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Performance of RAP-Based HRS-WC Mixtures Using Natural Rubber as Rejuvenator

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ABSTRACT

The growing demand for road pavement materials has encouraged the use of Reclaimed Asphalt Pavement (RAP) as a sustainable alternative. However, binder aging in RAP increases mixture stiffness, requiring rejuvenating agents to restore asphalt properties. This study aims to analyze the effect of Natural Rubber (NR) as a rejuvenating agent in RAP-based Hot Rolled Sheet-Wearing Course (HRS-WC) mixtures under unaged, Short-Term Oven Aging (STOA), and Long-Term Oven Aging (LTOA) conditions. The mixtures were designed using the Marshall method in accordance with RSNI M-01-2003, with NR contents of 0%, 5%, and 10% by weight of RAP asphalt. Performance evaluation included stiffness, deformation resistance, and fatigue resistance tests. The results indicate that NR affects the characteristics of RAP-based HRS-WC mixtures. The Indirect Tensile Stiffness Modulus (ITSM) decreases with increasing NR content, indicating improved flexibility and elasticity. However, stiffness increases after STOA and LTOA due to binder aging. The 10% NR mixture showed the best deformation resistance, with the lowest creep slope of 0.1284 under STOA. It demonstrated the highest fatigue resistance, achieving 10,311, 2,111, and 611 cycles to failure under unaged, STOA, and LTOA conditions, respectively. These findings demonstrate NR's potential as a rejuvenating agent for improving RAP-based HRS-WC performance and durability.

Keywords : Reclaimed Asphalt Pavement (RAP); natural rubber; ITSM; creep; ITFT

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1. INTRODUCTION

The increasing volume of traffic and axle loading has intensified the demand for aggregate and asphalt materials, while the continued use of virgin resources contributes to resource depletion, waste generation, and environmental impacts [1]. The green road concept promotes the principles of reduce, reuse, and recycle as an approach to achieving more sustainable pavement construction [2]. In this context, Reclaimed Asphalt Pavement (RAP) offers significant potential by reducing the consumption of virgin aggregate and asphalt, construction costs, and greenhouse gas emissions [3], [4]. At appropriate contents, RAP mixtures can provide performance comparable to conventional mixtures; however, the aged binder in RAP increases mixture stiffness and may compromise flexibility and cracking resistance [5]–[8].

The increased stiffness of aged RAP binder results from oxidation and the loss of lighter binder fractions during service, creating a need for rejuvenating agents to restore its physical and rheological properties [9],

[10]. Various rejuvenators, including softer asphalt binders and organic oils, have been investigated for this purpose [11], [12]. Natural Rubber (NR) is a promising alternative because of its availability in Indonesia and its ability to modify asphalt properties. Previous studies have reported that NR can improve softening characteristics, elasticity, resistance to permanent deformation, fatigue performance, and crack resistance [13]–[18]. Its application may therefore provide a sustainable approach for improving the performance of recycled asphalt mixtures while utilizing a renewable local resource.

Fatigue, stiffness, and permanent deformation are critical indicators of asphalt pavement performance under repeated traffic loading [19], [20]. HRS-WC, a gap-graded mixture commonly used as a wearing course, is characterized by good flexibility and durability; however, the incorporation of aged RAP binder may increase mixture stiffness and alter its viscoelastic behavior. Consequently, the effectiveness of NR in RAP-based HRS-WC should be evaluated using mechanical performance parameters rather than Marshall properties alone [21]–[23].

Previous studies have primarily examined NR as a rejuvenator through conventional asphalt and Marshall characteristics, including research reporting an optimum NR content of 5% [13]. Other investigations have addressed rejuvenation and rheological changes in aged asphalt [24], [25], but the combined effect of NR and simulated aging on RAP-based HRS-WC mixtures remains insufficiently evaluated. In particular, the performance of NR-rejuvenated RAP mixtures under unaged, Short-Term Oven Aging (STOA), and Long-Term Oven Aging (LTOA) conditions requires further investigation.

Therefore, this study evaluates the performance of RAP-based HRS-WC mixtures incorporating NR under unaged, STOA, and LTOA conditions. The assessment focuses on stiffness, fatigue resistance, and dynamic creep to determine the effectiveness of NR in mitigating the effects of aged RAP binder and improving the long-term performance of sustainable recycled asphalt mixtures.

