

LABORATORY STUDY ON THE PERFORMANCE OF AC28 - BINDER COURSE WITH INCREASING RAP CONTENT UP TO 50% AND RECOMMENDED REJUVENATOR DOSAGE

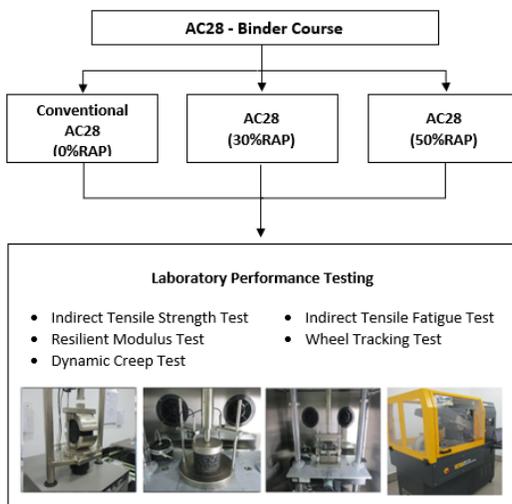
Teh Sek Yee*, Mohd Azli Ayob, Mohammad Riad Ramzi, Dini Dayana Mustaffa Kamal

United Engineers Malaysia Edgenta (UEMED) Research & Development Centre, Pavement Research Center (PRC), No. 21, Jalan Kamunting 2, Kawasan Perindustrian Jalan Kamunting, Bukit Beruntung, 48300, Selangor, Malaysia

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*Corresponding author
 ericteh@edgenta.com

Graphical abstract



Abstract

The pavement industry in Malaysia has embraced the use of environmentally friendly technologies and sustainable practices, one of which is the use of reclaimed asphalt pavement (RAP) in asphalt pavement. To support this initiative, a study was conducted to assess the performance of a Hot Asphalt Mix (HMA) of Asphaltic Concrete Binder Course (AC28 - Binder Course) with varying percentages of RAP content consisting of 0%RAP, 30%RAP and 50%RAP. Exploring higher RAP content in asphalt mixes will contribute to achieving environmental sustainability in road construction and maintenance practices. The performance of the asphalt mixtures in this study was assessed using a series of laboratory evaluations, including the Indirect Tensile Strength, Resilient Modulus, Dynamic Creep, Wheel Tracking, and Indirect Tensile Fatigue tests. Additional bitumen tests were conducted to verify the influence of rejuvenators on high-RAP binders and to establish the required dosage according to the condition of locally sourced RAP.

Keywords: binder course, RAP, rejuvenator, lab testing

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1.0 INTRODUCTION

The recycling of reclaimed asphalt pavement (RAP) has become an integral component of sustainable road construction worldwide. Initially driven in the 1970s by the rising costs of petroleum-based products, RAP recycling is now recognized as a standard practice for balancing environmental, economic, and technical objectives in pavement engineering [1–3]. By incorporating RAP into asphalt mixtures, the consumption of virgin aggregates and bitumen can be significantly reduced, contributing to lower production costs, conservation of natural resources, and reduced carbon emissions [4–8].

In Malaysia, RAP recycling aligns with the national agenda to achieve a 45% reduction in carbon emissions by 2030. Companies such as Edgenta PROPEL Berhad and the UEM Edgenta Pavement Research Centre (PRC) have spearheaded

research and field trials to accelerate the adoption of high-RAP mixtures under local climatic and traffic conditions. Previous studies in Malaysia demonstrated that asphalt concrete wearing and binder courses with up to 30% RAP content can perform comparably to conventional Hot Mix Asphalt (HMA), supporting its use in large-scale rehabilitation works [9–11].

Despite its benefits, the use of RAP at higher proportions introduces several challenges. Variability in RAP properties, particularly binder stiffness due to aging, can compromise mixture durability, flexibility, and resistance to fatigue cracking [12–15]. Laboratory and field evaluations worldwide suggest that RAP contents above 30% may require rejuvenating agents or softer binders to restore aged binder properties, improve workability, and maintain long-term performance [16–18]. However, the additional costs and handling requirements of

rejuvenators can limit their large-scale application in developing regions.

Recent studies have begun exploring the feasibility of using higher RAP percentages without rejuvenators by optimizing mix design parameters such as aggregate gradation, binder content, and compaction practices. For example, mixtures containing 40–50% RAP have shown promising improvements in stiffness and rutting resistance, though often at the expense of fatigue life [19–20]. These findings underscore the importance of balancing the structural advantages of stiffer mixes with the durability concerns associated with aged binders.

