FATIGUE PERFORMANCE OF RECYCLED ASPHALT PAVEMENT REJUVENATED WITH BIO-REJUVENATOR FROM COCONUT SHELL

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ABSTRACT

This study investigated the fatigue performance of recycled asphalt mixtures (reclaimed asphalt pavement, RAP) rejuvenated with a bio-rejuvenator derived from coconut shells (BioCS), specifically combinations with 30% RAP using a four-point bending test with strain-controlled and compared the results with the Austroads model. The study found that adding a bio-rejuvenator increased stiffness, reduced cracking, and improved fatigue life, with the optimal dosage of 23% by weight of RA binder (bitumen from RAP). The fatigue life decreased as the strain increased but adding BioCS to AC-WC mixtures containing up to 30% RAP still provided a better fatigue life than the AC-WC control mixture. BioCS is suitable for AC-WC mixtures containing up to 30% RAP in the 200 - 400 $\mu\varepsilon$ strain classification range. Furthermore, the fatigue failure values generated from laboratory testing using the four-point bending test were close to the Austroads model with a ratio of 0.9. This suggests that the variables from the Austroads model can be considered to build a fatigue life model of asphalt mixtures containing RAP and BioCS as rejuvenators. However, more research is needed to fully understand the long-term performance and environmental impact of using bio-rejuvenators in asphalt mixtures. Overall, this study supports using bio-rejuvenators derived from coconut shells as a sustainable alternative to petroleum-based rejuvenators for improving the fatigue life of recycled asphalt mixtures.

Keywords: *fatigue life, AC-WC, bio-rejuvenator, coconut shell, recycled material, four-point bending test*

INTRODUCTION

The use of recycled asphalt mixtures in pavement construction has gained popularity in recent years due to environmental and economic benefits. However, recycled asphalt mixtures are known to exhibit reduced fatigue life compared to virgin asphalt mixtures (Sobhan and Mashnad 2003; Mullapudi et al. 2015; Xiao 2006). To address this issue, bio-rejuvenators derived from renewable resources such as vegetable oils (Joni, Al-Rubaee, and Al-zerkani 2019) and animal fats have been proposed as an alternative to traditional chemical rejuvenators. One such bio-rejuvenator is derived from coconut shell (Sihombing and Sihombing 2022; Sugeng and Sihombing 2019; Sihombing et al. 2021; Sihombing, Subagio, Hariyadi, et al. 2020; Sihombing et al. 2019b; 2019a).

Several studies have been conducted to investigate the effectiveness of bio-rejuvenators in improving the performance of recycled asphalt mixtures. For example, a study by Texas DOT, 2011, conducted a study on the use of bioasphalt as a rejuvenating agent on 35% RAP + 5% RAS (Recycled Asphalt Shingles) using the Hamburg Wheel track test. The results showed that the mixture performed well and met the specifications, with a failure rate of 42,626 cycles (minimum of 10,000 cycles), rutting value of 12.5 mm, and indirect tensile strength of 1,045 kPa (specification range of 585 – 1,380 kPa) (Texas DOT 2017).

Elseifi et al., 2011 stated that the use of a biorejuvenator derived from sustainable biomass and RAP (recycled asphalt pavement) in hot mix asphalt can improve the performance at high temperatures as stiffness of the asphalt mixture increases. However, it may reduce the fracture properties of the asphalt mixture (Elseifi, Mohammad, and Cooper III 2011).

In Indonesia, a study by Sihombing (2020) utilized coconut shell waste to produce a rejuvenator for recycled materials that can be reused up to 30% of the total mixture weight. The study evaluated the performance of the asphalt mixture based on empirical criteria, namely Marshall stability, and mechanistic criteria, namely the resilient modulus of the asphalt mixture. Based on the study, it was found that the optimum value of using coconut shell bio-rejuvenator (BioCS) was 23% to restore the Marshall stability and resilient modulus performance of the recycled materials according to the standard specifications (Sihombing, Subagio, Hariyadi, et al. 2020).

The rejuvenating material used in this study is a type of bio-rejuvenator called tall's oil (Turner, Taylor, and Tran 2015; Veeraragavan 2014), which is produced from the pyrolysis process of coconut shell biomass. This involves heating the biomass in an airtight chamber at a temperature of up to 450 °C for 4-6 hours. Illustration of bio rejuvenator production is depicted in Figure 1.

Coconut shell was chosen as the biomass for producing the bio-rejuvenator due to it high lignin content of 29.4% (Aziz, Indraman, and Alawiyah 2011). Lignin has been found in several studies to have potential as a rejuvenating and antioxidant material for asphalt (Bishara, Robertson, and Mohoney 2005; Robertson, Bishara, and Mahoney 2006; Carrier et al. 2011; Pan 2012; Pérez et al. 2019; Pérez et al. 2019; Xie et al. 2017; Xu, Wang, and Zhu 2017). For example, Bishara et.al 2005 tested several types of lignin and found that they had an effect on the aging index. Williams and McCready (2008) researched commonly found lignin and found that bio-rejuvenators made from biomass containing lignin, such as co-products from ethanol production, combined with asphalt in varying amounts and evaluated according to Superpave and Performance Grade specifications, resulted in a greater range of temperature stiffening. Infrared spectroscopy also supported the idea that lignin acted as an antioxidant by reducing the oxidation of asphalt products (Williams and McCready 2008). Syahbirin et al. (2012) also found in their research that lignin has potential as an antioxidant, with the phenolic hydroxyl groups in lignin able to capture free radicals (Syahbirin et al. 2012).