2. RESEARCH METHOD

The study was conducted in connection with the *Scraping, Filling, and Overlay* (SFO) project on the Bali Mandara Toll Road. The laboratory phase of the study was carried out at the Highway Laboratory, Civil Engineering Program, Faculty of Engineering, Udayana University, Bukit Jimbaran. The primary equipment employed to determine the stiffness characteristics of the asphalt mixtures was the Dynapave UTM 30, which is available at the Highway Laboratory of the Faculty of Engineering, Udayana University.

Research Procedure:

The RAP material used in this study was obtained from the *cold milling* of the existing pavement layer from the SFO project on the Bali Mandara Toll Road. Sampling was performed at the RAP stockpile using a *composite sampling* method, with materials collected from several different locations to obtain a representative sample. The collected RAP was subsequently transported to the laboratory for extraction testing to determine the asphalt content, aggregate gradation, and other relevant material characteristics. The characterization results were then used as the basis for designing the HRS-WC mixture incorporating Natural Rubber (NR) as a rejuvenating agent.

The HRS-WC mixture contained 68.3% RAP by total aggregate mass. A total of 1,291.5 g of RAP material was used and supplemented with 599.8 g (31.7%) of virgin aggregate, resulting in a total aggregate mass of 1,891.3 g. The additional aggregate was proportioned to adjust the combined gradation so that it satisfied the specified HRS-WC gradation envelope.

Following the mixture design, HRS-WC specimens with varying NR contents were prepared and subjected to different aging conditions to investigate changes in their mechanical characteristics. One specimen ($n = 1$) was tested for each NR content and aging condition for the ITSM, dynamic creep, and ITFT evaluations. Therefore, the reported values represent individual test results rather than mean values, and standard deviation and error bars could not be calculated. Short-Term Oven Aging (STOA) was applied to represent the aging that occurs during the production, transportation, and placement of asphalt mixtures. The STOA treatment was performed by conditioning the asphalt mixture in an oven at approximately 135°C for 4 hours, following the AASHTO R30 procedure.

Long-Term Oven Aging (LTOA) was subsequently applied to simulate the aging experienced by asphalt mixtures throughout their service life. The LTOA treatment was conducted by conditioning the compacted specimens in an oven at 85°C for 5 days, in accordance with AASHTO R30. After the aging treatments, the specimens were evaluated through mechanical performance tests covering stiffness, permanent deformation resistance, and fatigue resistance. The resulting data from the unaged, STOA, and LTOA conditions were compared to determine the effects of NR incorporation and aging on the mechanical performance of RAP-based HRS-WC mixtures.

