Jurnal
Teknologi

Full Paper

FIELD PERFORMANCE OF HOT IN-PLANT PRODUCED ASPHALTIC CONCRETE WEARING COURSE (ACWC) WITH 30% RECLAIMED ASPHALT PAVEMENT (RAP)

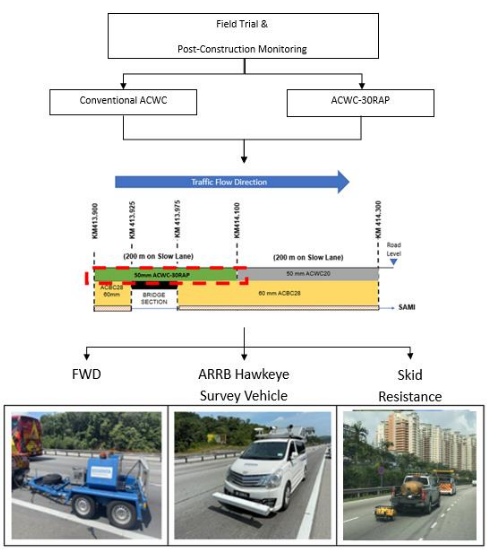
Sek Yee Teh[a]*, Md Yunus Ab Wahab[b], Nordin Yunus[b], Rino Effendy Abu Haris[a], Mohd Azli Ayob[a], Mohammad Riad Ramzi[a], Dini Dayana Mustaffa Kamal[a]

[a]United Engineers Malaysia Edgenta (UEMEd) Research & Development Centre, Pavement Research Center (PRC), Jalan Kamunting, Bukit Beruntung, 48300, Selangor, Malaysia
[b]Projek Lebuhraya Usahasama (PLUS) Berhad, Persada PLUS, Persimpangan Bertingkat Subang KM15, Lebuhraya Baru Lembah Klang, 47301, Petaling Jaya Selangor Darul Ehsan, Malaysia

Article history
Received
29 November 2023
Received in revised form
13 February 2024
Accepted
19 February 2024
Published Online
22 December 2024

*Corresponding author
ericteh@edgenta.com

Graphical abstract



Abstract

Hot in-plant recycling stands as an effective yet underutilized method in Malaysia for reusing pavement milling waste, resulting in insufficient established benchmarks and validated trials. The Utilization of Reclaimed Asphalt Pavement (RAP) can divert a significant amount of waste asphalt millings from landfills, while conserving energy and natural resources. This study focused on the recycled mixture, ACWC-30RAP, which integrated 30% Reclaimed Asphalt Pavement (RAP). In July 2022, a 400 m trial lay was conducted from KM413.90 to KM414.30 Southbound (SB), Section C3, along the PLUS North-South Expressway (NSE). Field tests were systematically conducted on both the ACWC-30RAP and conventional ACWC20 mixtures at different phases including month-6, month-9, and month-12 post-construction. The primary objective was to assess fundamental properties related to the structural stiffness of pavement layers as well as the pavement performance and condition for both trial sections using various field testing including Falling Weight Deflectometer (FWD) and Multi-Laser Profiler (MLP). Following the 12-month trial period, both the ACWC-30RAP and conventional ACWC20 mixtures experienced actual traffic loading and environmental conditions. Remarkably, the ACWC-30RAP demonstrated comparable field performance as the conventional ACWC20. This alignment in performance signified a promising avenue for employing the recycled mixture with high RAP content. Using ACWC-30RAP can also provide economic benefit, reducing the production cost by approximately 25%. In essence, the ACWC-30RAP had achieved an equivalent level of confidence to the conventional ACWC20 mixture, which was exclusively composed of virgin materials. This suggested the potential for production and application of ACWC-30RAP in expressway pavement rehabilitation projects.