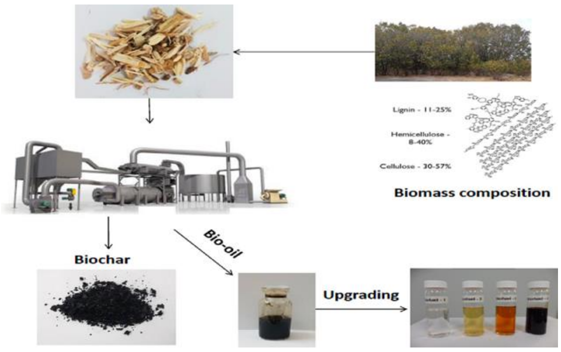


Figure 1. Biomass Pyrolisis Process (Hu and Gholizadeh 2019)

Recycled material or RAP consists of RA binder and RA aggregate. So, when using a rejuvenating agent, it is necessary to test its effect on aging asphalt, namely RA binder. In rheology properties, it was found that the addition of BioCS to RA binder can decrease the performance grade (PG) value from RA binder PG 112 to PG 76. This change in the PG value of RA binder indicates a rejuvenation process on the RA binder, which is asphalt that has undergone aging (Sugeng and Sihombing 2019; Sihombing, Subagio, Susanto, et al. 2020). The physical test results of BioCS are described in Table 1 with a physical description in Figure 2.

Overall, these studies suggest that the use of bio-rejuvenators can improve the fatigue performance of recycled asphalt mixtures. Therefore, the testing conducted is the fatigue life testing, considering that the material used is recycled material that has experienced a decrease in quality, including its resistance to fatigue.

Table 1. Physical Characteristics of BioCS

Properties	Unit	BioCS
Viscosity (60 °C)	Cps	< 100
Moisture content	%	10
Density	Kg/L	1.008
Appearance	-	Clear, Dark Brown Colored Flowable liquid

Figure 2. Bio-rejuvenator Coconut Shell (BioCS).

Fatigue is a phenomenon where cracks occur due to repeated loading caused by cyclic stress or strain that is still below the material's strength limit (Yoder and Witczak 1975). The magnitude of stress or strain depends on the wheel load, stiffness, and overall characteristics of the pavement.

Fatigue testing is conducted to obtain the relationship between stress and strain with fatigue life. When temperature and loading time remain constant, and stress is a variable, a logarithmic scale plot of stress and fatigue life will result in a linear relationship. The mix design variables that affect stiffness also influence the fatigue life of asphalt mixtures. These variables include aggregate type and gradation, filler type and content, asphalt type and content, mixture density, and air void content.

Austroads (Pearson 2011) derived the fatigue life relationship for asphalt mixtures based on variations in the modulus values, which can indicate the fatigue life. This relationship was derived from Shell's research (1978) and adjusted using field confidence factors that can be used in the field when the necessary parameters to determine the fatigue life from service life are unavailable, except for the Accelerated Loading Facility (ALF) experiments. The relationship is shown in equation (1).

In this study, fatigue tests were conducted on asphalt mixture containing recycled materials using bio-rejuvenator from coconut shell as a rejuvenating agent. The fatigue test results were then compared to the empirical model from Austroads (eq. 1) as a validation of the test results.

$$N_f = RF\left[\frac{6918(0.856V_b+1.08)}{S_{mix}{}^{0.36}\mu\varepsilon}\right]^5 \quad (1)$$

where:

N_f = Fatigue life (cycles)

V_b = The volume of asphalt binder in an asphalt mixture. (%)

$\mu\varepsilon$ = Initial tensile strain (microstrain)

S_{mix} = Asphalt mixture stiffness modulus (MPa)

RF = confidence level factor for asphalt mixture fatigue (Table 2)

Table 2. Reliability factor (RF) for asphalt mixture fatigue

The Desired Level of Confidence				
80%	85%	90%	95%	97.5%
4.7	3.3	2.0	1.0	0.5

This study aims to investigate the use of a bio-rejuvenator derived from coconut shell in improving the fatigue life of recycled asphalt mixtures in Indonesia. The study will evaluate the performance of the rejuvenated recycled asphalt mixture through laboratory tests such as the four-point bending beam fatigue test.

The results of this study can provide valuable insights into the potential of using bio-rejuvenators from renewable resources in the Indonesian pavement industry. The findings can help promote sustainable pavement practices and contribute to the development of a more environmentally friendly and resilient transportation infrastructure network in Indonesia.

METHODS

The materials used in this study are: (a) Bio-rejuvenator produced from the pyrolysis process (at a temperature of 450 °C) of coconut shell waste, hereafter referred to as BioCS; (b) Recycled material, namely reclaimed asphalt pavement (RAP) from the excavation of old road pavement in Karawang City, West Java, Indonesia, consisting of asphalt (hereafter referred to as RA binder) and aggregate (hereafter referred to as RA aggregate); and (c) Fresh binder asphalt used is pen 60/70 (PG 64) asphalt binder from PT Pertamina Indonesia and fresh aggregate from PT Kadi, Indonesia.

The method used in this research is by first preparing the equipment and materials, then conducting tests on the materials used, designing the asphalt mixture based on the aggregate gradation for the AC-WC asphalt mixture (Figure 3) until obtaining the optimum bitumen content (OBC) value based on the Marshall criteria for the AC-WC asphalt mixture. The values of mixing and compaction temperatures for (60-70) penetration graded can be shown in Table 3.