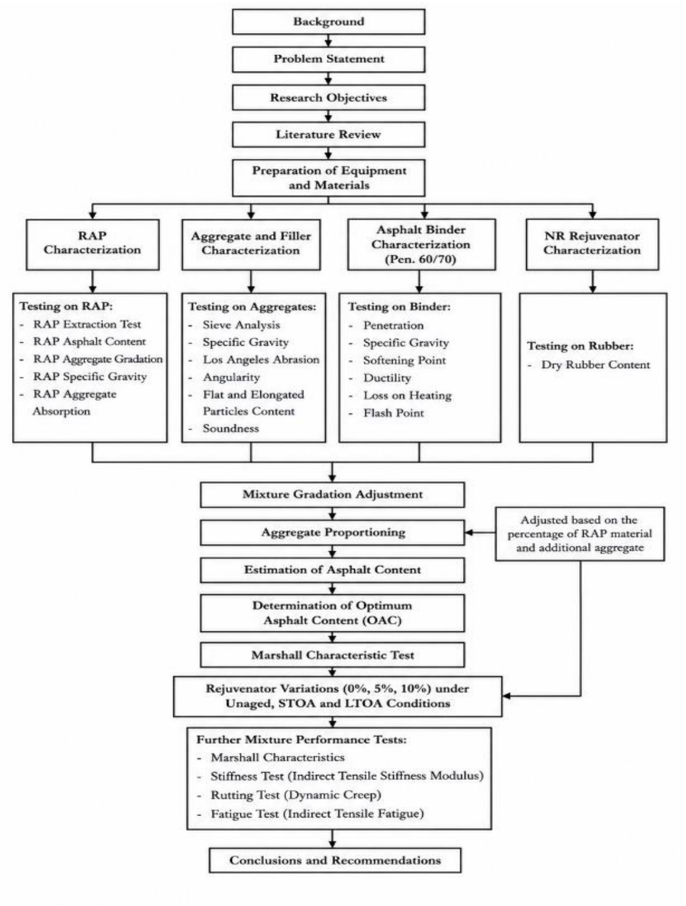

Figure 1. Research Flowchart

3. RESULTS AND DISCUSSION

The mechanical performance of RAP-based HRS-WC asphalt mixtures incorporating Natural Rubber (NR) was investigated under unaged, Short-Term Oven Aging (STOA), and Long-Term Oven Aging (LTOA) conditions. The mixtures were prepared with three NR contents, namely 0%, 5%, and 10% by weight of RAP asphalt, to evaluate the influence of NR incorporation on the behavior of recycled asphalt mixtures subjected to different aging conditions. The performance evaluation consisted of three principal mechanical parameters: stiffness, deformation resistance, and fatigue resistance. Stiffness was evaluated using the Indirect Tensile Stiffness Modulus (ITSM) test, while deformation behavior was assessed through the dynamic creep test. Fatigue performance was evaluated based on the number of loading cycles to failure under repeated loading. The results from these tests are presented separately to examine the effects of NR content and aging condition on the mechanical response of the RAP-based HRS-WC mixtures.

Data Analysis of Sample Test Results:

3.1 Indirect Tensile Stiffness Modulus (ITSM)

Table 1. Summary of Stiffness Characteristics of Unaged RAP Asphalt Mixtures with Different Natural Rubber (NR) Rejuvenator Contents

Mixture Type	ITSM (Mpa)
RAP Mixture with 0% NR Rejuvenator	15.775
RAP Mixture with 5% NR Rejuvenator	15.575
RAP Mixture with 10% NR Rejuvenator	15.318

Table 2. Summary of ITSM Values for STOA-Aged Asphalt Mixtures with Different Rejuvenator Contents

Mixture Type	ITSM (Mpa)
RAP Mixture with 0% NR Rejuvenator (STOA Condition)	15.827
RAP Mixture with 5% NR Rejuvenator (STOA Condition)	15.683
RAP Mixture with 10% NR Rejuvenator (STOA Condition)	15.550

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Table 3. Summary of ITSM Values for LTOA-Aged Asphalt Mixtures with Different Rejuvenator Contents

Mixture Type	ITSM (Mpa)
RAP Mixture with 0% NR Rejuvenator (LTOA Condition)	16.250
RAP Mixture with 5% NR Rejuvenator (LTOA Condition)	16.050
RAP Mixture with 10% NR Rejuvenator (LTOA Condition)	15.988

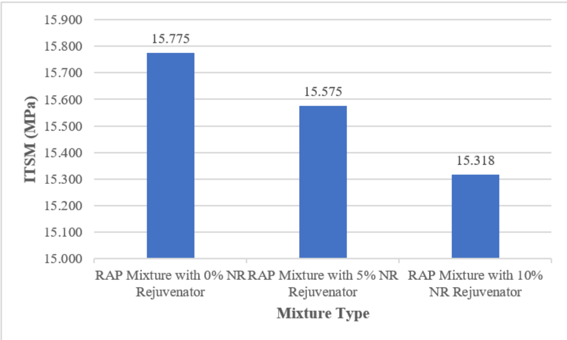

Figure 1. ITSM Values of Unaged Asphalt Mixtures with Different Rejuvenator Contents

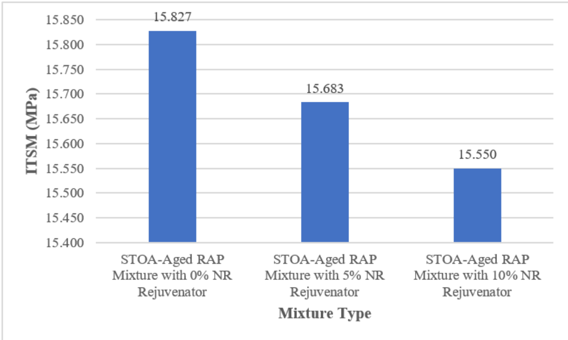

Figure 2. ITSM Values of STOA-Aged Asphalt Mixtures with Different Rejuvenator Contents

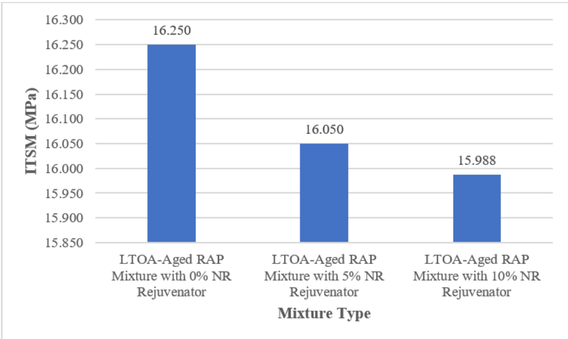

Figure 3. ITSM Values of LTOA-Aged Asphalt Mixtures with Different Rejuvenator Contents