Keywords: Hot-in plant recycling, ACWC20, 30% RAP, trial lay, field performance

Abstrak

Kitar semula di dalam loji panas merupakan kaedah yang efektif tetapi kurang dimanfaatkan di Malaysia bagi penggunaan semula sisa penghamparan lapisan jalan raya, dan menyebabkan kurangnya garis panduan yang ditubuhkan dan ujian yang disahkan. Penggunaan Reclaimed Asphalt Pavement (RAP) boleh menggantikan sejumlah besar sisa penghamparan lapisan jalan raya dan dalam masa yang sama dapat mengekalkan tenaga dan sumber semula jadi. Kajian ini memberi tumpuan kepada campuran yang dikitar semula ACWC-30RAP, yang meggunakan 30% RAP. Pada Julai 2022, ujian lapangan sepanjang 400 m dijalankan dari KM413.90 hingga KM414.10 Arah Selatan (SB), Seksyen C3, di Lebuhraya Utara-Selatan PLUS (NSE). Ujian lapangan dilakukan secara sistematik ke atas kedua-dua campuran ACWC-30RAP dan ACWC20 konvensional pada fasa yang berbeza, iaitu pada bulan-6, bulan-9, dan bulan-12 selepas pembinaan. Objektif utama adalah untuk menilai sifat-sifat asas berkaitan dengan keanjalan struktur lapisan penghamparan bagi kedua-dua bahagian ujian menggunakan pelbagai ujian lapangan termasuklah Falling Weight Deflectometer (FWD) and Multi-Laser Profiler (MLP). Selepas tempoh ujian 12 bulan, kedua-dua campuran ACWC-30RAP dan ACWC20 konvensional mengalami beban lalu lintas sebenar dan keadaan alam sekitar. Keputusannya, ACWC-30RAP menunjukkan prestasi lapangan yang setara dengan campuran ACWC20 konvensional. Kesepadanan prestasi ini telah menjanjikan kesesuaian dalam menggunakan campuran yang dikitar semula dengan kandungan RAP yang tinggi. Penggunaan ACWC-30RAP juga memberikan faedah ekonomi dengan mengurangkan kos pembuatan sebanyak kira-kira 25%. Pada dasarnya, ACWC-30RAP telah mencapai tahap keyakinan yang setara dengan campuran ACWC20 konvensional, yang terdiri secara eksklusif daripada bahan asli. Ini menunjukkan potensi untuk pembuatan dan penggunaan ACWC-30RAP dalam projek rehabilitasi jalan raya lebuhraya.

Kata kunci: Kitar semula panas, ACWC20, 30% RAP, ujian lapangan, prestasi lapangan

1.0 INTRODUCTION

Recycling existing asphalt pavement materials, such as Reclaimed Asphalt Pavement (RAP), to create new pavement materials offers significant savings in materials, costs, and energy. Aligned with the government's goal of reducing carbon emissions by 45% by 2030, Edgenta PROPEL Berhad (EPB) has initiated a green and sustainable waste management effort. To support this eco-friendly initiative, the UEM Edgenta Pavement Research Centre (PRC) has innovatively developed a new pavement product called ACWC-30RAP. This product is the result of research and development efforts focused on producing Hot Mix Recycling Asphalt. ACWC-30RAP incorporates RAP, obtained through cold milling of road construction waste, into the production of asphalt mixtures, enabling the reuse of materials and promoting sustainability in pavement construction.

Recycling Reclaimed Asphalt Pavement (RAP) has gained significant traction since the 1970s, largely influenced by factors like escalating inflation and higher crude oil costs [1]. The transition towards recycling asphalt pavement, initiated in the 1970s, has now become the norm rather than an exception due to its economic and eco-friendly advantages [2,3]. Reclaimed Asphalt Pavement (RAP) is acquired by milling deteriorated asphalt pavement. By blending RAP with fresh aggregates, high-quality asphalt mixtures can be created [4,5]. The Transportation Research Board [6] has classified Central Plant Recycling into two types: Cold Central Plant Recycling (CCPR), involving zero heat energy, and Hot Mix Recycling (HMR) which encompasses several key stages [7], initially, the existing pavement undergoes removal to a full or partial depth, allowing for the suitable resizing of Reclaimed Asphalt Pavement (RAP) materials. Following this, the appropriately sized RAP materials are processed at a Hot Central Plant Recycling unit. This step involves the integration of virgin aggregates, virgin bitumen, and a rejuvenating agent into the RAP materials. Finally, the resulting recycled asphalt mixture finds application either as a binder or a surfacing layer, based on the specific requirements or intended use within the pavement structure.

When Reclaimed Asphalt Pavement (RAP) is employed as a substitute for virgin aggregate in Hot Mix Asphalt (HMA), it serves as an artificial aggregate. This application results in a decreased reliance on virgin aggregates and a reduced necessity for expensive virgin asphalt binder. Additionally, utilizing RAP conserves energy, diminishes transportation expenses related to obtaining high-quality virgin aggregates, and potentially preserves natural resources [8-10].

When utilizing a high content of RAP, a key challenge arises from the variability in RAP aggregates, particularly the uneven distribution of bitumen coating, which impacts the performance of the recycled asphalt mixture [11,12]. The bitumen within the asphalt surface undergoes oxidation due to elevated temperatures and weathering effects, leading to increased stiffness and hardness [13,14]. This aging process progresses at a slower pace in recycled asphalt mixtures compared to traditional ones, mainly due to the presence of pre-existing aged bitumen in the RAP material [15]. Incorporating RAP also enhances the resistance of the recycled asphalt mixture against moisture damage and permanent deformation [16,17]. Nevertheless, the potential for premature cracking, attributed to the aged bitumen, poses a significant concern, especially in asphalt mixtures with RAP content exceeding 30% [18,19]. In such instances, the use of rejuvenators or softer grade virgin binders becomes necessary to restore the properties of aged bitumen [20]. These rejuvenators not only aid in restoring aged bitumen but also enhance the workability of asphalt mixtures with high RAP content [21].

