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Field performance of bitumen emulsion Cold Central Plant Recycling (CCPR) mixture with same day and delayed overlay compared with traditional rehabilitation procedures

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A R T I C L E I N F O

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A B S T R A C T

Cold Recycled Mixtures (CRM) offer many benefits, including cost-effectiveness and sustainability. Large existing Reclaimed Asphalt Pavement (RAP) stockpiles that represent an environmental and storage challenge can be used for bitumen emulsion Cold Central Plant Recycling (CCPR). A pavement rehabilitation demonstration project using Cold Recycled Mixture with Bitumen Emulsion (CRM-E) as binder course with 100% RAP was carried out on August 25, 2020. The project was divided into three sections to evaluate the mill and pave strategy using CRM-E as an alternative to traditional Hot Mixture Asphalt (HMA). The wearing course was the same asphalt concrete for the three sections. The difference between Section 1 and 2 that used CRM-E was to either pave the asphalt concrete overlay on the same day or to delay its application for 3 days to give additional time for the CRM-E to cure. Section 3 had no CCPR and consisted of two HMA layers. The field performance of the rehabilitated sections was monitored in 4 phases after 14 days, 3 months, 6 months and 12 months. The performance of the sections was assessed based on Falling Weight Deflectometer (FWD), field rutting measurements and cracking distress surveys. Cores were also taken over time to compare the CRM-E and HMA binder course properties in terms of resilient modulus, dynamic creep, indirect tensile strength and tensile strength ratio. The research showed that CRM-E and HMA performance was similar in terms of FWD deflections, field rutting, in situ cracking, and moisture resistance of the field cores. CRM-E showed superior performance in terms of resilient modulus and dynamic creep compared with asphalt concrete binder course based on testing of field cores taken after 6 and 12 months. The research showed that same day CRM-E HMA overlay is a viable construction option.

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1. Introduction

Cold recycling is an attractive rehabilitation approach in terms of cost-effectiveness and sustainability. Cold recycled mixture is defined as a process in which Reclaimed Asphalt Pavement (RAP) materials are combined with new asphalt and/or recycling agents to produce cold mixtures without the addition of heat [1]. Bitumen emulsion can be used as a recycling or bonding agent in the cold recycling process. Cold In-place Recycling (CIR) is performed on-site and uses a series of equipment, including tanker trucks, milling machines, crushing and screening unit, pugmill, windrow elevator, paver and rollers. Cold Central Plant Recycling (CCPR) is done by processing RAP millings and adding required components such as bitumen emulsion by mixing with a pugmill at an offsite location. The cold mixture is then transported by trucks and paved. The CCPR and CIR compaction processes are similar [2]. The use of cold recycled mixture has been recognized as highly cost-effective and sustainable [3–5]. It has also been shown that bituminous cold recycled mixtures offer improved mitigation of reflective cracking compared to conventional HMA overlay control Section [6]. In another study, the life cycle cost analysis demonstrated that cold recycling projects yielded lower net present values than the HMA project [7]. Furthermore, cold recycling technologies reduced energy consumption by 56–64% and decreased the greenhouse gas emissions by 39–46%. The monitored and predicted pavement performance showed similar trends in the first two years.

The challenge faced by a large HMA producer based in Taiping in Northern Malaysia is experienced by many other contractors in other parts of the world where RAP stockpiles are not being fully utilized and are mounting. The contractor's investigation on how to deal with excess RAP resulted in the decision to use CRM-E and the CCPR process as a highly sustainable and cost-effective way to consume RAP. The contractor set up a CCPR plant at their Taiping facility, conducted extensive CRM-E mixture design testing and constructed multiple CRM-E test sections to gain experience and confidence in the technology. One of the goals set by the contractor and the local pavement engineering firm is to use CRM-E as a rehabilitation technique on the expressway with a construction window limited to nighttime work and returning the road to traffic at the end of the shift. Case studies from China documenting the use of CRM-E as the binder course on heavy expressway traffic on multiple projects over the last 3 years with only 4–5 cm overlay paved on the same day were provided. This novel concept to implement CRM-E was well received but needed to be validated before implementation in Malaysia. The local road authority, Majlis Perbandaran Taiping (MPT), approved on November 21, 2019 to carry out a CRM-E demonstration on a municipal collector road section with 12,000 vehicles/day per lane on Jalan Taming Sari in Taiping City which is the second largest city in the Perak state of Malaysia on the west coast of the Malay Peninsula with a city population of more than 240,000 people. The construction and completion of the CRM-E demonstration was realized on October 25–28, 2020.

The main objective of this study is to compare the performance of CRM-E as a binder course with traditional HMA binder course. Additionally, the construction and monitoring of this demonstration project was divided in two CRM-E sections to assess the effect of placing the HMA wearing course overlay on the same day of the CRM-E compared to letting the CRM-E cure for 3 days before the overlay. A control section was a traditional HMA mill and pave rehabilitation composed of HMA binder course and HMA wearing course without CRM-E for comparison. This paper presents results related to the evaluation of the three sections based on destructive and non-destructive testing.

2. Background related to cold recycled mixture with bitumen emulsion

CRM-E is often compared to HMA, and some of the questions that are raised relate to the differences and impact of higher voids, slower curing rate, possible performance risk on heavily trafficked roadways and the need to traditionally wait for some time before overlaying a recycled layer with HMA. Average air voids of cold recycled mixtures are typically higher than HMA, but this does not prevent cold mixtures from performing adequately. It has been shown that cold recycling has a significantly different air void size distribution with a larger proportion of smaller size voids compared to asphalt concrete [8].

Laboratory cold recycled mix design is an important step. Researchers have proposed the addition of workability, compactability, and cohesion gain as three intermediate stages to be considered during the asphalt emulsion cold recycled mixture laboratory evaluation [9].

Resilient modulus of laboratory-produced samples or field cores and Falling Weight Deflectometer (FWD) tests are useful evaluation methods on the matter of strength development evaluation over time. Research indicates that bituminous cold recycled mixture stiffness, effective structural number and back-calculated layer modulus of bituminous cold recycled mixtures typically increase over time [10,11]. Strength development is positively affected by water loss [12].

What happens in the field and the ability for CRM-E to cure and gain strength over time is of great importance. Part of a cold recycled layer study produced with 2% cement and 3% emulsion was sealed with bitumen emulsion in a study aimed at evaluating the effect of prevented water evaporation on the curing process [13]. The moisture data recorded over a 90 day period in the field by the time domain reflectometer embedded probes showed that the initial curing rate of the mixture in sealed conditions when applying an asphalt membrane over the cold recycled layer was about 50% of the initial curing rate of the mixture cured in unsealed conditions. However, the effect of curing condition (unsealed/sealed) on the longer-term curing properties was negligible.

CRM-E binder course sections were studied for two years to better understand laboratory and field curing behavior [14]. The evolution of the average indirect tensile strength and stiffness modulus over the curing time was fitted with an asymptotic model. The oven-curing with free evaporation in the laboratory and sealed curing with restricted evaporation in the field led to the formation of a different microstructure. The study recommended for laboratory curing to be carried out both in sealed and unsealed condition at relevant curing temperatures and curing timeframes to have a complete understanding of the CRM-E behavior in the field. The research also emphasized the importance of compaction as there is a negative linear relationship between air voids and indirect tensile strength as well as air voids and stiffness modulus.