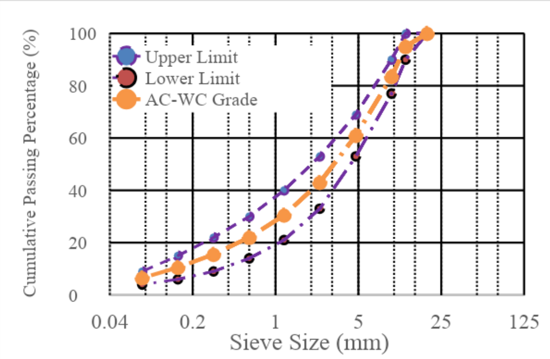


Figure 3. The aggregate gradation for AC-WC asphalt mixture (Directorate General of Highways 2018)

Table 3. Mixing and Compaction Temperature for Asphalt Binder

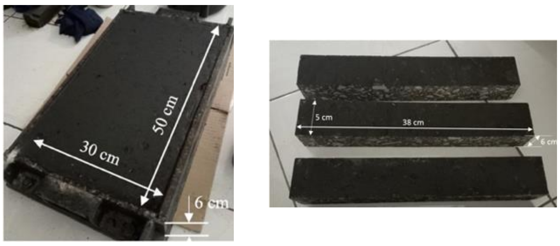
Type of Mixture	Temperature (°C)	
	Mixing	Compaction
AC-WC control	153	143
AC-WC + 10 RAP	153	143
AC-WC + 20 RAP	151	141
AC-WC + 30 RAP	148	138

In the analysis of fatigue resistance of asphalt mixture, information on the stiffness modulus of the asphalt mixture is also required. In this study, the stiffness modulus of the asphalt mixture was tested using the UMATTA test device (Figure 4) by measuring indirect tensile strength using repeated load test, referring to ASTM Designation D 4123-82 (ASTM D4123-82 1998), with loading pulse width of 250 ms, pulse repetition period of 3000 ms, at a testing temperature of 20 °C. Test specimens were made at the OBC condition in the form of cylinders with a diameter of 100 mm and thickness of (63.5 ± 2.5) mm, with 2 samples for each type of mixture.

(a) (b)

Figure 4. Resilient modulus test apparatus and test specimens of asphalt mixture: (a) UMATTA devices and (b) cylinder samples.

The preparation of fatigue specimens consists of coarse and fine aggregates and filler at the optimum bitumen content (OBC), followed by mixing, compaction, and cutting. All test specimens used for testing were cut to the size of a modified wheel tracking mold with dimensions of 50 cm x 30 cm x 6 cm (figure 5a). The specimens were in the form of rectangular beams made according to the specifications based on Tayebali's research in 1995, which were 38 cm x 6 cm x 5 cm (figure 5b).



(a) (b)

Figure 5. Test specimens for fatigue test: (a) initial compacted mold, (b) fatigue test specimens ready for testing.

The fatigue strength due to repeated loading on the AC-WC mixture was tested using the Four Point Bending Test (4PBT) device (Figure 6) based on the approach of the four-point bending testing technique (Figure 7) with controlled strain (controll strain) (Y. Hsien. Huang 2004), where failure or fatigue life is defined as the number of cycles at which the stress of the mixture reaches 50 percent of the initial stress given from the planned 300,000 cycles.

(a) (b)

Figure 6. Four point bending test apparatus: (a) testing control box, (b) testing device.

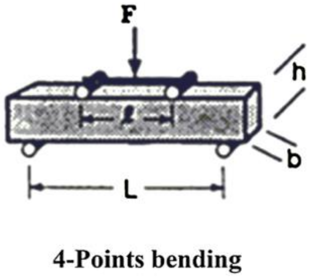


Figure 7. Fatigue Testing Technique with Four Point Bending Test Approach (Huang 2004)

The strain variations were 300 με, 400 με, and 500 με, with a load pulse width time of 124 microseconds, a loading frequency of 8.06 Hz, and condition the beams at the test temperature (typically 68°F (20°C)) for two hours. The stages of the research on the effect of using coconut shell bio-rejuvenator on AC-WC mixture containing recycled material can be seen in Figure 8. The types of materials and their compositions in the asphalt mixture used in this study are described in Table 4.

ANALYSES AND RESULTS

Aggregate

The aggregates used in this study were derived from RAP (RA aggregate) and fresh aggregates sourced from a stone crusher in Karawang, West Java, Indonesia. The use of fresh aggregates followed the mid-value of the AC-WC gradation (Figure 4) with a maximum nominal size of 19 mm.