In December 2021, ACWC-30RAP was developed at the UEM Edgenta Research & Development Centre - Pavement Research Centre (PRC) in Bukit Beruntung. ACWC-30RAP is a Hot In-Plant recycled asphalt mix with a 20mm nominal maximum aggregate size. It involved the use of 30% RAP and penetration grade (60/70 Pen) bitumen. For this research, ACWC-30RAP was developed for the wearing course layer that conforms to PLUS Specifications for ACWC20 with penetration grade (60/70 Pen) bitumen.

The performance of ACWC-30RAP was assessed through a trial on the PLUS North-South Expressway (NSE). The study involved comprehensive field testing, encompassing FWD, MLP equipped with Laser Crack Map, skid resistance tests, and pavement coring.

2.0 METHODOLOGY

The plant trial for ACWC-30RAP was conducted on 12 July 2022 at Lingkaran Premix Sdn. Bhd. (LPSB), Rawang. It was witnessed by representatives from PLUS, PRC, and Edgenta Infrastructure Services (EIS). The mix was produced in a specialized batch mixing plant equipped with recycling facilities, and the test outcomes were compared against the PLUS Specifications for ACWC20, employing a 60/70 pen. Bitumen.

The field trial commenced upon acceptance of the plant trial test results. Based on PLUS' approved pavement design and concurred by PLUS HQ, the treatment for the trial section involved 'MP110 + SAMI'. This method entailed milling the existing asphalt to a depth of 110 mm and subsequently laying a 60 mm layer of ACBC28 followed by a 50 mm layer of ACWC20/ACWC-30RAP atop a Stress Absorbing Membrane Interlayer (SAMI). The trial section was divided into two (2) sub-sections, i.e., one sub-section for ACWC-30RAP and the other for control ACBC28 (60/70 Pen), laid as a surfacing-layer. The pavement treatment options are as shown in Figure 1.

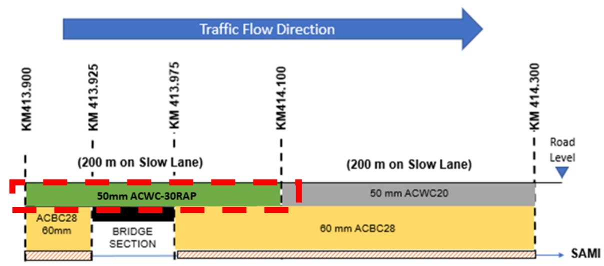


Figure 1 Schematic Diagram of Pavement Treatment Options

The post-performance monitoring of the pavement included quarterly assessments involving field testing, detailed analysis, evaluation, and observations specifically focusing on the performance of ACWC-30RAP and ACWC20. A summary of performance monitoring activities is shown in Table 1. The flow chart in figure 2 displays the progression of the field trial and pavement monitoring.

Table 1 Summary of Performance Monitoring Activities

Activities	Date
Field Trial	20 July 2022
Pavement Performance Monitoring Phase 1 (Month-0)	21 July 2022
Pavement Performance Monitoring Phase 2 (Month-6)	13 February 2023
Pavement Performance Monitoring Phase 3 (Month-9)	1 April 2023
Pavement Performance Monitoring Phase 4 (Month-12)	10 July 2023

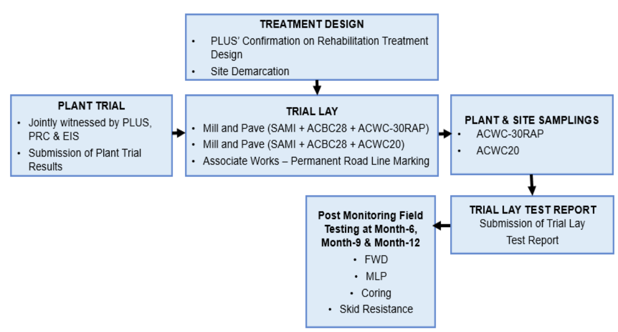


Figure 2 Flow Chart of ACWC-30RAP Trial Lay

To effectively monitor and assess the performance of the ACWC-30RAP trial lay, a series of field tests were conducted. These included the Falling Weight Deflectometer (FWD), Multi-Laser Profiler (MLP) equipped with Laser Crack Map functionality, skid resistance tests, and coring of the pavement. These tests were performed to comprehensively evaluate the condition and performance of the ACWC-30RAP section.

FWD tests on the Left Wheel Path (LWP) of the trial section were carried out on 13 February 2023 (Month-6), 11 May 2023 (Month-9) and 10 July 2023 (Month-12) to measure the deflection in the pavement when a falling weight impacts it. These tests were conducted at regular 20-meter intervals along the pavement. A photo of the FWD test in progress is shown in Figure 3.