Building on this body of knowledge, the present study investigates the laboratory performance of Asphaltic Concrete Binder Course (AC28 - Binder Course) incorporating 0%, 30%, and 50% RAP without the use of rejuvenators. The objective is to evaluate how increasing RAP content influences key mechanical properties including tensile strength, stiffness modulus, permanent deformation, fatigue resistance, and rutting performance, to identify the trade-offs involved in high-RAP mixtures under Malaysian conditions. This research aims to provide practical insights for the wider adoption of RAP-based pavement technologies that support sustainable infrastructure development.

2.0 METHODOLOGY

The asphalt mix design followed the Marshall procedure in accordance with ASTM D6926 and ASTM D6927 to determine the optimum bitumen content (OBC) for the conventional AC28 - Binder Course mixture. Aggregate gradation was established through sieve analysis, while the mixture volumetric properties including air voids, voids in mineral aggregates (VMA) and voids filled with bitumen (VFB) were measured following ASTM D2726. The OBC for AC28 - Binder Course was determined to be 4.90%. A summary of the Marshall and volumetric properties is shown in Table 1.

Table 1 Summary of Marshall Properties for AC28 - Binder Course

Marshall Properties	Properties at Optimum Bitumen Content (4.90%)	Specifications for AC28 - Binder Course 60/70 Pen. Bitumen
Density (Mg/m ³)	2.344	-
Stability (kg)	1,750	> 900 kg
Air Voids (%)	3.2	3 – 6 %
Voids Filled with Binder (%)	78.0	70 – 78 %
Flow (mm)	3.5	2 – 4 mm

The RAP used in this study was obtained from milling works carried out on the North–South Expressway. The collected RAP was subsequently processed through fractioning and screening at a dedicated RAP processing plant, as illustrated in Figure 1. The physical properties of the processed RAP aggregates are presented in Table 2. The RAP specifications shown in Table 2 were evaluated based on the Malaysian Public Works Department requirements, which permit up to a 20% deviation relative to the corresponding virgin aggregate specifications.



Figure 1 RAP after Fractioning and Screening into Different Sizes

Table 2 RAP Aggregate Properties

Aggregate Property	Result	Specifications
Aggregate Crushing Value (%)	22.57	< 30
10% Fines Value (kN)	223.71	> 128
Flakiness Index (%)	23.45	< 36
Specific Gravity – 19 mm RAP (Mg/m ³)	2.634	-
Specific Gravity – 6.4 mm RAP (Mg/m ³)	2.552	-
Water Absorption – 19 mm RAP (%)	0.768	< 2
Water Absorption – 6.4 mm RAP (%)	0.103	< 2

The recycled asphalt mixtures must also account for the bitumen content in the RAP which contributes to the overall bitumen content in the asphalt mix [21]. Hence, the recycled asphalt mixes with varying RAP content requires virgin bitumen content that was calculated based on the following formula.

$$E = C - (A \times B / 100)$$

where:

A = RAP bitumen content (%)

B = percentage of RAP content in the asphalt mixture (%)

C = target bitumen content in the asphalt mixture (OBC) (%)

E = required virgin bitumen content to be added (%)

The next step was the sample preparation where virgin aggregates were preheated to 170°C for at least four hours, while RAP was separately heated to 110°C to minimize further binder aging. The preheated aggregates and RAP were dry-mixed with hydrated lime before introducing the 60/70 penetration grade bitumen at 160°C. Wet mixing was then performed to achieve a uniform coating. The final mixture was compacted in preheated Marshall molds using 75 blows per face at 150°C.

A series of performance tests were conducted to evaluate the influence of RAP content on the mechanical properties of AC28 - Binder Course:

- Indirect Tensile Strength (ITS) Test: Conducted following AASHTO T283 to assess moisture susceptibility. The tensile strength ratio (TSR) was calculated based on the difference in results between the conditioned and unconditioned samples;
- Resilient Modulus (M_R) Test: Conducted at test temperatures of 25°C and 40°C following ASTM D4123. The M_R value was calculated based on the applied stress and the corresponding recoverable strain;
- Dynamic Creep Test: Conducted as per BS EN 12697-25 (Method A) to evaluate permanent deformation under cyclic uniaxial stress loading (300 kPa, 3600 cycles);
- Indirect Tensile Fatigue Test (ITFT): Performed using BS EN 12697-24 (Annex E) to measure fatigue life under repeated dynamic loading at 25°C; and
- Wheel Tracking Test: Conducted in line with BS EN 12697-22 to assess rutting susceptibility. Slab specimens (400 × 300 × 60 mm) fully submerged in water were tested under a load of 700 N at 60°C for up to 10,000 cycles or until 20 mm rut depth.