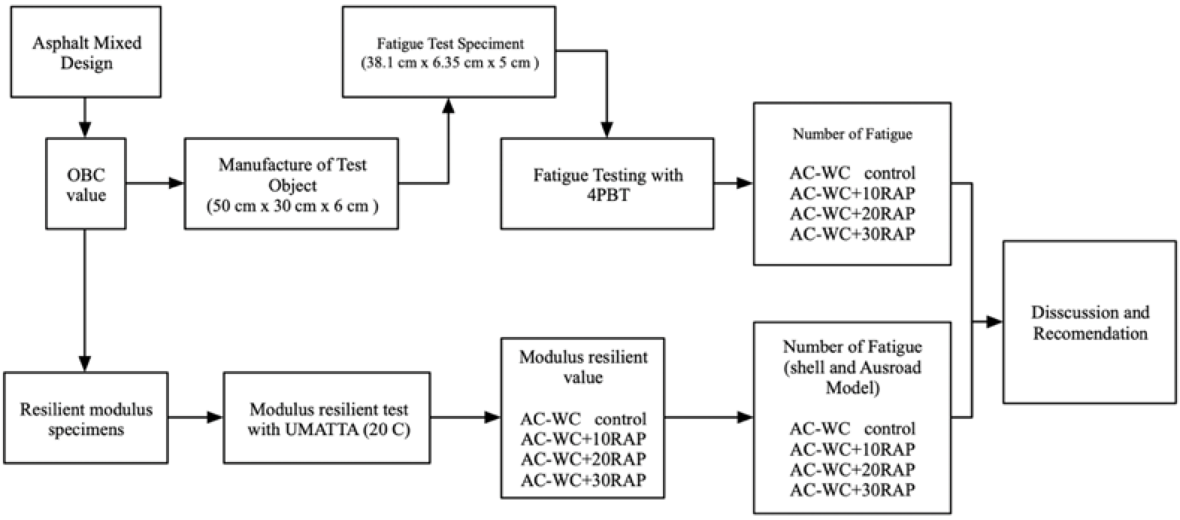


Figure 8. Research Method

Table 4. Number of Fatigue Test Specimens and Material Content Used

Type of Mixture	OBC (%)	Material Content in Mixtures (%)			Number of Specimens
		Pen 60/70	Fresh Aggregat	RAP	
AC-WC control	6.10	6.1	93.9	-	6
AC-WC + 10 RAP	5.90	5.5	84.5	10	6
AC-WC + 20 RAP	5.80	4.8	75.2	20	6
AC-WC + 30 RAP	5.75	4.2	65.8	30	6

Information :
The proportion of BioCS was 23% by weight of RA binder

Table 5. Properties of fine aggregate

Test Type	Test Method	Fresh Aggregate	RA aggregate
Density	ASTM C-128, 2007(ASTM C-128 2007)	2.61	2.25
Moisture absorption (%)		1.91	1.77

Meanwhile, the properties of the fresh aggregates can be seen in Tables 5 and 6 Based on the results of the fresh aggregate properties test, it is known that the aggregates in this study can be used to produce fatigue test specimens.

Recycled Material

The Recycled Asphalt Pavement (RAP) used in this study consists of asphalt binder (RA binder) and aggregate (RA aggregate). Based on the test results by separating RA binder and RA aggregate, it is known that the asphalt content of RAP is 5.15%, the rest is aggregate with a gradation as described in Table 7. From the sieve analysis results, it is known that the gradation of RA aggregate is in accordance with the gradation of AC-WC mixture aggregate, making it easier to combine RAP and fresh aggregate.

Table 6 Properties of course aggregate

Test Type	Test Method	Fresh Aggregate	RA aggregate
Density	ASTM 2013(American Society for Testing and Materials 2013)	2.64	2.49
Moisture absorption (%)		1.59	1.49
LA abrasion (%)	ASTM C131/C131M -14, 2014(ASTM C131/C131M -14 2014)	21.17	32.30

Table 7. Gradation of RA aggregate

Sieve Number	Retained (%)	Passing (%)	Spec Limits (%) of AC-WC gradation (Directorate General of Highways 2018)
¾”	0.0	100.00	100
½”	8.1	91.88	90-100
3/8”	11.0	80.86	77-90
No.4	17.9	62.98	53-69
No.8	19.5	43.48	33-53
No.16	12.2	31.29	21-40
No.30	8.0	23.24	14-30
No.50	6.7	16.58	9-22
No.100	10.0	6.57	6-15
No.200	3.1	3.50	4-9
Pan	3.5		

Asphalt Binder Pen 60/70 (PG 64)

Pen 60/70 (PG 64) is a commonly used asphalt binder in Indonesia for flexible pavement. Based on the results of dynamic shear rheometer (DSR) temperature sweep test, it is known that the critical temperature to achieve a minimum value of G*/sin δ 1.00 kPa in unaged binder asphalt condition is 65.3 °C, in rolling thin film oven test (RTFOT) or aging during production is 63.6 °C, and in pressurized aging vessel test (PAVT) or asphalt binder aging during pavement service life is 23.7 °C.

Tabel 8. Asphalt Binder Properties

Property	Unit	Pen 60/70	RA binder	RA binder + 23% BioCS
Performance Grade (PG)	ºC	64	112	76
Stiffness Modulus (Sbit)	KPa	540.9	60,240	838.5
Penetration (25 ºC, 5 s)	0.1 mm	65	10	65
Viscosity (135 ºC)	cSt	409.6	-	463.5
Softening point	ºC	51	80	54
Ductility (25 ºC, 5cm/min)	cm	>100	38	>100
Flash point	ºC	340	240	325
Specific gravity	-	1.02	1.02	1.06
Penetration RTFOT	°C	56	-	54
Ductility RTFOT	cm	110	-	115
Mass loss	% weight	0.149	0.75	0.51

The bio-rejuvenator content used in the design of AC-WC asphalt mixture containing RAP was obtained from the results of testing the effect of BioCS addition to RA binder according to Sihombing's study in 2019 on the penetration and softening point parameters. The BioCS content used was 23% by weight of RA binder. The properties of asphalt used in this study are described in Table 8.

The asphalt binder testing results show that Pen 60/70 used in this study meets the Bina Marga 2018 (Rev 2) general specification, as well as the RA binder after adding 23% BioCS. The original PG value of RA binder was 112, but after adding BioCS, it became PG 76, the original penetration value of 10 dmm increased to 65 dmm, and so on, which indicates that every asphalt binder property parameter from RA binder + 23% BioCS meets the specifications. This asphalt binder material testing shows that it can be used to produce fatigue test specimens.