Figure 3 FWD Test in Progress

Pavement temperature plays a crucial role in the accuracy of FWD test results and needs to be standardized to a common temperature. To address this, temperatures at depths ranging from 75 to 100 mm below the pavement surface and air temperatures were meticulously recorded during the post-construction testing phase. These recorded temperatures were subsequently compared with the baseline temperature obtained during pre-construction testing, enabling a comparison to evaluate any temperature-related variations impacting the FWD test outcomes.

MLP survey was carried out on 15 February 2023 (Month-6), 12 April 2023 (Month-9) and 10 July 2023 (Month-12). The survey utilized the Hawkeye 2000 road scanner, an MLP equipment and system developed by the Australian Road Research Board (ARRB) shown in Figure 4.

Figure 4 Scanning Road Surface by ARRB Hawkeye Survey Vehicle (Hawkeye 2000)

The ARRB survey vehicle efficiently captured road surface condition data at operational speeds, encompassing ride quality measurements such as the International Roughness Index (IRI), rutting measurements, and evaluations of surface cracks.

Coring works were performed on 13 February 2023 (Month-6), 11 April 2023 (Month-9) and 10 July 2023 (Month-12). A 100 mm diameter rotary core was employed to extract complete-depth asphalt samples from the trial sections, allowing for the examination of sample thickness and overall material condition. Figure 5 shows the coring works in progress.

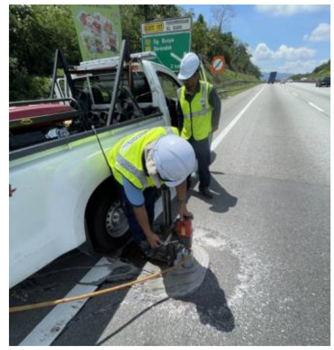


Figure 5 Coring Works in Progress

Skid resistance test was carried out on 14 April 2023 (Month-9) and 10 July 2023 (Month-12). The Grip Tester was used to evaluate the skid resistance, as shown in Figure 6. Skid resistance is a significant safety assessment parameter since low skid resistance can lead to skidding accidents and a lack of braking distance during emergency braking.

Figure 6 Mark 2 Grip Tester for Measuring Skid Resistance

3.0 RESULTS AND DISCUSSION

During the plant trial, loose ACWC-30RAP material was gathered and subjected to testing at the laboratory facilities under LPSB. The testing conducted aligned with the specified guidelines and the approved Inspection Test Plan (ITP). A summary of the plant trial test results is outlined in Table 2.

Table 2 Summary of Plant Trial Test Results for ACWC-30RAP

Descriptions	Plant Trial Test Results	PLUS Specification ACWC20 60/70 Pen. Bitumen
Marshall Stability (kg)	1693.9	**> 1000**
Refusal Air Voids (%)	3.1	**> 3**
Air Voids (%)	3.5	**3 – 5**
Voids Filled with Binder (%)	77.3	**77 – 83**
Flow (mm)	2.9	**2 – 4**
Stiffness value (kg/mm)	594.3	**≥ 350**
Immersion Index (%)	90.3	**> 80**
Optimum Bitumen Content (60/70 Pen. Grade with RAP) (% by Weight of Total Mix)	5.17	**OBC 5.4 (JMF 5.1 – 5.7 %)**

During the trial lay, the materials for ACWC-30RAP were collected to study the physical and rheological properties of the aggregates and binders both virgin and RAP. Table 3 displays the RAP and virgin aggregates properties. The RAP aggregates achieve the same specifications as virgin aggregates however considering the varying quality of the RAP, 20% deviation from the virgin aggregates specifications is permissible.

Table 3 Virgin Aggregates and RAP Aggregates Properties

Test	Virgin Aggregates	RAP Aggregates	PLUS Specifications
Aggregate Crushing Value (%)	21.2	24.71	< 25
10% Fines Value (kN)	221.7	224.04	> 160
Flakiness Index (%)	17.7	17.7	< 30

The rheological properties of the virgin bitumen and recovered RAP bitumen was tested and the results are shown Table 4. Currently, in Malaysia no standard can be referred to for rheological properties on extracted bitumen recovered from RAP which varies greatly depending on the RAP sources. The field trial will validate that at 30% RAP content, the aged bitumen would not compromise the pavement performance.

Table 4 Virgin Bitumen and RAP Recovered Bitumen Properties

Description	Virgin Bitumen Test Result	RAP Recovered Bitumen Test Results	Specification for 60/70 Pen Bitumen
Original Binder			
Penetration (0.1 mm)	63	13	60 - 70
Ring and Ball Softening Point (°C)	52.3	52.8	47 - 56
Ductility (mm)	100+	-	> 100
Flash Point (°C)	313	-	> 232
Dynamic Shear Rheometer G/sin δ at 64°C (kPa)	1.71	-	-
Binder After Rolling Thin Film Oven			
Mass Loss (%)	0.29	-	< 0.8

Loose samples of ACWC-30RAP mixture were taken from the site on the Slow Lane during the first day of the trial, dated 20 July 2022. The samples were taken to the PRC laboratory for further testing to ensure the asphalt mix meets all the specifications as part of the quality control and assurance. At PRC, riffling boxes reduced the samples into smaller representative portions. Initial test to determine its binder content and aggregate gradation was carried out, followed by preparation of the marshall pills to determine the Marshall properties. Table 5 shows a summary of the ACWC-30RAP trial lay test results. The ACWC-30RAP has fulfilled all PLUS specifications.