These tests collectively provided insight into the tensile strength, stiffness, deformation resistance, fatigue behavior and rutting performance of AC28 - Binder Course mixtures with varying RAP contents.

Lastly, study was carried out on RAP bitumen properties and the effects of rejuvenator on binder properties using multiple rejuvenating agents. A total of three (3) rejuvenators were used to restore the original properties of the oxidised and aged bitumen in the RAP. These rejuvenators were sourced from multiple suppliers and tested with the recovered RAP bitumen to determine the optimum dosage and cost-effectiveness. The bitumen present in the RAP was extracted using methylene chloride in a centrifuge binder extractor, after which the recovered binder was processed with a Binder Recovery unit to remove the solvent. The recovered RAP binder was subsequently blended with the rejuvenator after which the virgin bitumen was incorporated using a High Shear Mixer to ensure adequate dispersion and homogeneity as shown in Figure 2. The Penetration and Softening Point of the blended bitumen were evaluated according to ASTM standards to ensure that its properties were comparable to those of virgin bitumen.



Figure 2 Mixing of Rejuvenator, Recovered RAP Binder and Virgin Bitumen

3.0 RESULTS AND DISCUSSION

3.1 Moisture Susceptibility and Tensile Strength

For indirect tensile strength test, the results for the asphalt mixes with increasing RAP content are as shown in Table 3.

Table 3 Summary of Indirect Tensile Strength Test Result

Mix Description	Indirect Tensile Strength (MPa)		Tensile Strength Ratio (%)
	Unconditioned	Conditioned	
Conventional AC28 - Binder Course (No RAP)	0.915	0.763	87.47
AC28 - Binder Course 30% RAP	1.501	1.313	83.38
AC28 - Binder Course 50% RAP	2.186	1.774	81.14

Table 3 shows that the TSR values are above the 80% threshold. This indicates that these asphalt mixes are not susceptible to moisture damage, according to AASHTO T283. The fact that it has good tensile strength retention after conditioning suggests that it will likely maintain its performance and durability when exposed to moisture.

Among the mixes, the Conventional AC28 - Binder Course (No RAP) has the highest TSR value, indicating the highest resistance to aging and deterioration under the given conditioning conditions. This suggests that the Conventional AC28 - Binder Course (No RAP) mixture may provide better long-term performance and durability than the other mixes mentioned. Interestingly, the tensile strength increased with RAP content, with the 50% RAP mixture exhibiting the highest ITS values. This improvement can be attributed to the stiffened binder and enhanced aggregate interlock present in RAP, which strengthens the mixture structure. However, the slightly lower TSR values in RAP mixtures suggest a reduction in binder flexibility, which could affect long-term cracking performance. Similar findings have been reported in other high-RAP studies where stiffness gains coincided with reduced flexibility [22].

3.2 Stiffness and Resilient Modulus

The Resilient Modulus (M_R) of HMA can indicate the stiffness of the mix. Figure 3 shows the M_R results after Indirect Tensile Stiffness Modulus (ITSM) Test.

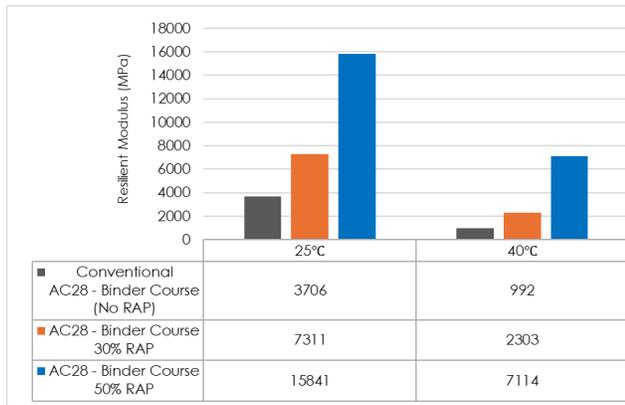


Figure 3 Resilient Modulus (M_R) of AC28 - Binder Course

Based on the graph shown in Figure 3, increasing the percentage of RAP content in the asphalt mixture generally increases the M_R at 25°C and 40°C. The M_R is a measure of the stiffness of the mixture and its ability to resist deformation under load. The 50% RAP mixture recorded the highest stiffness. This trend is consistent with global observations that RAP increases mixture stiffness due to the presence of aged binder. The higher RAP content contributes to an increase in M_R due to factors such as enhanced aggregate interlock and the stiffness of the aged binder. However, it is important to find the right balance, as excessive RAP content can not only negatively affect the mixture workability, durability and long-term performance, but it also raises concerns over cracking susceptibility under repeated traffic loading and thermal stresses. Thus, balancing stiffness and durability remains a key challenge in designing high-RAP mixes.