Stiffness Modulus of Asphalt Mixture

The stiffness modulus test of asphalt mixture was conducted to determine the Smix parameter, which is one of the variables needed to predict the fatigue value using the fatigue model equation. The empirical fatigue model used in this study is the Ausroad model (eq. 1). The fatigue resistance analysis results from this model were then compared to the fatigue resistance value of asphalt mixture produced from the 4PBT test.

The results of the asphalt mixture's resilient modulus testing are presented in Table 9 along with other variables needed for fatigue life analysis based on the Ausroads model.

Based on the results of the asphalt mixture stiffness modulus test, it can be determined that increasing the RAP content in the mixture will increase the stiffness of the mixture. With the increasing stiffness of the asphalt mixture, the risk of cracking will also increase, therefore it is necessary to conduct an analysis or testing related to the fatigue resistance for every asphalt mixture containing recycled material.

Table 9. Smix and other supporting variables are used in the analysis of Load repetition to failure (Nf)

Type of Mixture	Smix (MPa)	Vb (%)	Initial tensile strain (με)
AC-WC control	6174	13.81	0.000298
	6174	13.81	0.000401
	6174	13.81	0.000499
AC-WC + 10 RAP	6946	13.40	0.000300
	6946	13.40	0.000400
	6946	13.40	0.000501
AC-WC + 20 RAP	7354	13.16	0.000300
	7354	13.16	0.000399
	7354	13.16	0.000502
AC-WC + 30 RAP	7510	13.01	0.000300
	7510	13.01	0.000400
	7510	13.01	0.000498

Flexural Fatigue

The effect of bio-rejuvenator on the flexural fatigue of the mixture can be observed based on the value of load repetitions to failure (cycles) (Nf) that occur on the AC-WC mixture containing up to 30% RAP compared to the AC-WC control.

In Figure 9, it is shown that the greater the strain, the smaller the Nf that occurs. For the same strain value, the addition of RAP will reduce Nf. However, when compared to the control mixture, the value is still higher, indicating that the addition of BioCS to the AC-WC mixture containing up to 30% RAP can provide better fatigue resistance than the control AC-WC mixture.

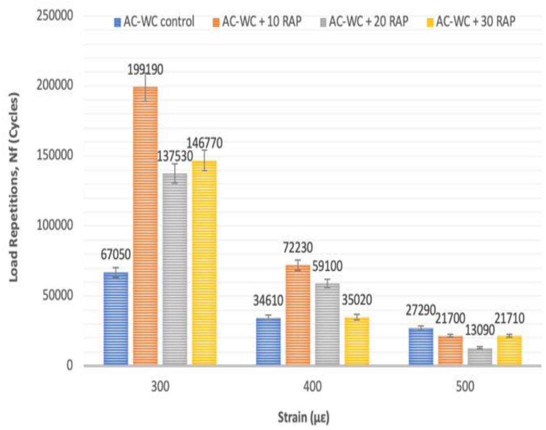


Figure 9. Fatigue resistance of mixtures with RAP and BioCS as rejuvenator

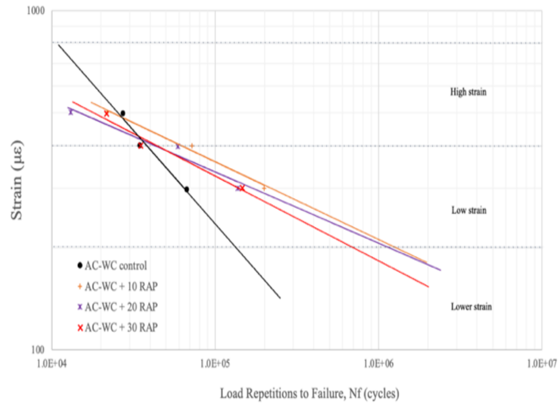


Figure 10. Flexural fatigue graph of AC-WC mixtures with RAP

The higher the applied strain, the faster the asphalt mixture experiences failure. Based on the results of the 4PBT test, it is known that fatigue resistance is influenced by changes in strain, where the number of repetitions decreases as the strain load increases. Based on this, fatigue resistance is analyzed using the parameters of the number of repetitions and the change in strain load. Both parameters are related in a log-log function, where the higher the slope produced, the lower the resistance to fatigue. Therefore, in Figure 9, the relationship between strain and load repetitions is depicted to observe the slope produced by each asphalt mixture.

Figure 10 shows the linear regression between ln(ε) and ln(Nf), resulting in a suitable formula as described in Table 10. Based on the analysis results, it can be seen that the R^2 value for all formulas is close to 1, indicating a very good linear fitting.

Table 10. Linier fitting fatigue resistance of mixtures

Type of Mixture	Equation	R^2	A
AC-WC control	ln(ε) = -0.55ln(Nf)+11.759	0.97	-0.55
AC-WC + 10 RAP	ln(ε) = -0.23ln(Nf)+8.529	0.99	-0.23
AC-WC + 20 RAP	ln(ε) = -0.21ln(Nf)+8.243	0.95	-0.21
AC-WC + 30 RAP	ln(ε) = -0.25ln(Nf)+8.668	0.96	-0.25

In general, the formula obtained is as shown in equation 2:

$$\ln(\varepsilon) = A \ln(Nf)+B \quad (2)$$

The resulting equations show that the value of A<0, B>0; A and B can be identified as fatigue resistance. Therefore, the smaller the value of |A|, the greater the resistance of the mixture to fatigue.