Table 5 Summary of Trial Lay Test Results for ACWC-30RAP

Descriptions	Conventional ACWC20	ACWC-30RAP	PLUS Specification ACWC20 60/70 Pen
Marshall Stability (kg), (Minimum) (Number of blows = 75)	1105	1356	**≥ 1000**
Flow Value (mm)	3.03	3.65	**2 – 4**
Air Voids (%)	3.5	3.5	**3 – 5**
Voids Filled with Binder (%)	77.9	77.5	**77 – 83**
Stiffness Value (kg/mm)	365.4	371.6	**≥ 350**
Bitumen Content (%) (60/70 Pen. Grade with RAP) (% by Weight of Total Mix)	5.36	5.16	**5.1 – 5.7**
Average Core Density (%)	98.8	98.3	**98 – 100**

The bitumen was extracted from the loose samples using the Centrifuge Binder Extractor and the loss of mass was measured to determine the bitumen content. After the bitumen extraction, the combined aggregates were oven-dried to remove all moisture before sieve analysis was carried out to determine the aggregate gradation. The results are shown in Table 6, both aggregate grading and bitumen content conform to PLUS Specifications for ACWC20.

Table 6 Aggregate Gradation and Bitumen Content Results for ACWC-30RAP

Aggregate BS Sieve Size (mm)	Percentage Passing (%)	PLUS Specification ACWC20 60/70 Pen
25.00	100.0	100
20.00	96.9	92 – 100
14.00	83.6	70 – 84
10.00	71.2	58 – 76
5.00	51.5	40 – 56
2.36	36.4	28 – 42
1.18	26.1	20 – 32
0.60	18.8	12 – 24
0.30	13.2	7 – 17
0.15	8.6	5 – 13
0.075	5.8	5 – 9
Bitumen Content	5.16	5.34% ± 0.3%

The FWD employ non-destructive testing methods to evaluate asphalt pavement performance. Widely adopted globally, the FWD effectively assesses the structural condition and load-bearing capacity of pavement layers, closely simulating real load conditions [22,23]. This monitoring is crucial for understanding the pavement's integrity.

During testing, variations in pavement response led to slight fluctuations in the FWD contact pressure from point to point. To ensure a consistent comparison of deflections across all test points, the FWD data were normalized to a standardized pressure of 0.7 MPa. Seven deflection readings, measured by geophones d1 to d7, were obtained at fixed radial distances (0, 0.3, 0.6, 0.9, 1.2, 1.5, and 2.1 meters) from the centre of the loading plate. Additionally, deviations in pavement temperature could impact the FWD test outcomes. Therefore, the FWD data were further adjusted to a standard temperature of 35°C to ensure uniformity. Table 7 outlines the key deflection parameters from the FWD that signify the overall performance of the pavement layers. The FWD central deflection (d_1) indicator used in interpreting the FWD test results are given in Table 8.

Table 7 FWD Key Deflection Parameters

Deflection Parameter	Description
Central Deflection (d_1)	Indicator of overall pavement response
Deflection difference (d_1-d_2) (d_2 = deflection at 0.3m radius)	Indicator of response from asphalt layers
Deflection difference (d_2-d_2) (d_4 = deflection at 0.9m radius)	Indicator of response from granular layers
Outer difference (d_6) (d_6 = deflection at 1.5m radius)	Indicator of response from subgrade

Table 8 FWD Central Deflection (d_1) Indicator

Pavement Condition	Central Deflection, d_1 (mm x 10^{-3})
Good	< 400
Fair	400 – 700
Poor	> 700

Statistical analysis was carried out to evaluate the FWD test results based on the key deflection parameters. The results are summarised in Table 9.

Table 9 Summary of FWD Test Results based on Key Deflection Parameters

	50th Percentile Deflection Parameter (mm x 10^{-3}) on Overall Deflection (d_1)		
Section	**Phase 2**	**Phase 3**	**Phase 4**
ACWC-30RAP	128	134	138
ACWC20	110	118	108

According to the data presented in Table 9, the 50th percentile central deflection (d1) consistently suggests that both ACWC-30RAP and ACWC20 trial sections maintain similar deflection measurements throughout the one-year monitoring period. These findings indicate that all the trial sections exhibit a consistent and good structural condition overall.