Bitumen emulsion CIR and CCPR techniques and the use of CRM-E were traditionally limited to low to medium traffic volume roadways, but CRM-E has been used successfully on higher traffic volume pavements, including Interstate highways. Modern emulsified asphalts used for cold recycling are typically solventless and engineered to cure quickly. The bituminous cold recycling layer can gain enough strength shortly after compaction, and traffic can be allowed back on the cold recycled mat if needed at the end of the day [15].

The combined effect of bitumen and cement is effective at improving the high temperature stability of the cold recycled mixtures [16]. The analysis of the temperature corrected FWD moduli showed that the stiffness of the CRM-E layers continued to increase for up to 3–5 years.

Cement usage in CRM-E is highly beneficial as it contributes to improving moisture damage resistance, reducing permanent deformations, increasing stiffness modulus and the fatigue life of the mixtures [17].

Stiffness or modulus value is a key parameter of pavement structural design methodologies. Modulus values of the various pavement layers are used to calculate stresses and strains under traffic at key pavement locations to use transfer equations or predictive models then to estimate distress values or the time to specific distress thresholds. Calibration factors are needed to refine the models to ensure that predictions can match actual field performance. It is a critical step as such calibration factors are material types specific. A method using relationships between the laboratory fatigue test results and the actual traffic data was proposed to compare fatigue properties and establish shift factors [18]. The study's main objective was to investigate the fatigue characteristics of in-service CRM-E mixtures cored from the pavement using laboratory Indirect Tensile Fatigue Test and one HMA mixture from the same pavement for comparison. The calculated shift factor value of the CCPR mixture of 105.6 was much larger than the HMA mixture shift factor value of 8.9, further illustrating how different the calibration factors can be between different mixture types. In another study looking at rutting, the mechanistic-empirical pavement structural design program over predicted the rut depth of the cold recycled sections compared to the HMA one [7]. The pavement performance results confirmed that the bottom-up fatigue cracking was a negligible distress mode for cold recycled asphalt pavements.

Service life of cold recycled pavements has been reported to range from 20 to 34 years when the cold recycled mix is used in conjunction with an overlay [19]. It was also reported that the barriers to the increased use of cold recycled mixtures were lack of agency experience, lack of experienced contractors and unfamiliarity with quality assurance testing and construction guidelines.

The time needed or required before return traffic and/or overlay is in the mind of many people interested in CRM-E. Ongoing research aims to develop time-critical tests for asphalt-treated materials and provide guidelines for using these tests for process control and product acceptance to give the agency a basis for determining when the pavement can be opened to traffic and surfaced [20].

The ability to correlate laboratory and field evolution of cold recycled mixture curing is of great interest and value. A study based on materials and data from six cold in place recycled projects used laboratory fabricated specimens that were oven-cured at a temperature of 25 °C which was equivalent to the average air temperature observed in the project locations during field evaluation. One of the motivations was the ability to reliably simulate in-situ curing of CIR mixtures in the laboratory to provide a more efficient alternative to determining the required curing time. Material properties evolve faster in the field as compared to the controlled laboratory curing condition, but a strong relationship existed between the field and laboratory curing evolution times. Higher mechanical properties in the field were consistently measured on projects that utilized active filler from the effect of continued hydration [21].

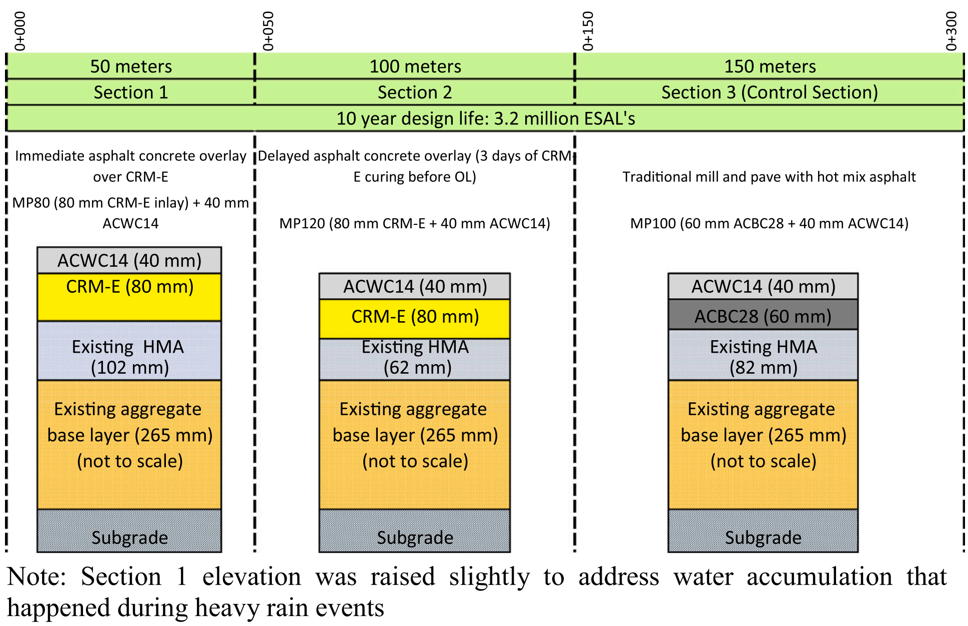


Fig. 1. Rehabilitation sections on Jalan Taming Sari road in Taiping, Malaysia. Note: Section 1 elevation was raised slightly to address water accumulation that happened during heavy rain events.

3. Research objectives

This study aims to evaluate the performance of mill and pave using bitumen emulsion cold recycling combined with a Hot Mix Asphalt (HMA) concrete overlay compared to traditional mill and pave using only HMA. The research also investigates the effect of same-day HMA overlay over the bitumen emulsion cold recycled layer versus 72 h of curing of the cold recycled mat before placing the asphalt concrete overlay. The three pavement rehabilitation sections shown in Fig. 1 that have been closely evaluated over 12 months have the same final HMA overlay type and thickness. The total project rehabilitation length is 300 m divided in 3 sections as follows:

- Section 1 (CRM-E with immediate asphalt concrete overlay) MP80 and OL40:

o Milling 80 mm of existing asphalt concrete;
o Laying 80 mm of bitumen emulsion CCPR;
o Laying 40 mm of the asphalt concrete overlay (Asphalt Concrete Wearing Course with 14 mm maximum aggregate size - ACWC14) on the same day as the CRM-E (within 4 h); and
o Section 1 total length is 50 m.

- Section 2 (CRM-E with delayed asphalt concrete overlay) MP120:

o Milling 120 mm of existing asphalt concrete;
o Laying 80 mm of bitumen emulsion CCPR;
o CRM-E cured for 3 days before applying the HMA overlay;
o Laying 40 mm of ACWC14; and
o Section 2 total length is 100 m.