3.3 Permanent Deformation and Rutting Resistance

Table 4 shows the dynamic creep test results for 0% RAP, 30% RAP and 50% RAP asphalt mixes. Figure 4 compares the permanent deformation test results. The results provide information on the performance of the mixtures regarding their resistance to permanent deformation (rutting) and their ability to withstand repeated loading. Table 5 shows the wheel tracking test results for rut depth.

Table 4 Summary of Dynamic Creep Test Results

Mix Description	Permanent Deformation (mm)	Dynamic Creep Modulus (MPa)
Conventional AC28 - Binder Course (No RAP)	0.439	44.7
AC28 - Binder Course 30% RAP	0.319	61.5
AC28 - Binder Course 50% RAP	0.206	95.1

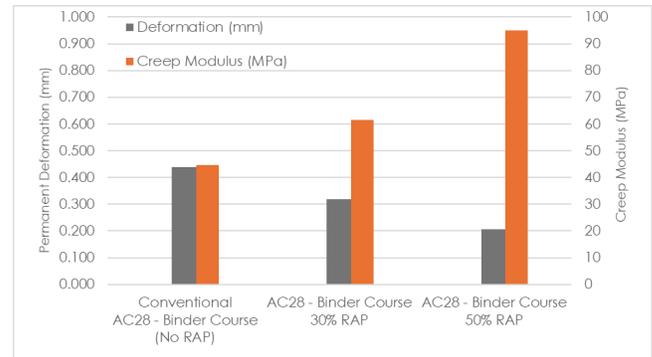


Figure 4 Permanent Deformation and Dynamic Creep Modulus Results of AC28 - Binder Course

Table 5 Summary of Wheel Tracking Test Results

Mix Description	Rut Depth (mm)
Conventional AC28 - Binder Course (No RAP)	9.19
AC28 - Binder Course 30% RAP	2.58
AC28 - Binder Course 50% RAP	1.97

The 50% RAP mixture achieves the lowest rut depth and highest creep modulus, confirming its superior resistance to rutting. These results align with the Wheel Tracking Test outcomes, where the 50% RAP mix records the lowest rut depth of 1.97 mm compared to 9.19 mm in the conventional mix. The improvement in rutting resistance can be explained by the increased stiffness and load-bearing capacity imparted by RAP aggregates and binder, thereby potentially decreasing the risk of permanent deformation.

3.4 Fatigue Cracking Resistance

Table 6 and Figure 5 show the stress levels and fatigue life relationships for 0% RAP, 30% RAP and 50% RAP asphalt mixes.

Table 6 Summary of Indirect Tensile Fatigue Test Results

Mixture Description	Stress level (kPa)	Cycles to Failure (N_f)
Conventional AC28 - Binder Course (No RAP)	650	244
	800	138
	950	101
AC28 - Binder Course 30% RAP	650	3244
	800	2008
	950	538
AC28 - Binder Course 50% RAP	1550	441
	1700	151
	1800	64

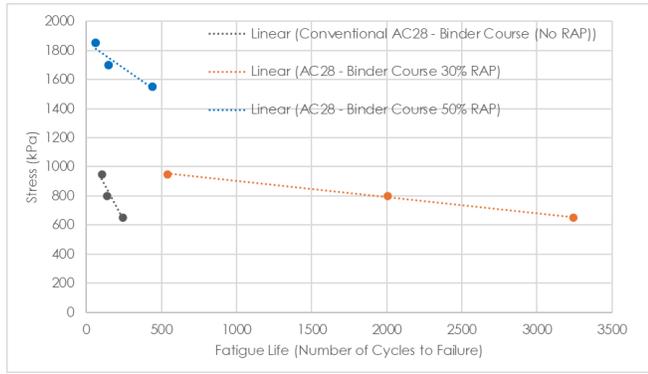


Figure 5 Stress vs Fatigue Life of AC28 - Binder Course

Based on the results presented in Table 6, It is important to note that the fatigue results for the 50% RAP mixture were obtained at higher applied stress levels compared to the 0% and 30% RAP mixes. Due to the significantly higher stiffness of the 50% RAP mixture, these elevated stress levels were necessary to generate comparable tensile strains and to ensure that specimen failure occurred within a practical testing cycle limit. As a result, the AC28 - Binder Course mixture with 50% RAP exhibits lower fatigue life under the higher applied stresses and shows greater fatigue sensitivity, as illustrated in Figure 5. In contrast, the 30% RAP mixture demonstrates notably better fatigue performance and is the least sensitive to increasing stress levels, indicating that moderate RAP content enhances fatigue resistance while very high RAP content reduces mixture flexibility. Therefore, for better fatigue resistance, the AC28 - Binder Course mixture with 30% RAP is preferable over the 50% RAP mixture, highlighting the importance of optimising RAP content for desired performance in asphalt mixtures.