The qualitative evaluation of FWD deflection profiles allows for an assessment of the relative condition of pavement layers and the subgrade. Typically, higher deflections suggest a poorer pavement condition, while any peaks observed in the deflection profiles signify areas of relatively lower structural performance within those specific regions. A comparison between all phases of FWD central deflection (d1) profiles is shown in Figure 7.

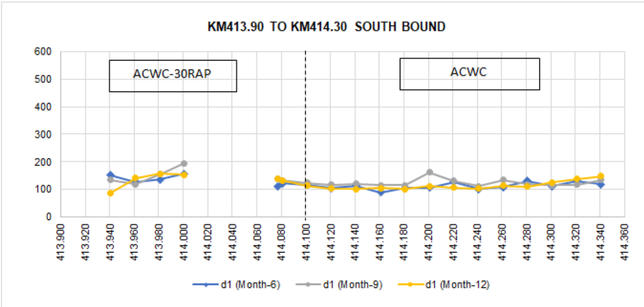


Figure 7 Comparison of FWD Central Deflections (d1) for all Phases

The FWD deflection profiles, aligning with the findings in Table 10, consistently portray all subsections as being in good condition, demonstrating minimal deviations in the deflection patterns throughout the one-year monitoring period. Both sets of results collectively indicate that the pavements are presently performing satisfactorily. Furthermore, these findings imply that employing ACWC-30RAP as a substitute for ACWC20 would likely lead to negligible differences in structural performance.

The MLP is designed to assess surface texture and condition, influencing factors such as safety, noise levels, and driving comfort [24]. Moreover, it offers valuable insights into the state of underlying pavement layers. In the evaluation of functional conditions for the ACWC-30RAP and ACWC20 trial sections, analysis of rutting and surface cracks was conducted using the MLP results. The Multi Laser Profiler was specifically employed during Phase 2, Phase 3, and Phase 4 for this assessment.

Rutting measurements were conducted utilizing an MLP test vehicle, and the data collected on the Slow Lane was analysed at intervals of 10 m. The rutting test outcomes for ACWC-30RAP and ACWC20 are presented in Table 10 and Table 11, respectively.

Table 10 Rutting Indicators and Results for ACWC-30RAP (All Phases)

Pavement Condition	Rutting (mm)	Phase 2	Phase 3	Phase 4
Good	<5.0	88%	81%	69%
Fair	> 5 – ≤ 10	12%	19%	31%
Poor	> 10 – ≤ 20	-	-	-
Very Poor	≥ 20	-	-	-

Table 11 Rutting Indicators and Results for ACWC20 (All Phases)

Pavement Condition	Rutting (mm)	Phase 2	Phase 3	Phase 4
Good	<5.0	100%	100%	95%
Fair	> 5 – ≤ 10	-	-	5%
Poor	> 10 – ≤ 20	-	-	-
Very Poor	≥ 20	-	-	-

The rutting test results for ACWC-30RAP and ACWC20 trial sections during Phase 4 show more rutting has occurred as compared to Phase 3 and Phase 2. Based on the rutting test results, all the trial sections show fair to good resistance to rutting under the same loading conditions, However, it is noteworthy that the maximum rut depth detected for ACWC-30RAP is marginally low, below 7 mm while it was around 6 mm for ACWC20.

Surface cracks were monitored and documented utilizing Automated Crack Detection (ACD) cameras affixed to the MLP test vehicle. The Hawkeye software, developed by the Australian Road Research Board (ARRB), was employed to process and interpret the results of the crack tests. The ACD results and parameters are outlined in Table 12 and Table 13.

Table 12 Surface Crack Indicators and Test Results for ACWC-30RAP (All Phases)

Pavement Condition	All Cracks (%)	Phase 2	Phase 3	Phase 4
Good	< 5	100%	100%	100%
Fair	≥ 5 – < 10	-	-	-
Poor	≥ 10 – < 20	-	-	-
Very Poor	≥ 20	-	-	-

Table 13 Surface Crack Indicators and Test Results for ACWC20 (All Phases)

Pavement Condition	All Cracks (%)	Phase 2	Phase 3	Phase 4
Good	< 5	100%	100%	100%
Fair	≥ 5 – < 10	-	-	-
Poor	≥ 10 – < 20	-	-	-
Very Poor	≥ 20	-	-	-

The ACD results consistently show 100% good condition with no surface cracks for the ACWC-30RAP and ACWC20 trial sections.

Skid resistance survey was performed using Grip Tester (GT) and was analysed and derived to Grip Number (GN), which represents the existing surface condition of the pavement along the expressway. The GN value was then converted to a Sideways-Force Coefficient Routine Investigation (SCRIM) value using the following equation:

$$\textbf{SCRIM Value} = \textbf{0.89} \times \textbf{GripNumber}$$

The result was then compared to the Acceptable Level (AL) and Investigatory Level (IL) as set out by the Malaysian Highway Authority (MHA) in Pavement Durability Performance Measure (PDPM7) for skid resistance of SCRIM value. The results are tabulated in Table 14.