- Section 3: Control Section (traditional asphalt concrete rehabilitation scheme) MP100:

o Milling 100 mm of existing asphalt concrete;
o Laying 60 mm of asphalt concrete (Asphalt Concrete Binder Course with 28 mm maximum aggregate size - ACBC28);
o Laying 40 mm of ACWC14 on the same day as the ACBC28 (within 4 h); and
o Section 3 total length is 150 m

The field performance of each of the three sections has been evaluated over one year in terms of distress surveys, FWD and testing of 100 mm diameter field cores as outlined in Table 1. The one-year timeframe was divided into four periods or evaluation phases to evaluate any changes that may occur as a function of time in the pavement binder course properties and better understand trends.

The pavement performance monitoring Phase 1 consists of only laboratory testing conducted using core samples collected from the trial sections at Jalan Taming Sari in Taiping after 14-days of the trial construction. The results are to be compared to the approved mix design. Performance monitoring for Phase 2, Phase 3 and Phase 4 includes field testing to assess the pavement condition and laboratory testing of core samples obtained from the trial sections with a total of 10–12 cores obtained from each section for each phase. The field core testing will be limited to the CRM-E, and ACBC28 binder course layers for comparison purposes as all the sections received the same ACWC14 overlay wearing course mixture, and the main differences between the three sections come from the CRM-E and ACBC28 layers. The results will be compared to evaluate the pavement behavior and trends over time.

The Resilient Modulus test was conducted according to ASTM D4123 [22]. The Dynamic Creep Test, also known as the Repeated Load Axial Test, was performed according to BS EN 12697–25 (Method A) [23].

4. Project site and rehabilitation information

4.1. Site selection

A joint visit between MPT, the local pavement engineering firm and the contractor was conducted on February 29, 2020, to select a suitable location for the CRM-E field trial. The agreed location is on Jalan Taming Sari by the Taiping Prison and the Perak Museum. A road length of 300 m was divided into 150 m length for the CRM-E field trial and 150 m length for the conventional asphalt concrete. It was found that the existing main pavement distresses and defects on Jalan Taming Sari were fatigue cracking, polishing of the wearing surface aggregate and raveling degradation at the cold paving joints as shown in Fig. 2 along the path of the rehabilitation sections. Overall drainage condition is poor with no well-established ditches or other ways to remove water away from the pavement during

Table 1
Summary of field and laboratory testing to be conducted over 12 months.

	Phase Time after construction Testing date in the field	1 14 days Sept. 7 2020	2 3 months Dec. 1 2020	3 6 months March 9 2021	4 12 months Sept. 6 2021
Non-destructive	Falling Weight Deflectometer (FWD)	–	✓	✓	✓
	Rutting laser profiler and cracking surveys	–	✓	✓	✓
Field cores	Resilient Modulus Test	✓	–	✓	✓
	Dynamic Creep Test	–	–	✓	✓
	Indirect Tensile Strength Test and Tensile Strength Ratio (TSR)	✓	–	✓	✓

(a) Typical existing road condition in the CRM-E section

(b) Typical existing road condition in the traditional HMA Mill and Pave section

(c) Starting and ending points of the rehabilitation demonstration project

Fig. 2. Location of the rehabilitation sections on Jalan Taming Sari road in Taiping (Malaysia) and typical existing pavement condition.

heavy rains.

4.2. Pre-construction testing and proposed structural sections

Pavement coring was carried out to determine the thickness of the existing asphalt concrete layers, the type and extent of cracks and the general condition of the materials on the trial sections. Five cores were taken along the 300-meter trial section to assess the thickness of the existing different layers. The site investigation indicated that the asphalt concrete ranged between 150 and 210 mm for an average of 182 mm, and the aggregate base thickness ranged between 225 and 295 mm for an average of 265 mm.

The structural condition of the existing pavement was determined using Falling Weight Deflectometer (FWD) by measuring deflection basins every 20 m. FWD average back-calculated subgrade modulus was 122 MPa, 117 MPa and 112 MPa for Sections 1, 2 and 3, respectively. The subgrade modulus was consistent throughout the project.

The average annual daily traffic is estimated to be 12,000 vehicles/day per lane with 12.6% trucks. MPT requested a 10-year design and the estimated design life in terms of Equivalent Single Axle Loads (ESAL) of 80 kN (18,000 lb.) was determined to be 3.2 million ESAL's. The pavement structural design performed by the consultant and approved by MPT resulted in the proposed rehabilitation sections shown in Fig. 1.

5. Bitumen emulsion cold central plant recycling project materials and placement

5.1. Reclaimed Asphalt Pavement (RAP)

Recycled Asphalt Pavement (RAP) gathered over the years in a large stockpile is fractionated in three sizes for bitumen emulsion CCPR use. The materials are stockpiled in the three size fractions of 0–4.75 mm, 4.75–14 mm and 14–28 mm as shown in Fig. 3b. The CRM 100% RAP blend target gradation was established by using 25% of the 0–4.75 mm RAP stockpile, 40% of the 4.75–14 mm RAP stockpile and 35% of the 14–28 mm RAP stockpile. The proposed RAP blend met AASHTO MP31 guidelines for medium gradation as shown in Table 2. The bitumen content of the RAP is 4.3%. The mixture was produced using 100% RAP. No additional virgin aggregates were used. The proposed RAP stockpile percentages were established to use the original RAP in its entirety to minimize RAP waste. Some of the key benefits of RAP fractionation in CCPR production are control of the maximum RAP aggregate size, improved mixture consistency, enhanced quality control capabilities, and more precise monitoring of RAP moisture content during production and minimizing segregation.

5.2. Bitumen emulsion

The bitumen emulsion met the Malaysian requirements pursuant to clause 4.10.2.3 of JKR/SPJ/2008 for bitumen emulsion cold recycling with representative properties reported in Table 3 [24]. The bitumen emulsion was produced using 60/70 pen paving grade bitumen asphalt. It is worth noting the bitumen emulsion would also meet typical standards used in the United States for cold recycling applications.

5.3. Characteristics of the cold recycled mixture with bituminous emulsion

Portland cement can be used in cold recycling applications in order to increase stiffness and early strength. Improvements of key bitumen emulsion cold mixture properties from Portland cement can be explained by a range of mechanisms, including the rate of bitumen emulsion coalescence after compaction, cement hydration and enhancement of binder viscosity [25]. There can be issues with the pavement performance if either too little or too much cement is used. Early heavy traffic could cause rutting and deterioration of the pavement surface if there is not enough cement in the mix to provide early stiffness. Pavement performance could decrease due to cracking associated with either shrinkage or the mixture brittleness if too much cement is used.

Previous research was conducted to evaluate the effect of Portland cement content on CRM-E performance based on rate of increase in initial strength, moisture susceptibility, rutting resistance using a wheel tracker, and low temperature beam cracking resistance [26]. It was established that the use of Portland cement was necessary and that the optimum cement content was 1.5%.

Enough emulsion is required to ensure adequate mixture cohesion, fatigue and cracking resistance. The Chinese national specification for asphalt pavement recycling specifies that the percentage of asphalt bitumen residue should be in the range of 1.8–3.5% by dry weight of mixture for emulsion cold recycled mixture [27]. This means that the emulsion content should be in the range of 3.0–5.8% when using an emulsion residue content of 60%. The specification also mentions that the cement content should not surpass 1.8% and preferably not exceed 1.5%.

