/m^3]	[MJ/m^3]
50	100,0	7650	159,000	1210,00	0,092800	7,96E-05	5,87E-02
100	100,0	7740	145,000	1120,00	0,084800	2,91E-05	6,33E-02
500	108,0	8330	151,000	1260,00	0,088100	1,92E-05	8,50E-02
1000	101,0	7780	155,000	1210,00	0,090800	1,93E-05	1,02E-01
5000	91,4	7070	144,000	1020,00	0,084400	3,78E-04	1,13E+00
9180	49,6	3840	159,000	610,00	0,093100	9,77E-05	2,51E+00

Table 13. Four-point bending fatigue test results for various cycles (Sample 6)

Cycle	Initial Stiffness	Stiffness	Micro Strain	stress	Deformation	Dissipated Energy	Cumulative Dissipated Energy
[-]	[%]	[MPa]		[kPa]	[µe]	[MJ/m^3]	[MJ/m^3]
50	100,0	5130	196,000	1010,00	0,098600	9,41E-05	3,29E-02
100	100,0	1660	145,000	241,00	0,072800	1,23E-05	3,40E-02
500	99,3	1650	150,000	248,00	0,075500	1,28E-05	3,88E-02
1000	98,7	1640	152,000	249,00	0,076200	1,11E-05	4,45E-02
5000	99,9	1660	150,000	250,00	0,075600	6,40E-06	7,37E-02
10000	95,6	1590	150,000	239,00	0,075500	9,52E-06	1,12E-01
20000	93,6	1560	150,000	233,00	0,075300	9,89E-06	2,09E-01
30000	93,5	1560	151,000	234,00	0,075700	1,11E-05	3,18E-01
40000	93,2	1550	148,000	230,00	0,074600	1,14E-05	4,35E-01
50000	94,1	1560	150,000	234,00	0,075300	1,27E-05	5,56E-01
100000	93,2	1550	150,000	233,00	0,075600	9,00E-06	1,13E+00
150000	87,9	1460	149,000	217,00	0,074700	1,20E-05	1,67E+00
175000	49,7	827	153,000	126,00	0,076900	1,02E-05	1,96E+00

Table 14. Four-point bending fatigue test results for various cycles (Sample 7)

Cycle	Initial Stiffness	Stiffness	Micro Strain	stress	Deformation	Dissipated Energy	Cumulative Dissipated Energy
[-]	[%]	[MPa]		[kPa]	[μe]	[MJ/m^3]	[MJ/m^3]
50	100,0	10200	141,000	1440,00	0,080900	3,40E-05	1,34E-03
100	100,0	10200	150,000	1530,00	0,086200	4,35E-05	3,28E-03
500	92,5	9400	150,000	1410,00	0,085800	4,50E-05	2,24E-02
1000	91,6	9310	150,000	1400,00	0,086100	4,46E-05	4,51E-02
5000	89,0	9050	151,000	1360,00	0,086500	4,30E-05	2,24E-01
10000	87,8	8930	150,000	1340,00	0,086100	4,76E-05	4,56E-01
20000	85,4	8680	150,000	1300,00	0,085900	4,66E-05	9,17E-01
30000	82,9	8430	150,000	1260,00	0,085800	4,62E-05	1,38E+00
40000	81,1	8240	150,000	1240,00	0,086300	4,41E-05	1,83E+00
50000	79,1	8040	150,000	1200,00	0,085900	4,54E-05	2,28E+00
100000	67,2	6830	151,000	1030,00	0,086500	3,94E-05	4,38E+00
200000	52,6	5350	150,000	801,00	0,086000	3,01E-05	7,73E+00
227000	50,0	5080	149,000	757,00	0,085400	2,84E-05	8,55E+00

Table 15. Four-point bending fatigue test results for various cycles (Sample 8)

Cycle	Initial Stiffness	Stiffness	Micro Strain	stress	Deformation	Dissipated Energy	Cumulative Dissipated Energy
[-]	[%]	[MPa]		[kPa]	[μe]	[MJ/m^3]	[MJ/m^3]
50	100,0	4930	145,000	714,00	0,084000	5,48E-06	6,85E-04
100	100,0	5170	150,000	773,00	0,086700	6,47E-06	9,94E-04
500	98,3	5080	150,000	764,00	0,087200	4,60E-06	3,53E-03
1000	98,1	5070	149,000	757,00	0,086600	2,87E-06	5,45E-03
5000	94,7	4890	150,000	732,00	0,086700	2,54E-07	1,06E-02
10000	94,3	4870	149,000	726,00	0,086500	6,04E-08	1,66E-02
20000	96,4	4980	151,000	755,00	0,087800	2,94E-06	3,67E-02
30000	101,0	5200	147,000	767,00	0,085600	5,66E-06	7,61E-02
40000	101,0	5220	150,000	783,00	0,087000	6,43E-06	1,29E-01
50000	102,0	5290	150,000	795,00	0,087100	6,05E-06	1,92E-01
100000	106,0	5460	150,000	820,00	0,087100	1,86E-06	4,78E-01
200000	84,9	4390	150,000	660,00	0,087200	2,87E-05	2,51E+00
300000	82,0	4240	150,000	638,00	0,087200	3,12E-05	5,31E+00
400000	80,2	4150	151,000	625,00	0,087500	3,32E-05	8,36E+00
500000	78,9	4080	149,000	607,00	0,086400	3,16E-05	1,15E+01
600000	78,1	4040	153,000	619,00	0,088900	3,79E-05	1,49E+01
800000	77,1	3990	150,000	596,00	0,086700	3,32E-05	2,21E+01
1000000	78,8	4080	149,000	609,00	0,086600	2,25E-05	2,77E+01
1700000	81,0	4190	152,000	637,00	0,088300	2,96E-05	4,75E+01