Table 14 Summary of SCRIM Value in Phase 4

Pavement Condition	SCRIM Value	Slow Lane	
		ACWC-30RAP	ACWC20
Acceptable	≥ 0.38	100%	100%
Investigatory Level	< 0.38	-	-

The results reveal that both sections have obtained SCRIM (>=0.38) values, which exhibit good skid resistance in Phase 4.

In the final phase scheduled at the end of the one-year trial period, core samples were obtained from the trial sections. The extracted core samples exhibit an average thickness ranging from 52 mm to 112 mm. Cores with thicknesses lower than 110 mm suggest that the ACBC layers might have experienced crumbling. This variation in thickness indicates potential localized deterioration in the ACBC layers.

4.0 CONCLUSION

To assess the performance of the ACWC-30RAP trial lay, comprehensive field testing was conducted, encompassing FWD, MLP equipped with Laser Crack Map, skid resistance tests, and pavement coring. The FWD deflection test results revealed that both the ACWC-30RAP and traditional ACWC20 trial sections sustained good structural conditions throughout the one-year trial duration. Minimal changes in the deflection profiles indicated satisfactory pavement performance, suggesting that the pavements were currently functioning well. The rutting test results for ACWC-30RAP and ACWC20 trial sections showed relatively fair to good pavement performance indicators over one year as detected by the MLP. The results from the Automated Crack Detection (ACD) tests indicated the absence of noticeable reflective cracks on the surface layer of both the ACWC-30RAP and traditional ACWC20 trial sections. In essence, this study served to validate the efficacy of ACWC-30RAP as a suitable material for the surfacing course layer, offering an alternative to the conventional ACWC20. The trial demonstrated that ACWC-30RAP exhibited a comparable performance to the laboratory-designed mix when subjected to real traffic loads and environmental conditions. Future research will focus on increasing the RAP content in the recycled mixtures as well as exploring different recycling techniques and integrating RAP with other types of asphalt mixes and additives.

Acknowledgement

This research is fully supported by PLUS Berhad and Edgenta PROPEL Berhad (EPB). The authors fully acknowledged PLUS and EPB for the fund which makes this important research viable and effective.

Conflicts of Interest

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

References

[1] Brock, J. D. and Richmond, J. L. Milling and recycling. R. Yang, S. Kang, H. Ozer, I. L. Al-Qadi. 2015. Environmental and Economic Analyses of Recycled Asphalt Concrete Mixtures based on Material Production and Potential Performance. *Resour. Conserv. Recycl.* 104: 141–151. https://doi.org/10.1016/j.resconrec.2015.08.014.

[2] J. Montanez, S. Caro, D. Carrizosa, A. Calvo, X. Sanchez. 2020. Variability of the Mechanical Properties of Reclaimed Asphalt Pavement (RAP) Obtained from Different Sources. *Constr. Build. Mater.* 230: 116968. https://doi.org/10.1016/j.conbuildmat.2019.116968.

[3] J. S. Chen, C. C. Huang, P. Y. Chu, K. Y. Lin. 2007. Engineering Characterization of Recycled Asphalt Concrete and Aged Bitumen Mixed Recycling Agent. *J. Mater. Sci.* 42: 9867–9876. https://doi.org/10.1007/s10853-007-1713-8.

[4] Singh, Bhupendra, Nikhil Saboo, and Praveen Kumar. 2017. Effect of Short-term Aging on Creep and Recovery Response of Asphalt Binders. *Journal of Transportation Engineering, Part B: Pavements.* 143(4): 04017017. https://doi.org/10.1061/JPEODX.0000018.

[5] Ameri, Mansourkhaki, & Daryaee. 2018. Evaluation of Fatigue Behavior of High Reclaimed Asphalt Binder Mixes Modified with Rejuvenator and Softer Bitumen. *Construction and Building Materials.* 191: 702–712. https://doi.org/10.1016/j.conbuildmat.2018.09.182.

[6] Yang, S.-H., & Lee, L.-C. 2016. Characterizing the Chemical and Rheological Properties of Severely Aged Reclaimed Asphalt Pavement Materials with High Recycling Rate. *Construction and Building Materials.* 111: 139–146. https://doi.org/10.1016/j.conbuildmat.2016.02.058.

[7] Miró, Rodrigo, *et al.* 2011. Evaluation of High Modulus Mixture Behaviour with High Reclaimed Asphalt Pavement (RAP) Percentages for Sustainable Road Construction. *Construction and Building Materials*. 25(10): 3854–3862. https://doi.org/10.1016/j.conbuildmat.2011.04.006.

[8] Sang-Yum Lee, Tri Ho Minh Le, Yeong-Min Kim. 2023. Full-scale and Laboratory Investigations on the Performance of Asphalt Mixture Containing Recycled Aggregate with Low Viscosity Binder. *Construction and Building Materials*. 367: 130283. https://doi.org/10.1016/j.conbuildmat.2022.130283.