Balanced mixture design approaches applied to cold recycling have been proposed to optimize the mixture in terms of rutting and cracking resistance [28,29].

(a) Original RAP stockpile (millings) (b) Fractionated RAP in three sizes

Fig. 3. RAP stockpiles before and after fractionation.

Table 2
CRM granulometric bands and adopted RAP blend gradation.

Sieve (mm)		37.5	31.5	25	20	19	10	5	4.75	2.36	0.6	0.425	0.075
RAP Fine Stockpile: 0–4.75 mm		100	100	100	100	100	100	95	94	54	13	8	3.5
Medium RAP Stockpile: 4.75–14 mm		100	100	100	100	100	99	31	30	11	5	3	1.5
Coarse RAP Stockpile: 14–28 mm		100	100	100	94	89	18	5	4	3	2	1	0.5
RAP Blend (25/40/35 Fine/Medium/Coarse)		100	100	100	98	96	71	38	37	19	6	4	1.5
Malaysia CCPR Proposed Limits	Upper	100	–	–	100	–	90	75	–	60	–	35	7
	Lower	100	–	–	60	–	40	30	–	15	–	2	1
AASHTO MP31 Medium Gradation	Upper	–	–	100	–	96	–	–	65	–	14	–	–
	Lower	–	–	100	–	85	–	–	40	–	4	–	–
AASHTO MP31 Coarse Gradation	Upper	–	100	100	–	92	–	–	45	–	7	–	–
	Lower	–	100	85	–	75	–	–	30	–	1	–	–

Table 3
Bitumen emulsion properties.

Properties	Test Result	Requirement
Viscosity, Saybolt Furol at 25 °C (sec):	35	20–100
Settlement, 5 days (%):	3.8	0–5
Storage stability test, 24 hr (%):	0.26	0–1
Sieve test (%):	0	0–0.1
Cement mixing test (%):	0	0–2.0
Distillation for oil, by volume of bitumen emulsion (%):	0	0–5
Distillation for residue (%):	61.5	60 minimum
Penetration for residue (dmm):	75.6	60–200
Ductility of residue, 25 °C, 5 cm/min (cm):	62	40 minimum
Solubility in trichloroethylene (%):	99.5	97.5 minimum
Particle charge test:	Positive	Positive

It was shown that bitumen emulsion cold recycling properties were satisfactory in terms of wheel tracking rutting resistance and cracking resistance measured according to the IDEAL-CT with a cement content of 1.5% and bitumen emulsion content of 3.5% [30].

The CRM-E mixture design for the Taiping project was performed following the AASHTO PP86 guidelines [31]. Some of the main steps in the CRM-E design include:

- Analysis of RAP and RAP blend selection;
- Formulation of the bitumen emulsion;
- Determination of optimum water content;
- Mixture preparation at selected cement and bitumen emulsion contents;
- Compaction of specimens using 100 mm diameter molds and 75 blows each side; and
- Curing of compacted, unsealed specimens at 60 °C for 48 h in a forced draft oven. After curing, specimens were cooled to ambient temperature for at least 12 h. ITS and Marshall stability tests at the required temperatures were conducted within 24 h.

CRM-E property requirements were assessed according to both Malaysia CIR JKR/SPJ/2008-S4 and AASHTO MP31 [24,32]. Ordinary Portland cement type I according to ASTM C150/C150M was used [33]. The compaction of the CRM in the field does not happen right after the mixture is produced at the CCPR location. There is usually a time delay between mixing and compaction as the mixture needs to be transported to the job site and go through the paver. This was accounted for in the design by waiting for two hours between mixing and compaction in the laboratory based on the Taiping project conditions. The optimum bitumen emulsion content was determined to be 3.5% bitumen emulsion with 1.5% cement by weight of dry RAP. The minimum recommended RAP pre-wet

Table 4
CRM-E properties at 3.5% bitumen emulsion and 1.5% cement by weight of dry RAP.

Properties	Results	Minimum Requirements	
		AASHTO MP31	JKR
Air voids, %[a]	12.7	Report	NA
25 ℃ Dry ITS, MPa	0.340	0.31	0.2
25 ℃ Wet ITS, MPa	0.415	NA	0.15
TSR[b], %	100	70	NA
40 ℃ Marshall Stability, kN	9.1	5.56	NA

Notes:
[a] Typical 100% RAP CRM-E air voids between 9% and 14%
[b] ITS: Indirect Tensile Strength, TSR: Tensile Strength Ratio = (Wet ITS/Dry ITS)

water was determined to be 2.6% by weight of RAP resulting in a total moisture content of 3.8% by weight of CRM-E mixture after emulsion was added. Such total moisture content was suitable for full coating, and adequate mixture workability after 2 h (to simulate the expected time in the field between mixing and placement) with the mixture flowing without resistance when loading the molds before compaction. The resulting CRM-E properties are reported in Table 4 based on the testing of 3 replicates for each property. It is noted that wet ITS exceeded dry ITS which can sometimes happen in the mixture design stage as a result of extra cement hydration when conditioning specimens in water.

Hamburg Wheel Tracking (HWT) rut testing per AASHTO T324 was performed on cured samples for 48 h in a forced draft oven at 60 ℃ to further assess the rutting and moisture resistance of the CRM-E [34]. HWT results in both dry and wet mode at 50 ℃ produced with 3.5% bitumen emulsion and 1.5% cement are shown in Fig. 4. There was no stripping inflection point noticeable on the wet rutting curves, and the average measured rut depths for two samples in wet or dry modes were all less than 4 mm after 20,000 passes. The emulsion cement combination was highly effective at improving rutting resistance of CRM-E. Rutting of less than 12.5 mm after 20,000 passes is usually considered satisfactory when testing HMA.

5.4. Hot mixture asphalt concrete materials

The asphalt bitumen used for the Asphalt Concrete Binder Course 28 (ACBC28) mixture is 60/70 pen grade, with an aggregate blend showing 99.6% passing the 28 mm sieve size. The optimum binder content based on 75 blow Marshall mixture design is 4.88% by weight of mixture that yielded a density of 2.361, Marshall stability of 14,520 N (minimum requirement of 8,830 N), Marshall flow of 3.6 mm (requirement between 2 and 4 mm), air voids of 4.2% (requirement between 3% and 6%), Voids in the Mineral Aggregate of 15.6, and Voids Filled with Asphalt of 73% (requirement between 70% and 78%).