Based on the results of the ITSM tests, increasing the Natural Rubber (NR) content in the RAP mixture tends to reduce stiffness values under all test conditions, namely without aging, STOA, and LTOA. This decrease indicates that NR acts as a rejuvenating agent that enhances the elastic properties and flexibility of the binder, thereby reducing the stiffness of the mixture caused by RAP asphalt aging. On the other hand, STOA and LTOA treatments consistently increased the ITSM values across all mixture variations as a result of oxidation, evaporation of light fractions, and binder hardening during the aging process. The highest stiffness value was obtained in the mixture without NR addition, while the lowest value was found in the mixture with a 10% NR content. These findings indicate that the use of NR is effective in restoring the flexibility of RAP mixtures, while the aging process remains the dominant factor increasing the stiffness of asphalt mixtures.

3.2 Permanent Deformation Resistance

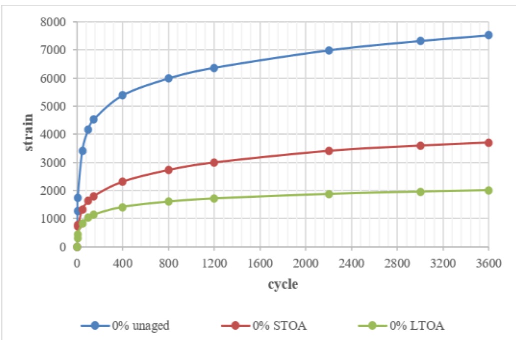

Figure 4. Creep slope values for unaged mixtures

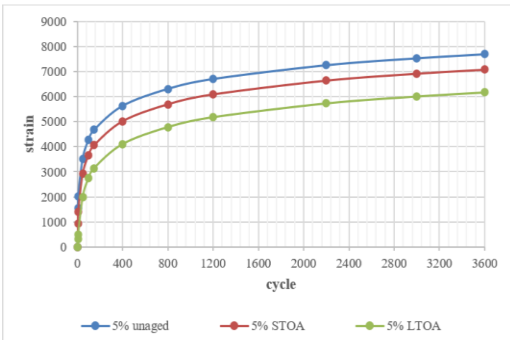

Figure 5. Creep slope values for STOA mixtures

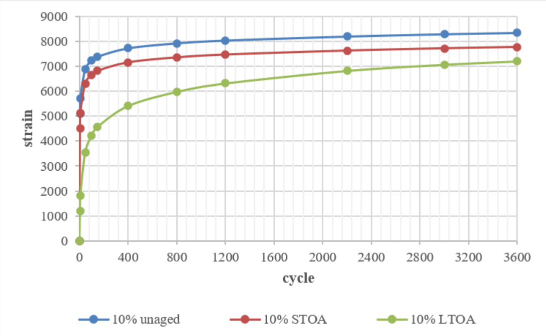

Figure 6. Creep slope values for LTOA mixtures

Table 4. Creep Slope Values of RAP-Based HRS-WC Mixtures Under Different Aging Conditions

NR	Unaged	STOA	LTOA
0% NR	0,4823	0,2956	0,1222
5% NR	0,4126	0,4126	0,4126
10% NR	0,1284	0,1284	0,3705

Based on the dynamic creep test results, the creep response of RAP-based HRS-WC mixtures varied with NR content and aging condition. Under unaged conditions, the 10% NR mixture exhibited the lowest creep slope (0.1284), indicating the greatest resistance to permanent deformation, whereas the 0% NR mixture showed the highest creep slope (0.4823). After STOA, the 10% NR mixture maintained the lowest creep slope (0.1284), while the 5% NR mixture exhibited the highest value (0.4126). Under LTOA, the 0% NR mixture produced the lowest creep slope (0.1222), followed by the 10% NR (0.3705) and 5% NR (0.4126) mixtures. These results indicate that the influence of NR on permanent deformation resistance depends on both NR dosage and the aging condition. aging level plays an important role in controlling the creep response of RAP mixtures, with 10% NR providing the most favorable permanent deformation resistance performance.