From the analysis results, it can be concluded that the AC-WC mixture containing RAP with BioCS as rejuvenator is more resistant to fatigue compared to the AC-WC control mixture. When compared, the order of fatigue life for the four mixtures is: AC-WC+20RAP > AC-WC+10RAP > AC-WC+30RAP > AC-WC control.

Pavement Interactive classifies strain into 3 levels, namely: high strain (400-800 microstrain), low strain (200-400 microstrain), and lower strain (50-100 microstrain) (The Pavement Tools Consortium 2020). The classification of strain is related to the amount of time required for the asphalt mixture to experience failure during laboratory testing to evaluate the fatigue resistance of asphalt mixtures with strain control.

Table 11. Prediction of Fatigue Failure of Austroad Mix Model

Type of Mixture	Load Repetitions to Failure, Nf (cycles)		Ratio
	4PBT	Ausr	Lab/Ausr
ACWC control	67050	365470	0.18
	34610	82835	0.42
	27290	27761	0.98
AC-WC + 10RAP	199190	244776	0.81
	72230	58086	1.24
	21700	18845	1.15
AC-WC + 20RAP	137530	202016	0.68
	59100	48543	1.22
	13090	15398	0.85
AC-WC + 30RAP	146770	184960	0.79
	35020	43892	0.80
	21710	14674	1.48
Average			0.90

DISCUSSIONS

Based on the grouping of strains according to the Pavement Interactive classification, it can be observed from Figure 10 that: (a) High strain level (400 – 800 microstrain): AC-WC+10RAP has a higher fatigue life than the AC-WC control; (b) Low strain level (200 – 400 microstrain) : the entire mixture has a higher fatigue life than the AC-WC control; and (c) Lower strain level (50 – 100 microstrain) : AC-WC+10RAP dan AC-WC+20RAP intersect at a single point at a strain of 180 microstrain with Nf = 2x106.

Based on this grouping, it can be inferred that BioCS is suitable for AC-WC mixtures containing up to 30% RAP in the 200 - 400 με strain classification range.

The fatigue resistance of asphalt mixtures can also be determined through theoretical fatigue failure prediction based on a model. In this study, the model used is the Austroads model.

Austroads also developed a formula to predict the fatigue life of asphalt mixtures. By using the asphalt volume, strain, and stiffness modulus of the mixture, the prediction of the fatigue life is obtained using Equation (1). The results of the Austroads Model's fatigue life prediction can be seen in Table 11.

Based on the analysis of the fatigue failure ratio of the empirical Austroads model and the mechanistic testing using 4PBT, it is known that the average ratio produced is 0.9. This indicates that the fatigue failure results are not significantly different between empirical and mechanical approaches. Therefore, for further development of this research, the variables from the Austroads model can be considered to build a fatigue failure model of asphalt mixtures containing RAP and BioCS as rejuvenators.

CONCLUSION

The conclusion of the research on the fatigue performance of recycled asphalt mixture rejuvenated with bio-rejuvenator from coconut shell is that the use of bio-rejuvenator derived from coconut shells has shown potential as a sustainable alternative to traditional petroleum-based rejuvenators in improving the fatigue life of recycled asphalt mixtures. The experimental results showed that the addition of bio-rejuvenator to the recycled asphalt mixture resulted in increased stiffness, reduced cracking, and improved fatigue life.

Moreover, the fatigue life testing on AC-WC mixtures containing RAP and rejuvenated with BioCS shows that as the strain increases, the fatigue failure decreases. At the same strain, the AC-WC+RAP mixture shows that increasing the amount of RAP in the mixture will reduce the fatigue life value of the asphalt mixture. However, when compared to the control AC-WC, the value is still greater. This indicates that the addition of BioCS to AC-WC mixtures containing up to 30% RAP can provide better fatigue life than the control ACWC mixture.

The value of fatigue failure generated from laboratory testing using the four point bending Test was close to the Austroads model with a ratio of 0.9. Therefore, for further development of this research, the variables from the Austroads model can be considered to build a fatigue life model of asphalt mixtures containing RAP and BioCS as rejuvenators.

Testing the fatigue resistance of asphalt mixtures containing up to 30% RAP using the local Indonesian rejuvenator, BioCS, proves that this bio-rejuvenator can address the vulnerability of recycled mixtures to fatigue. This has been a significant factor contributing to the failure of using recycled materials on road pavements.

Furthermore, the findings suggest that the optimal dosage of bio-rejuvenator is 23% by weight of RAbinder. However, it is important to note that further research is needed to fully understand the long-term performance and environmental impact of using bio-rejuvenators in asphalt mixtures.

With coconut production of 2.87 million tons per year (Statistik Indonesia 2022), coconut shell waste produced in Indonesia is 12% or around 360 thousand tons per year (Irawan and Dwi 2017), the use of coconut shell bio-rejuvenator as a recycled material for rejuvenating materials is potentially one way to solve the need for domestic rejuvenating agents (reducing imports of rejuvenating agents) as well as the problem of processing coconut shell waste which is increasing every year.

REFERENCES

American Society for Testing and Materials. 2013. "ASTM C127-15: Standard Test Method for Density , Relative Density (Specific Gravity), and Absorption of Coarse Aggregate." *ASTM Standard Book*, no. C: 1–6.

ASTM C-128. 2007. "Standard Test Method for Density, Relative Density (Specific Grafity), and Absorption of Fine Aggregate."