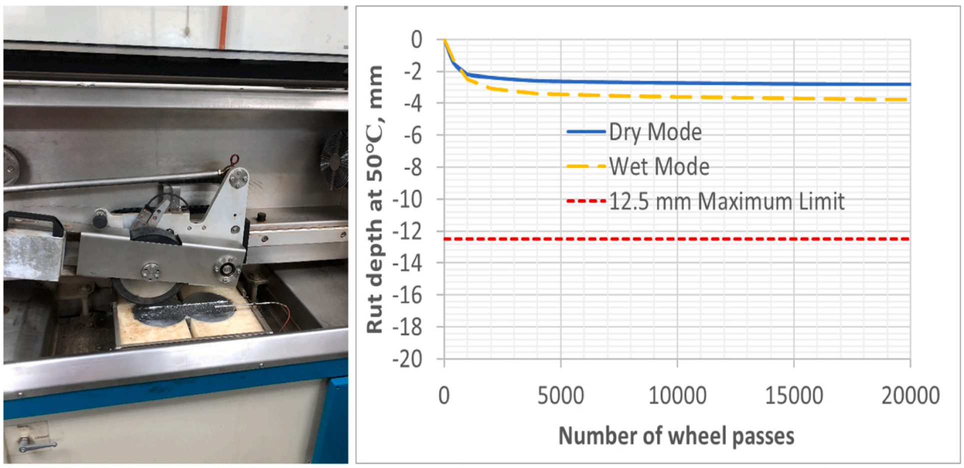
The asphalt bitumen used for the Asphalt Concrete Wearing Course 14 (ACWC14) mixture is 60/70 pen grade with an aggregate blend showing 100 passing the 20 mm sieve size and 96% passing the 14 mm sieve. The optimum binder content based on 75 blow Marshall mixture design is 5.24% by weight of mixture that yielded a density of 2.320, Marshall stability of 10,400 N (minimum requirement of 7,850 N), Marshall flow of 3.1 mm (requirement between 2 and 4 mm), air voids of 4.5% (requirement between 3% and 7%), Voids in the Mineral Aggregate of 16.1, and Voids Filled with Asphalt of 72% (requirement between 65% and 75%).

5.5. Bitumen emulsion CCPR production and construction

A dual shaft pugmill is used to produce the bitumen emulsion CCPR mixture. The three fractionated RAP stockpiles are fed into three cold bins and recombined according to the mixture design Job Mix Formula (JMF). The recombined RAP blend travels onto a conveyor belt, and cement is added shortly before entering the pugmill, where water and bitumen emulsion are mixed with 100% RAP. The fully coated mixture coming out of the pugmill (Fig. 5a) then travels onto a conveyor belt to reach an elevated surge bin (Fig. 5b) used to load transportation trucks destined for the paving site. Plant calibration ensures that the CCPR mixture components are precisely metered according to the JMF.

Some of the key paving operations for the construction of the CCPR sections are outlined as follows:

- Milling depth is checked closely to be within the allowable tolerances;
- Loose material or debris are removed from the milled surface areas by using a power broom;
- This is followed by a compressed air blower and, if necessary, scrapped using hand tools to remove all objectionable material that could act as a bond breaker;



(a) HWT testing device (b) CRM-E HWT results at 50°C

Fig. 4. Hamburg Wheel Tracking (HWT) test results on CRM-E.

(a) Use of dual shaft pugmill to produce bitumen emulsion CCPR mixture
(b) Loading of truck with CCPR mixture
(c) Paving of the CRM-E mix
(d) Compaction of the CRM-E mat

Fig. 5. Production and placement of the bitumen emulsion CCPR mixture.

- Tack coat is sprayed on the cleaned surface by using the distributor's hand spraying system;
- The CRM-E is laid with a paver (Fig. 5c) in accordance with construction drawings without any heat applied to the screed;
- Compaction (Fig. 5d) is carried out using the established rolling pattern from the previous project trial. The rolling pattern includes tandem 10 Ton (2 passes minimum), 16 Ton steel roller (4 passes minimum) and 18 Ton pneumatic tire roller (6 passes minimum);
- Field Quality Control is conducted to ensure that 97% minimum of the laboratory density is achieved in the field. The sand cone displacement method can be used to check in place bitumen emulsion cold recycling compaction during construction [35];
- A rapid set bitumen emulsion tack coat is applied immediately after compaction of the CCPR;
- Curing time for the CCPR is set at 4 h before overlay with ACWC14 for Section 1;
- Curing time for the CCPR is set at 72 h before overlay with ACWC14 for Section 2;
- The ACWC14 is laid with a paver in a single layer of 40 mm in accordance with construction drawings;
- Compaction of the ACWC14 is carried out using the specified type of compactors (vibratory tandem roller and pneumatic tire roller) and the rolling pattern established from a previous test strip;
- The surface of the wearing course is finished to the grade and line as required by the JKR specifications. Joint inspection and dipping are checked for compliance.

Curing of CRM-E is affected by environmental conditions. Daily temperatures and precipitations were collected from the official closest national weather station located at Lubuk Merbau (75.5 m above sea level, latitude of 4°26′N and longitude of 100°54′E) 19 km away from the project. The average daily temperature for the first three days after CRM-E construction ranged from 26.5°C to 26.9°C. The maximum and minimum temperatures were 32.9°C and 21.9°C respectively for the first three days. There were scattered thunderstorms with light rain for less than 30 min after the compaction of the CRM-E was completed on the first day of CRM-E construction.

It did not rain for the following two days. The wind speed was less than 10 km/hour for the first three days after construction of the CRM-E.

Seven day running average minimum, maximum and average temperatures, as well as accumulated daily precipitation are shown in Fig. 6 from the first construction day on August 25, 2020 to the total monitoring period one year later. The daily temperature over the one-year period ranged between a minimum of 19.0°C and a maximum of 37.2°C with an average of 26.9°C. The 7-day running average daily temperature over the one-year period ranged between a minimum of 21.4°C and a maximum of 35.4°C with an average of 26.9°C. Malaysia ranks as the 8th country in the world with the largest annual precipitation. Taiping is also known as the wettest town in Malaysia. Fig. 6 attests of the extremely high accumulated annual precipitation of 2036 mm of rain between October 25, 2020 and October 25, 2021. The month of November 2020 with 291 mm of precipitation was the second wettest month of year within one year after construction of the CRM-E. The fact that the month following construction in November 2020 had 291 mm of rain is a real test for CRM's ability to resist moisture damage when exposed to high precipitation in early life.

RAP moisture and total mixture moisture was monitored as part of the CRM-E production quality control process. The high level of precipitations in Taiping resulted in relatively high RAP stockpile moistures during the Taiping project with an average moisture content of 1.7% in the 14–28 mm RAP stockpile, 3.9% moisture in the 4.75–14 mm RAP stockpile and 5.6% moisture in the 0–4.75 mm RAP stockpile. This led to an average moisture content in the CRM-E mixture of 4.8% by weight of mixture after the emulsion was added which is 1% higher than the minimum recommended in the mixture design. Despite this higher total moisture content, the mixture did not show any visible draindown or emulsion running off when unloading the CRM-E from the transportation trucks into the paver hopper. Furthermore, the CRM-E mat did not show any waves or unusual behavior under the action of the rollers during compaction. Covered RAP stockpiles can be considered and built in the future as part of the RAP management plan and control of stockpile moisture especially in environment with high precipitations. Research has shown the importance of properly balancing water and cement contents to maximize indirect tensile strength and modulus stiffness [36].