However, adding a rejuvenator to the AC28 - Binder Course mixture with 50% RAP may potentially enhance fatigue performance as rejuvenators help to restore the aging properties of RAP, improving flexibility, durability, and fatigue resistance [23]. This leads to increased elasticity, reduced stiffness, and improved resistance to fatigue cracking in the mixture.

3.5 Selection of Rejuvenator Dosage

An examination of RAP bitumen properties and the reaction to various rejuvenators on bitumen properties based on 50% RAP content were conducted at PRC. The study involved testing three (3) rejuvenators from different suppliers, each used at a specific dosage. The study aimed to assess their effectiveness in restoring the aged and oxidised bitumen in the RAP to a level comparable to conventional 60/70 pen. bitumen. The different dosages recommended by supplier were based on the total weight of recovered RAP bitumen. These studies considered factors such as optimum dosage and cost-effectiveness. Table 7 shows the properties of virgin bitumen and recovered RAP bitumen. Meanwhile, Table 8 shows the properties of recovered RAP bitumen blended with virgin bitumen and rejuvenator.

Table 7 Properties of the Virgin Bitumen and Recovered RAP Bitumen

Description	Penetration (0.1mm)	Softening Point (°C)
Virgin Bitumen	58	52.0
RAP Bitumen	< 10	78.0

Table 8 Properties of the Recovered RAP Bitumen Blended with Virgin Bitumen and Rejuvenator

Rejuvenator	Recommended Dosage (%)	Penetration (0.1mm)	Softening Point (°C)
Reju-X	8	45	-
	10	51	-
	12	56	48.3
Reju-Y	11	35	-
	13	42	54.3
	15	80	-
Reju-Z	8	25	-
	10	30	-
	12	59	51.4

The rejuvenators were evaluated based on two main criteria which are their ability to restore the binder's Penetration value and Softening Point to levels similar to the virgin binder, and the consistency of their performance with varying dosages. Based on the results, the optimum rejuvenator dosage by total weight of recovered RAP bitumen for Reju-X, Reju-Y and Reju-Z are 12%, 13% and 12%, respectively. The results indicate all rejuvenators have successfully restored the binder properties, improving the aging characteristics of the reclaimed binder from RAP. Higher dosages required more than the initial recommended dosage proposed by the supplier were needed for all rejuvenators due to the excessive stiffness and aging of the reclaimed binder. Further recycled asphalt mixture performance test is required to evaluate the performance of AC28 - Binder Course mixture with 50% RAP using rejuvenator.

4.0 CONCLUSION

The introduction of RAP with varies percentages in the asphalt mixes, even without a rejuvenator, had resulted in the mixes having good tensile strength and lower susceptibility to moisture damage. Higher RAP content mixes that contained aged binder had also demonstrated increase in stiffness as well as rutting and deformation resistance under loading.

The evaluation of the AC28 - Binder Course asphalt mixtures incorporating 30% and 50% RAP content demonstrated that RAP percentage played a critical role in determining fatigue performance. The mixture containing 30% RAP exhibited superior fatigue resistance, indicating that lower RAP contents can help maintain adequate flexibility and delay fatigue cracking. Conversely, the mixture with 50% RAP showed

reduced fatigue performance, likely due to increased stiffness associated with higher proportions of aged binder.

However, the introduction of a rejuvenator into the 50% RAP mixture presented a viable solution for overcoming these limitations. The rejuvenators helped to restore the aged binder's chemical and physical characteristics, enhancing flexibility, elasticity, and overall durability. This suggested that, with proper rejuvenation treatment, mixture with high RAP content may achieve fatigue performance comparable to or better than mixture with lower RAP content, optimising sustainability without compromising structural integrity.

Therefore, it is important to optimise the RAP content for desired performance in asphalt mixes. It is highly recommended to incorporate rejuvenators to restore the aged RAP binder properties for mixtures with RAP content above 30%.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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