ASTM C131/C131M-14. 2014. "Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine." *Annual Book of American Society for Testing Materials ASTM Standards,West Conshohocken, USA,* 04 (Note 2): 5–8. https://doi.org/10.1520/C0131.

ASTM D4123-82. 1998. "Test Method for Indirect Tension Test for Resilient Modulus for Bituminous Mixtures." Annual Books of ASTM Standar.

Aziz, Tamzil, M Furqon Indraman, and Ucu Alawiyah. 2011. "Pemanfaatan Tempurung Kelapa Dan Tempurung Sawit Untuk Pembuatan Asap Cair Sebagai Penghilang Bau Pada Lateks Dengan Metode Pirolisis." *Jurnal Teknik Kimia* 17 (8): 41–48.

Badan Pusat Statistik. n.d. *Statistik Indonesia 2022*.

Bishara, S W, R E Robertson, and D Mohoney. 2005. "Lignin as an Antioxidant: A Limited Study on Asphalts Frequency Used on Kansas Roads." In *The 42nd Peterson Asphalt Research Conference, Cheyenne, WY*.

Carrier, Marion, Anne Loppinet-Serani, Dominique Denux, Jean Michel Lasnier, Frédérique Ham-Pichavant, François Cansell, and Cyril Aymonier. 2011. "Thermogravimetric Analysis as a New Method to Determine the Lignocellulosic Composition of Biomass." *Biomass and Bioenergy*. https://doi.org/10.1016/j.biombioe.2010.08.067.

Directorate General of Highways. 2018. "General Specification of Bina Marga 2018 For Road and Bridge Construction Work (Revision 2)." Jakarta: Directorate General of Highways, Ministry of Public Work and Housing.

Elseifi, Mostafa A, Louay N Mohammad, and Samuel B Cooper III. 2011. "Laboratory Evaluation of Asphalt Mixtures Containing Sustainable Technologies." *Journal of the Association of Asphalt Paving Technologists* 80 (Highways; Materials; Pavements; I23: Properties of Road Surfaces; I31: Bituminous Binders and Materials): pp 227-254. https://trid.trb.org/view/1135205.

Guduru, Gurunath, Chethan Kumara, Bharath Gottumukkala, and Kranthi K Kuna. 2021. "Effectiveness of Different Categories of Rejuvenators in Recycled Asphalt Mixtures." *Journal of Transportation Engineering, Part B: Pavements* 147 (2): 04021006. https://doi.org/10.1061/jpeodx.0000255.

Hu, Xun, and Mortaza Gholizadeh. 2019. "Biomass Pyrolysis: A Review of the Process Development and Challenges from Initial Researches up to the Commercialisation Stage." *Journal of Energy Chemistry*. Elsevier B.V. https://doi.org/10.1016/j.jechem.2019.01.024.

Huang, B., X. Shu, and E. G. Burdette. 2006. “Mechanical Properties of Concrete Containing Recycled Asphalt Pavements.” *Magazine of Concrete Research*. https://doi.org/10.1680/macr.2006.58.5.313.

Huang, Baoshan, Xiang Shu, and Guoqiang Li. 2005. “Laboratory Investigation of Portland Cement Concrete Containing Recycled Asphalt Pavements.” *Cement and Concrete Research*. https://doi.org/10.1016/j.cemconres.2005.05.002.

Huang, Yang Hsien. 2004. *Pavement Analysis and Design Second Edition)*.

Irawan, Anton, S. Latifah Upe, and I. P. Meity Dwi. 2017. “Effect of Torrefaction Process on the Coconut Shell Energy Content for Solid Fuel.” In *AIP Conference Proceedings*. https://doi.org/10.1063/1.4979226.

Joni, Hasan H., Rasha H.A. Al-Rubaee, and Mahdi A. Al-zerkani. 2019. “Rejuvenation of Aged Asphalt Binder Extracted from Reclaimed Asphalt Pavement Using Waste Vegetable and Engine Oils.” *Case Studies in Construction Materials* 11: e00279. https://doi.org/10.1016/j.cscm.2019.e00279.

Kabir, Shahid, Ammar Al-Shayeb, and Imran M. Khan. 2016. “Recycled Construction Debris as Concrete Aggregate for Sustainable Construction Materials.” In *Procedia Engineering*. https://doi.org/10.1016/j.proeng.2016.04.191.

Mullapudi, Ramya Sri, K Sudhakar Reddy, Gubbala Chaitanya, Ramya Sri, and Kusam Sudhakar Reddy. 2015. “Fatigue Performance of Bituminous Mixes Containing Reclaimed Asphalt Pavement (RAP) Material Performance Evaluation of Cast-in-Situ Short Paneled Concrete Pavements (SPCP) on Lean Concrete Base View Project,” no. December. https://www.researchgate.net/publication/283291906.

Pan, Tongyan. 2012. “A First-Principles Based Chemophysical Environment for Studying Lignins as an Asphalt Antioxidant.” *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2012.06.012.

Pearson, Derek. 2011. “Pavement Design.” In *Deterioration and Maintenance of Pavements*, 233–43. https://doi.org/10.1680/dmp.41141.233.

Pérez, Ignacio, Ana R. Pasandín, Jorge C. Pais, and Paulo A.A. Pereira. 2019. “Feasibility of Using a Lignin Containing Waste in Asphalt Binders.” *Waste and Biomass Valorization* 0 (0): 0. https://doi.org/10.1007/s12649-019-00590-4.