Air voids of the CRM-E cores taken from the roadway after 14 days, 6 months and 12 months are summarized in Table 5. All the cores were taken in the left wheel path where the pavement experiences higher loading as compared to the right wheel path based on pavement crown and the fact that traffic in Malaysia drives on the left side of the roadway. The average CRM-E air voids of the various sections and time phases varied between 12.3% and 15.1% compared to the mixture design target value of 12.7%. The relative compaction level ranged from 97.2% and 100.4% when comparing field CRM-E cores and mixture design target CRM-E mixture bulk specific gravity. This level of field air voids is considered acceptable for CRM-E compared to the mix design target value as the average relative compaction density was in excess of 97% for all the sections. Further analysis indicates that the average air voids of the CRM-E section with same day HMA overlay was statistically lower than the section with 3-day delayed HMA overlay for cores taken after 14 days and 12 months with an absolute difference in air voids of 2.8% and 1.0% respectively. The average difference between CRM-E with and without same day overlay was not statistically significant after 6 months but showed an absolute difference of 1.1%. It can be said that applying the HMA on the same day resulted in a reduction of air voids of at least 1% compared to delaying the HMA overlay by 3 days. This observation is of value as lower voids improve mixture performance and should be further investigated or verified on future CRM-E projects. There is no noticeable change in CRM-E air voids overtime under the effect of traffic. Specifically, the average air voids of the CRM-E sections with same day HMA overlay were 12.3%, 12.7% and 12.5% after 14 days, 6 months and 12 months respectively.

6. Results and discussion

6.1. Resilient modulus

Three cores 100 mm in diameter were used for resilient modulus testing of each specific section and phase. Core specimens were

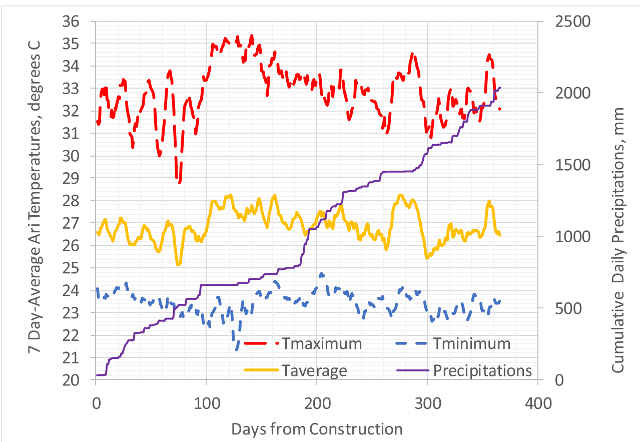


Fig. 6. Environmental conditions nearest to the project for one year since the first day of construction.

Table 5
Field air voids of CRM-E sections as a function of time and HMA overlay timeframe.

CRM-E Section		Time after construction that cores are obtained for performance testing	Air Voids (from field cores*), %			t-test P-value
			Average	Standard Deviation	COV, %	
1	Same Day HMA	14 days	12.3	0.665	5.4	
2	3-Day Delayed HMA	14 days	15.1	0.988	6.5	0.0033
1	Same Day HMA	6 months	12.7	1.290	10.2	
2	3-Day Delayed HMA	6 months	13.8	0.469	3.4	0.1448
1	Same Day HMA	12 months	12.5	0.411	3.3	
2	3-Day Delayed HMA	12 months	13.5	0.206	1.5	0.0048

Note: (*) Calculations were based on 4 cores for each section

tested in two orientations set at 0° and 90° angles to the diametrical plane. A dynamic load of 1270 N was applied vertically along the diametrical plane of the specimen, and the horizontal deformation was measured. The resilient modulus was determined from the stress applied and recoverable strain under the dynamic load. Tests were carried out at temperatures of 25 °C and 35 °C.

A comparison of the resilient modulus for CRM-E and ACBC28 after 14 days, 6 months and 12 months is presented in Fig. 7. The error bars represent one standard deviation.

The resilient modulus results for all sections show an expected positive trend over time, as the resilient modulus at both test temperatures increases in between phases. The average CRM-E Section 1 (same day overlay) modulus is greater than Section 2 (3-day delayed overlay) at Phase 1 (after 14 days) by 64% at 25 °C and 47% at 35 °C. Immediate placement of the HMA overlay positively impacted the CRM-E modulus value. The lower air voids of CRM-E by 2.8% experienced by placing the HMA on the same day compared to waiting for 3 days was a noteworthy occurrence that yielded greater modulus value. Immediate HMA overlay did not adversely impact CRM-E stiffness in the very early life of the pavement, which should minimize concerns related to opening traffic soon after the overlay is placed on the same day over CRM-E. In addition to the additional density gain in the CRM-E, placing the HMA overlay on the same day may contribute to increasing stiffness by forcing some moisture to escape from the CRM-E as a result of the HMA overlay heat exposure and providing accelerated curing from this construction approach.

CRM-E largest modulus increase took place within half a year after placement. After 6 months, the CRM-E modulus value with or without delayed overlay exceeded the ACBC28 HMA binder course modulus value by at least 19% at 25 °C and 59% at 35 °C. After 12 months, CRM-E modulus value with or without delayed overlay exceeded the ACBC28 HMA modulus value by at least 28% at 25 °C and 68% at 35 °C. The superiority of CRM-E compared to ACBC28 is greater at 35 °C than at 25 °C. This could indicate a better rutting resistance of CRM-E compared to ACBC28 at the higher temperature of 35 °C.

It is also worth noting that the resilient modulus temperature susceptibility of CRM-E is lower than ACBC28. Specifically, after 12 months, the modulus value at 35 °C is 66% of what it is at 25 °C for CRM-E with same day overlay. The modulus value at 35 °C is 72% of what it is at 25 °C for CRM-E with 3-day delayed day overlay while the modulus value at 35 °C is 50% of what it is at 25 °C for ACBC28. In other words, the ACBC28 modulus reduction as temperature is increased is greater than CRM-E.

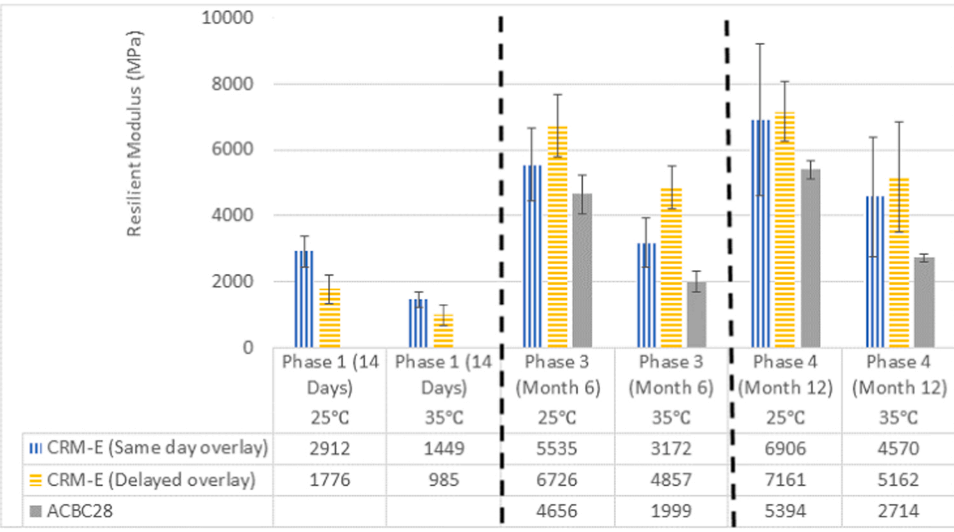


Fig. 7. Resilient modulus for CRM-E and ACBC28 after 14 days, 6 months and 12 months.