Table 16. Four-point bending fatigue test results for various cycles (Sample 9)

Cycle	Initial Stiffness	Stiffness	Micro Strain	stress	Deformation	Dissipated Energy	Cumulative Dissipated Energy
[-]	[%]	[MPa]		[kPa]	[µe]	[MJ/m^3]	[MJ/m^3]
50	100,0	3410	143,000	490,00	0,083300	2,04E-05	1,52E-03
100	100,0	3690	150,000	555,00	0,087300	2,65E-05	2,80E-03
500	99,9	3690	151,000	555,00	0,087400	2,66E-05	1,32E-02
1000	96,2	3550	152,000	539,00	0,088200	2,81E-05	2,67E-02
5000	90,3	3330	153,000	509,00	0,088700	2,92E-05	1,36E-01
10000	91,8	3390	149,000	504,00	0,086300	2,38E-05	2,68E-01
10500	90,3	3330	151,000	504,00	0,087800	2,64E-05	2,80E-01

Table 17. Four-point bending fatigue test results for various cycles (Sample 10)

Cycle	Initial Stiffness	Stiffness	Micro Strain	stress	Deformation	Dissipated Energy	Cumulative Dissipated Energy
[-]	[%]	[MPa]		[kPa]	[µe]	[MJ/m^3]	[MJ/m^3]
50	100,0	488	381,000	186,00	0,191000	2,68E-05	4,80E-04
100	100,0	1020	13,300	13,50	0,006690	9,71E-08	9,20E-04
107	41,6	423	460,000	195,00	0,231000	2,40E-05	1,02E-03

Table 18. Average of fatigue test results of first batch of 4 test samples

Type 1 Wearing Course	Sample 1	Sample 2	Sample 3	Sample 4	Average	SD	% SD
Target Amplitude: 150.0(microstrain)	150	150	150	150	150	0,00	
Frequency: 10.0Hz	10,00	10,00	10,00	10,00	10	0,00	
Temperature: 0.0°C	0,00	0,00	0,00	0,00	0,00	0,00	
Initial Stiffness	9160	1070,00	7820,00	7270,00	6330	3595	0,57
Stiffness change	49,90	48,80	50,00	50,00	49	0,59	0,01
Cumulative Dissipated Energy MJ/m^3	6,85	0,02	2,87	19,90	7,41	8,79	1,19
Number of cycles	181000	811	62100	613000	214227	276172	1,29
Time Elapsed (min)	301,67	1,35	103,50	1021,67	357	460,29	1,29
Time Elapsed (hour)	5,03	0,02	1,73	17,03	5,95	7,67	1,29

The results of any fatigue test are affected by the loading mode, which can be divided into two different test categories: controlled stress (or load) and controlled stress (or displacement). Fatigue test failure (or number of cycles to failure) is defined in various ways, and sometimes arbitrarily, and the value specified depends on the loading mode [20].

Four-point bending is favored since failure can initiate in an area of uniform stress between the two center loads. This method of loading is also said to be more sensitive to mixture variables such as binder type or aggregate grading [21].

The fatigue data, obtained by means of four-point bending tests carried out at 10 Hz and 20°C under strain control mode, have been analyzed according to both the conventional stiffness reduction approach and the energy ratio method; the latter focused on the dissipated energy concept. Compared to the control mixes, prepared with a full limestone aggregate structure, the hot mix asphalt containing RAP has presented higher resistance to loading cycles, especially at 40% RAP also under post ageing conditions. The improvements in the fatigue life observed for the RAP mixes have been even more relevant using the polymer modified binders, particularly in the case of the hard modified one. Although the experimental fatigue data have outlined an extremely positive effect of RAP on the fatigue performance of the hot mix asphalt tested, a broad generalization of the RAP influence to different asphalt concrete has to be very carefully taken in consideration. The fatigue analysis conducted using the empirical approach and the energy ratio method has led to the same qualitative ranking of the mixes considered; however quantitative differences have been observed that cannot be neglected. The energy ratio approach has identified a fatigue life that has been always lower than that determined by the empirical method, for all the cases studied; therefore, the conventional stiffness reduction approach should be carefully used to avoid an overestimation of the fatigue resistance of the mixes [22].