Pérez, Ignacio Pérez, Ana María Rodríguez Pasandín, Jorge Carvalho Pais, and Paulo Antonio Alves Pereira. 2019. “Use of Lignin Biopolymer from Industrial Waste as Bitumen Extender for Asphalt Mixtures.” *Journal of Cleaner Production* 220: 87–98. https://doi.org/10.1016/j.jclepro.2019.02.082.

Porter, Ken. 2009. “Recycled Materials.” In *Austroads*.

Robertson, Raymond E, Safwat Wahba Bishara, and Donna Mahoney. 2006. “Lignin as Antioxidant: Limited Study on Asphalts Frequently Used on Kansas Roads.” In . Washington, DC United States: Transportation Research Board. https://trid.trb.org/view/776247.

Sihombing, Atmy, and Reza Sihombing. 2022. “Bioasbuton as an Alternative Binder for Hot Mix Asphalt.” *Proceedings of the Conference on Broad Exposure to Science and Technology 2021 (BEST 2021)* 210 (Best 2021): 86–92. https://doi.org/10.2991/aer.k.220131.014.

Sihombing, Atmy, Bambang Subagio, Eri Hariyadi, and Anwar Yamin. 2019a. “Bio-Asphalt on Asphalt Mixture Containing RAP.” In *IOP Conference Series: Materials Science and Engineering*. Vol. 673. https://doi.org/10.1088/1757-899X/673/1/012026.

Sihombing, Atmy, Bambang Subagio, Eri Susanto, and Anwar Yamin. 2019b. “The Effect of Bioasphalt on Aged Asphalt.” *IOP Conference Series: Materials Science and Engineering* 508 (1). https://doi.org/10.1088/1757-899X/508/1/012041.

Sihombing, Atmy, Bambang Subagio, Eri Susanto, and Anwar Yamin. 2020. “Development of Resilient Modulus Model Proposed for Bio-Asphalt as Modifier in Asphalt Concrete Containing Reclaimed Asphalt Pavement.” *International Journal of GEOMATE* 19 (71): 130–36. https://doi.org/10.21660/2020.71.68349.

Sihombing, Atmy, Bambang Subagio, Eri Susanto, and Anwar Yamin. 2021. “Chemical, Morphological, and High Temperature Rheological Behaviour of Bioasbuton® as an Alternative Binder for Asphalt Concrete in Indonesia.” *Journal of King Saud University - Engineering Sciences* 33 (5): 308–17. https://doi.org/10.1016/j.jksues.2020.07.006.

Sihombing, Atmy, Bambang Subagio, Eri Susanto, and Anwar Yamin. 2020. “Mechanical Properties of Bio-Asphalt on Recycled Asphalt Pavement Binder.” *Lecture Notes in Civil Engineering*. https://doi.org/10.1007/978-3-030-48679-2_50.

Sobhan, Khaled, and Mehedy Mashnad. 2003. "Fatigue Behaviour of a Pavement Foundation with Recycled Aggregate and Waste HDPE Strips." *Journal of Geotechnical and Geoenvironmental Engineering*. https://doi.org/10.1061/(ASCE)1090-0241(2003)129:7(630).

Sugeng, Bambang, and Atmy Sihombing. 2019. "Utilization Bioasphalt as a Modifier in Aged Asphalt."

Syahbirin, G., A.A. Darwis, A. Suryani, and W. Syafii. 2012. "Potential of Lignosulphonate of Eucalyptus Lignin from Pulp Plant as Dispersant in Gypsum Paste." *Procedia Chemistry*. https://doi.org/10.1016/j.proche.2012.06.048.

Texas DOT. 2017. "Data Penelitian Mengenai BituTechRAP Periode 2008 – 2015, Merupakan Hasil Penelitian Asphalt Green Aphalt Technoloies LLC Tahun 2011, Hydrogreen Bioasphalt, Bioenergy, Tahun 2009 Dan Avello® Bioenergy, Iowa State University, Amerika 2011." 2017.

The Pavement Tools Consortium. 2020. "Flexural Fatigue." 2020. https://pavementinteractive.org/reference-desk/testing/pavement-tests/flexural-fatigue/.

Turner, Pamela, Adam Taylor, and Nam Tran. 2015. "LABORATORY EVALUATION OF SYLVAROADTM RP 1000 REJUVENATOR."

Veeraragavan, Ram Kumar. 2014. "An Investigation of the Performance of Hot Mix Asphalt (HMA) Binder Course Materials with High Percentage of Reclaimed Asphalt Pavement (RAP) and Rejuvenators." *Paper Knowledge . Toward a Media History of Documents* 7 (2): 107–15.

Williams, R. Christopher, and Nicolaus S McCready. 2008. *The Utilization of Agriculturally Derieved Lignin as an Antioxidant in Asphalt Binder*. Vol. 2.

Xiao, Feipeng. 2006. "Development of Fatigue Predictive Models of Rubberized Asphalt Concrete (RAC) Containing Reclaimed Asphalt Pavement (RAP) Mixtures," 213.

Xie, Shangxian, Qiang Li, Pravat Karki, Fujie Zhou, and Joshua S. Yuan. 2017. "Lignin as Renewable and Superior Asphalt Binder Modifier." *ACS Sustainable Chemistry and Engineering*. https://doi.org/10.1021/acssuschemeng.6b03064.

Xu, Guangji, Hao Wang, and Hongzhou Zhu. 2017. "Rheological Properties and Anti-Aging Performance of Asphalt Binder Modified with Wood Lignin." *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2017.06.151.

Yoder, E. J., and M. W. Witczak. 1975. *Principles of Pavement Design*. *Principles of Pavement Design*. https://doi.org/10.1002/9780470172919.