[9] Timm, D. H., J. R. Willis and A. Kvasnak. 2011. Full-Scale Structural Evaluation of Fatigue Characteristics in High Reclaimed Asphalt Pavement and Warm-Mix Asphalt. Transportation Research Record. *Journal of the Transportation Research Board*. 2208: 56–63. https://doi.org/10.3141/2208-08.

[10] Ameri, Mahmoud, Ali Mansourkhaki, and Daryoosh Daryaee. 2018. Evaluation of Fatigue Behavior of High Reclaimed Asphalt Binder Mixes Modified with Rejuvenator and Softer Bitumen. *Construction and Building Materials*. 191: 702–712. https://doi.org/10.1016/j.conbuildmat.2018.09.182.

[11] Veeraragavan, Ram Kumar, *et al.* 2017. Laboratory Comparison of Rejuvenated 50% Reclaimed Asphalt Pavement Hot-Mix Asphalt with Conventional 20% RAP Mix. *Transportation Research Record.* 2633(1): 69–79. https://doi.org/10.3141/2633-09.

[12] Bastola, Nitish & Souliman, Mena & Dessouky, Samer. 2022. Structural Health Assessment of Pavement Sections in the

Southern Central States Using FWD Parameters. 209–218. https://doi.org/10.1061/9780784484609.023.

[13] Marecos, V., Fontul, S., de Lurdes Antunes, M., & Solla, M. 2017. Evaluation of a Highway Pavement using Non-destructive Tests: Falling Weight Deflectometer and Ground Penetrating Radar. *Construction and Building Materials*. 154: 1164–1172. https://doi.org/10.1016/j.conbuildmat.2017.07.034.

[14] Yaacob, Haryati & Hassan, Norhidayah & Hainin, Mohd Rosli & Rosli, Muhammad. 2014. Comparison of Sand Patch Test and Multi Laser Profiler in Pavement Surface Measurement. *Jurnal Teknologi.* 70. https://doi.org/10.11113/jt.v70.3497.

[15] Chattanooga. 2007. TN: ASTEC, Technical Paper T-127.

[16] Tebaldi, Gabriele, *et al*. 2018. Cold Recycling of Reclaimed Asphalt Pavements. Testing and Characterization of Sustainable Innovative Bituminous Materials and Systems. Springer, Cham. 239–296. https://doi.org/10.1007/978-3-319-71023-5_6.

[17] Dughaishi, H. A., J. A., Bilema, M., Babalghaith, A. M., Mashaan, N. S., Yusoff, N. I. M., Milad, A. 2022. Encouraging Sustainable use of RAP Materials for Pavement Construction in Oman: A Review. *Recycling*. 7(3): 35. https://doi.org/10.3390/recycling7030035.

[18] Osvaldo Munoz-Cáceres, *et al*. 2021. Mechanical Performance of Sustainable Asphalt Mixtures Manufactured with Copper Slag and High Percentages of Reclaimed Asphalt Pavement. *Construction and Building Materials.* 304: https://doi.org/10.1016/j.conbuildmat.2021.124653.

[19] Mogawer, Walaa S., *et al*. 2016. Performance Characteristics of High Reclaimed Asphalt Pavement Containing Bio-modifier. *Road Materials and Pavement Design.* 17(3): 753–767. https://doi.org/10.1080/14680629.2015.1096820.

[20] Hoyos, L. R., Puppala, A. J., Ordonez, C. A. 2011. Characterization of Cement-fiber-treated Reclaimed Asphalt Pavement Aggregates: Preliminary Investigation. *ASCE J. Mater. Civ. Eng.* 23(7): 977–989. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000267.

[21] Transportation Research Board. 1978. Recycling Material for Highways, NCHRP Synthesis No. 54. Transportation Research Board.

[22] Henrikas Sivilevicius, Justas Braži ̄unas, Olegas Prentkovskis. 2017. Technologies and Principles of Hot Recycling and Investigation of Preheaeted Reclaimed Asphalt Pavment Batching Process in an Asphalt Mixing Plant. *Applied Sciences.* 7(11): 1104. https://doi.org/10.3390/app7111104.

[23] D. Vandewalle, V. Antunes, J. Neves, A. C. Freire. 2020. Assessment of Eco-friendly Pavement Construction and Maintenance using Multi-recycled Rap Mixtures. *Recycling*. 5: 1–21. https://doi.org/10.3390/recycling5030017.

[24] Ben Moins, *et al*. 2022. On the Road Again! An Economic and Environmental Break-even and Hotspot Analysis of Reclaimed Asphalt Pavement and Rejuvenators. *Resources, Conservation and Recycling.* 177. https://doi.org/10.1016/j.resconrec.2021.106014.