Table 19. Average of fatigue test results of first batch of 6 test samples

Type 1 Wearing Course	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10	Average	SD	% SD
Target Amplitude: 150.0 (micro strain)	150	150	150	150	150	150	150	0,00	
Frequency: 10.0Hz	10,00	10,00	10,00	10,00	10,00	10,00	10,00	0,00	
Temperature: 0.0°C	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	
Initial Stiffness	3840,00	827,00	5080	4190	3330	423,00	2948	1846	0,63
Stiffness change	49,60	49,70	50,00	81	90,3	41,60	59,12	12,42	0,21
Cumulative Dissipated Energy MJ/m^3	2,51	1,96	8,55	47,50	0,30	0,00	10,14	21,79	2,15
Number of cycles	9180	175000	227000	1700000	11000	107	353714	786970	2,22
Time Elapsed (min)	15,30	291,67	378,33	2833,33	18,33	0,18	589,52	1311,62	2,22
Time Elapsed (hour)	0,26	4,86	6,31	47,22	0,31	0,00	9,83	21,86	2,22

The fatigue characteristics of asphalt mixtures have been investigated using the dissipated energy concept. It was reported that the cumulative dissipated energy of an asphalt mixture can be related to its failure life significantly. Strong relationship exists between the total dissipated energy and the number of loading cycles to failure and such relationship is not affected by loading mode, temperature, frequency, temperature, but it is highly dependent on material type [23].

The fatigue performance of asphalt mixture is the research hotspot of asphalt pavement. The factors that affect the fatigue performance of asphalt mixture mainly include the test method, material factor, loading frequency, test temperature, etc. In terms of test methods, indoor tests are primarily used in the world, including the direct tensile test, indirect tensile test, and four-point bending test. The fatigue test results obtained by different test methods and different specimen sizes are different [24].

Fatigue life estimates vary between identical samples. Although the briquettes have been produced with great care under the same conditions, a high degree of variation is obtained between certain samples, while high agreement is achieved between certain samples.

Stiffness values decrease with increasing number of loading cycles. At this point, there is a decrease in the applied stresses to achieve the same deformation. The stiffness values after the number of cycles applied to obtain 50% stiffness reduction; in most of the briquettes, it can differ 2-3 times between identical samples. The difference in the number of loadings required for 50% stiffness reduction is much higher. In terms of long-term performance of mixtures, this result indicates that the structure of the mixture (homogeneity, interlocking) is much more important than the number of loading cycles. It is the internal composition of the pavement that causes the mixture to maintain the desired performance under higher loading numbers in maintaining long-term performance. Based on this result, it shows that homogeneous production of mixtures will result in similar expected performances and correct implementation of pavement rehabilitation strategies.

The four-point fatigue test can be successfully used to determine the fatigue strength of mixtures. When the standard deviations are taken into account, the range of variability between the fatigue strengths of SBS-D-HL added mixtures made on ten identical samples in 50% RAP modified mixtures is high and inconsistency is observed. It is considered that this issue is due to the absence of a rejuvenating oil in the composition, aggregate angularity and segregation effects. Also, as a suggestion, it is foreseen that more compatible values can be obtained under water damage conditioning due to the presence of HL in the body. In this regard, other studies should be carried out. It is also considered that the inconsistencies are due to the inability to manage the diffusion issue between the RAP and the original mixture. In fact, silicate minerals come into the composition due to the presence of diatomite, and the material that surrounds the RAP material during the scraping process is also silicate elephants. In this respect, it is considered that water damage may occur at a high rate in the mixture. The presence of HL is at a point where it can also manage water damage, but the fact that no water damage has been applied to the samples (for example, confirmatory and effective observable Modified Lottman Water Damage Modeling) minimizes the HL effect at this point. It is recommended that a similar additive methodology be investigated conditionally on water damage in future research.

Conclusions

During its service life, asphalt pavement is subjected to numerous repetitions of bending that create fatigue damage. Four-point bending tests can be performed at different temperatures and loading frequencies. Test; it is used to determine the fatigue life of materials under bending forces and the stiffness of asphalt mixtures is determined. The results are fatigue and stiffness characteristic of the asphalt pavement as a function of temperature and frequency (master curves). A temperature of 20°C can be applied to allow more loading of test briquettes. However, experiments can also be performed at lower and higher temperature values due to the features of the testing machine. Fatigue issue may vary depending on the parameters of the test methods and test types. Fatigue under additive interactions and experimental parameters are a complex and not yet fully elucidated research topic. It seems possible to draw the following conclusions from this study.

Fatigue was tested at 0°C to observe the effect of selected additive alternatives on fatigue performance at low temperatures. Four point bending fatigue test results in 50%RAP modified asphalts, SBS and low ratio HL-D added beam samples give compatible and inconsistent values.

Mixtures have been tested without water damage. In case of water damage to the briquettes, it is considered that the effect of the HL in the body will create more consistent results between the samples.

It is considered that the unavoidable angularity effect and segregation are effective in the different results of the four-point fatigue tests. Examining the difference between identical samples in fatigue for different pavement types will be the subject of further research.

The diffusion mechanism between the RAP and the original mixture is essential.

As a result of 50% stiffness reduction, the difference in the remaining stiffness values is usually 2-3 times, while there are huge differences between the cycle numbers that cause this. In terms of sustainable and long-term performance, the homogeneity of the pavement composition appears to be essential, having a much more pronounced effect than the number of loadings.

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