CRM-E Section 2 with delayed overlay has higher resilient modulus at both test temperatures (25 °C and 35 °C) than Section 1 (same day overlay) after 6 months. This difference is reduced after 12 months with the average CRM-E delayed overlay modulus being 4% greater than the CRM-E same day overlay modulus at 25 °C. The average CRM-E delayed overlay modulus is 13% greater than the CRM-E same day overlay modulus at 35 °C.

6.2. Dynamic creep test

Three cores 100 mm in diameter were used for dynamic creep testing of each specific section and phase. The purpose of the dynamic creep testing is to determine the permanent deformation of asphalt by measuring the deformation of a test specimen subjected to the repeated uniaxial stress load of 0.3 MPa on a cylindrical-shaped specimen for 3600 cycles. The same core samples tested in the non-destructive Resilient Modulus Test were used. The test was conducted at a temperature of 40 °C as typically specified in Malaysia to evaluate the rut resistance of bituminous mixtures. Pre-conditioning of the specimen was performed with a stress load of 20 kPa for 600 s. The deformation was measured in the same direction using two Linear Variable Differential Transducers (LVDT).

A comparison of the permanent deformation in terms of accumulated micro strains for CRM-E and ACBC28 between Phase 3 and Phase 4 is presented in Fig. 8. Lower accumulated micro stain is indicative of greater rutting resistance. The error bars represent one standard deviation.

One year after construction with the pavement under constant traffic loading, all the sections are slightly less susceptible to permanent deformation, as can be inferred from the results of Phase 4 (12 months) compared to Phase 3 (6 months). The percent reduction in micro strain between 6 and 12 months were 18%, 24% and 15% respectively for CRM-E with same day HMA overlay, CRM-E with 3-day cure before HMA overlay and ACBC28 HMA. The CRM-E percent reductions in micro strain were greater for CRM-E than HMA. This confirms that CRM-E tends to become more rut resistant than HMA over time.

Both CRM-E sections have less accumulated permanent deformation than ACBC28 at each phase. CRM-E with same day HMA overlay or CRM-E with 3-day delayed HMA overlay both have lower accumulated strain than ACBC28. CRM-E with or without delayed overlay is estimated to be more rutting resistant than ACBC28 when measured after 6 or 12 months.

CRM-E Section 2 (3-day delayed overlay) shows lower permanent deformation than CRM-E Section 1 (same day overlay) after both 6 months (Phase 3) and 12 months (Phase 4). The dynamic creep accumulated micro strain results are consistent with the resilient modulus test results seen in Fig. 7. Mixtures with higher stiffness values at high temperature are generally expected to have greater rutting resistance.

6.3. Indirect tensile strength and tensile strength ratio testing

Indirect Tensile Strength (ITS) testing was carried out on field cores obtained from Sections 1, 2 and 3 with the purpose of comparing the properties of the CRM-E and ACBC28 layers over time. Moisture sensitivity was assessed by conditioning specimens and evaluating TSR of unconditioned and condition specimens as defined in AASHTO PP-86 [31]. Four cores 100 mm in diameter were used for ITS testing of each specific section and phase. Core samples were divided into two sets. One set is unconditioned (referred to as dry samples), while the other set is conditioned in a water bath at 25 °C for 24 h before testing (referred to as wet samples). Testing was conducted at 25 °C using the Marshall Stability Tester at a 50.8 mm/minute deformation rate. The Tensile Strength (TSR) ratio was calculated by dividing the conditioned ITS by the unconditioned ITS to evaluate moisture resistance. The JMF established an unconditioned ITS value of 0.340 MPa and a TSR of 100% on cured laboratory samples.

ITS results of the field cores are summarized in Fig. 9. The error bars represent one standard deviation. Only two ACBC28 cores were tested for dry and wet ITS after 6 months (Phase 3) and 12 months (Phase 4).

The average CRM-E Section 1 (same day overlay) dry ITS is greater than Section 2 (3-day delayed overlay) at Phase 1 (after 14 days)

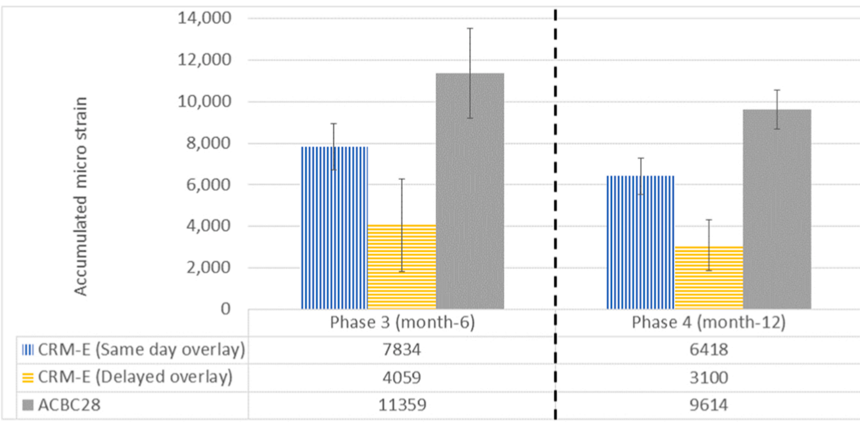


Fig. 8. Accumulated micro strain (permanent deformation) from dynamic creep for CRM-E and ACBC28 after 6 months and 12 months.

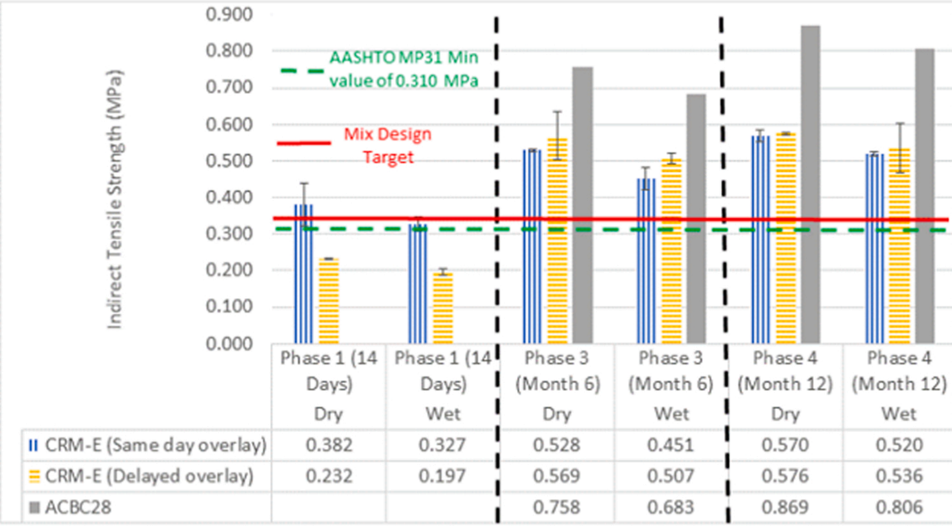


Fig. 9. Indirect Tensile Strength (ITS) results of the CRM-E and ACBC28 materials obtained from field cores 14 days, 6 months and 12 months.

by 39%. Immediate placement of the HMA overlay positively impacted the CRM-E ITS value. As in the case of the resilient modulus results, it is believed that the lower air voids of CRM-E by 2.8% of Section 1 compared to Section 2 experienced by placing the HMA on the same day compared to waiting for 3 days was a key factor in yielding greater ITS value. In addition to the extra density gain in the CRM-E, placing the HMA overlay on the same day may contribute to increasing ITS by forcing some moisture to escape from the CRM-E as a result of the HMA overlay heat exposure and providing extra curing from this accelerated moisture loss.