3.3 Indirect Tensile Fatigue Test (ITFT)

Table 5. Summary of Fatigue Resistance Values of Asphalt Mixture

Description	Nf	Tensile Stress	Strain
HRS-WC 0% NR			
Unaged	6951	1300	308
STOA	1291	1300	187
LTOA	261	1300	111
HRS-WC 5% NR			
Unaged	6311	1300	311
STOA	821	1300	203
LTOA	411	1300	120
HRS-WC 10% NR			
Unaged	10311	1300	539
STOA	2111	1300	217
LTOA	611	1300	137

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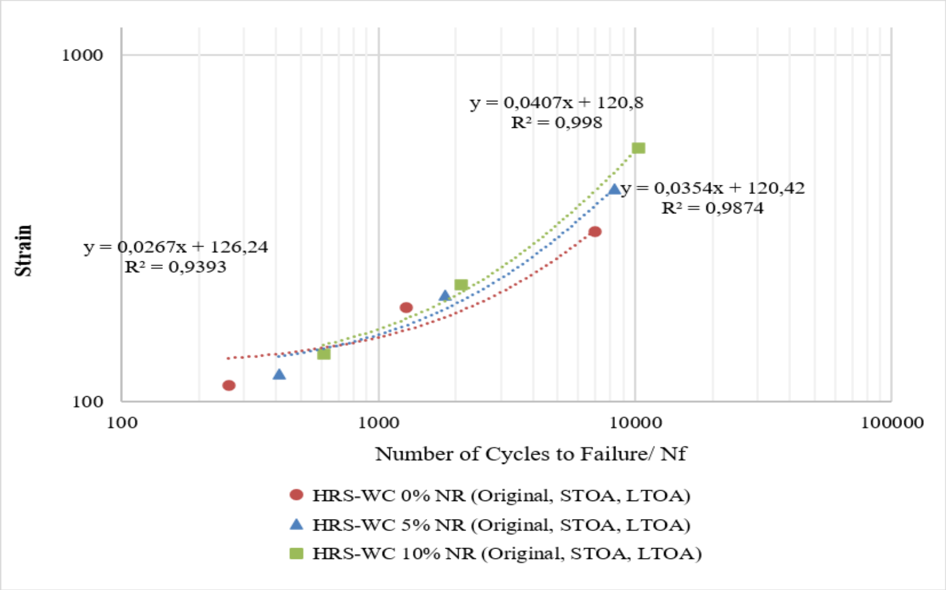

Figure 7. Relationship Between Number of Cycles to Failure (Nf) and Strain during the Indirect Tensile Fatigue Test (ITFT)

The ITFT results showed that the fatigue response of the HRS-WC mixtures was dependent on NR dosage and aging condition. The incorporation of 5% NR did not consistently improve fatigue resistance compared with the 0% NR mixture. Under unaged and STOA conditions, the 5% NR mixture exhibited lower Nf values (6,311 and 821 cycles, respectively) than the corresponding 0% NR mixture (6,951 and 1,291 cycles). Under LTOA conditions, however, the 5% NR mixture exhibited a higher Nf value of 411 cycles compared with 261 cycles for the 0% NR mixture. In contrast, the 10% NR mixture consistently exhibited the highest Nf values under all aging conditions, reaching 10,311 cycles under unaged conditions, 2,111 cycles after STOA, and 611 cycles after LTOA. These results indicate that the influence of NR on fatigue resistance was dosage-dependent, with 10% NR providing the most favorable fatigue performance among the investigated NR contents.

4. CONCLUSION

Based on the mechanical performance evaluation of RAP-based HRS-WC mixtures incorporating Natural Rubber (NR), the addition of NR was associated with changes in the stiffness, deformation resistance, and fatigue performance of the asphalt mixture. The incorporation of NR tended to reduce the stiffness modulus (ITSM), which may be related to the increased elasticity and flexibility of the binder, while aging treatments (STOA and LTOA) tended to increase mixture stiffness due to binder hardening and oxidation. In terms of deformation resistance, the mixture containing 10% NR demonstrated comparatively lower permanent strain accumulation, as indicated by its lower creep slope values. Aging treatments generally resulted in lower strain levels and higher mixture stiffness, which tended to limit permanent deformation. Regarding fatigue performance, the incorporation of NR tended to increase the mixture's resistance to repeated loading and higher strain levels, with the 10% NR mixture showing the highest Number of Cycles to Failure (Nf) under the tested conditions. Although aging treatments tended to reduce Nf and strain capacity across the mixtures, the 10% NR mixture consistently exhibited comparatively better fatigue performance. Overall, based on the observed mechanical performance, the incorporation of 10% Natural Rubber as a rejuvenating agent in RAP-based mixtures showed the most favorable balance among flexibility, deformation resistance, and fatigue cracking resistance, although it was accompanied by a slight reduction in mixture stiffness.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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