The dry ITS of Section 1 (same day overlay) and Section 2 (delayed overlay) were 0.382 MPa and 0.232 MPa respectively after 14 days compared to the design target of 0.340 MPa and the minimum specification limit of 0.310 MPa. Based on the ITS strength development behavior in the field over time, a conservative estimate is that both the design target and minimum specification limit can be exceeded after one month of curing in the field either with immediate or delayed overlay based on the Taiping project conditions. The design target according to ASSHTO PP86 is obtained after curing the unsealed specimens in the laboratory in a forced draft oven at 60 °C. This curing condition is not representative of the field conditions and hinders cement hydration resulting in lower ITS values when using cement than what can be achieved in-situ. CRM-E from both Sections 1 and 2 were able to easily exceed the design value of 0.340 MPa after 6 months.

The CRM-E dry and wet ITS values increased noticeably between the 14 days to 3-month time frame for both Section 1 (same day overlay of the CRM-E) and Section 2 (3-day delayed overlay of the CRM-E). CRM-E Section 1 and Section 2 showed a dry ITS increase of

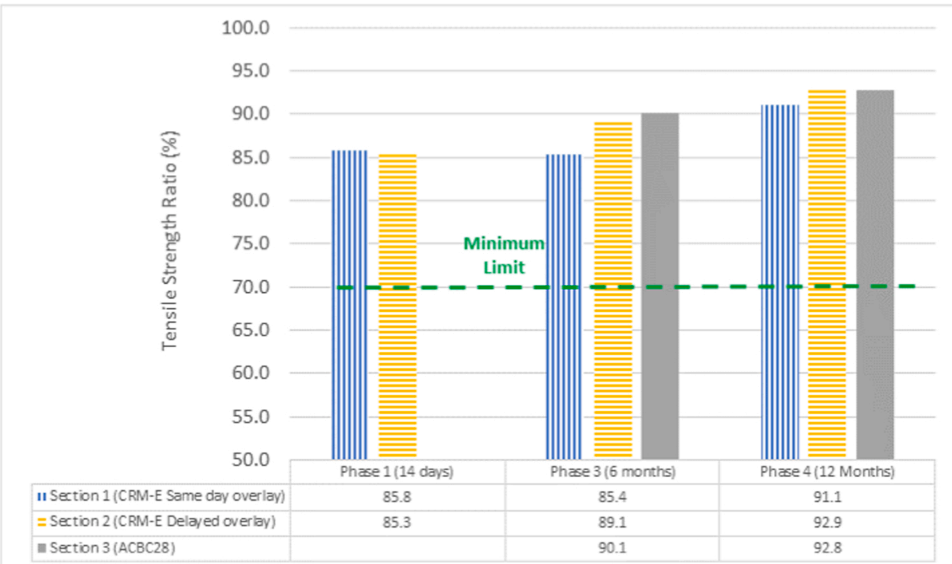


Fig. 10. Tensile Strength Ration (TSR) results of the CRM-E and ACBC28 materials obtained from field cores after 14 days, 6 months and 12 months.

38% and 146% respectively between 14 days and 6 months. The wet ITS followed a similar trend with an increase of 38% and 157% respectively. CRM-E ITS continued to increase between 6 and 12 months but at a slower rate. Specifically, CRM-E with same day overlay (Section 1) and CRM-E with delayed overlay (Section 2) showed a dry ITS increase of 8% and 1% respectively between 3 and 6 months.

CRM-E ITS values from Sections 1 and 2 were within 1% after 12 months. The effect of either waiting 3 days before placing the HMA overlay over the CRM-E or placing the overlay on the same day did not have much impact on dry ITS after 12 months.

ACBC28 dry and wet ITS values are significantly greater than CRM-E. It is to be expected as ITS is highly sensitive to air voids with lower voids resulting in higher ITS values. ACBC28 design voids is close to 4%, while CRM-E average design air voids were 12.7%.

TSR results of the field cores are summarized in Fig. 10. All the binder course mixtures exceeded the minimum TSR requirement of 70% with values ranging between 85% and 93% between 14 days and 12 months. The overall trend is that TSR increased for all the mixtures between 14 days and 12 months. The TSR results after 12 months were 91.1%, 92.9% and 92.8% for CRM-E with same day overlay, CRM-E with delayed overlay and ACBC28 binder courses respectively. This indicates that all the mixtures should be moisture resistant based on the TSR results.

6.4. Falling weight deflectometer (FWD)

FWD testing was performed every 20 m along the 300-meter-long project. The seven deflection readings were measured by geophones d_1 to d_7 at standardized radial distances (0, 0.3, 0.6, 0.9, 1.2, 1.5, 2.1 m) from the center of the loading plate with a load pressure of 700 kPa. Air and pavement surface temperatures were recorded during testing at each FWD drop location. Additionally, holes were drilled to measure the temperature at the mid bituminous layer depth. The center FWD deflection parameters (d_1) can be used as an indication of overall pavement response [37,38]. The bituminous layer mid depth temperature was used to convert the center deflections to a reference temperature of 21°C [39]. The lower d_1, the stronger the pavement. A value of d_1 less than 500×10^{-3} mm can be used as an indication that the pavement is structurally sound [40].

A comparison between all sections and phases of FWD central deflection (d_1) profiles is shown in Fig. 11. Fiftieth percentile deflections are presented in Table 6 for comparison by section over time. The average pre-condition was very similar between Section 1 and Section 3 with center deflection within 5%. Section 2 pre-condition had an average deflection 20% greater than Section 3 revealing a slightly weaker pavement structure. CRM-E Section 1 (same day overlay) showed a reduction in central deflection from 335×10^{-3} mm to 309×10^{-3} mm between 3 and 12 months or 7.8% decrease. CRM-E Section 2 (3-day delayed overlay) showed a reduction in central deflection from 365×10^{-3} mm to 334×10^{-3} mm between 3 and 12 months or 8.5% decrease. The effect of immediate or delayed HMA overlay over the CRM-E had a negligible effect on average center deflection change between 3 and 12 months. The reduction in average deflection for both CRM-E sections indicates that the CRM-E layers contribute to improving the overall structural roadway capacity between 3 and 12 months. This effect was not observed for Section 3 with the full HMA mill and pave option as the average center deflection increased by 4.3% between 3 and 12 months indicating that the structure is getting slightly weaker.

The FWD center deflection results indicate that all the sections are in a good structural condition after 12 months with average d_1 central deflection noticeably less than 500×10^{-3} mm.

The average deflection (d_6) that is 1.5 m from the center and indicative of subgrade condition was consistent for all the sections and phases as deflections remained unchanged over time indicating that no subgrade weakening is occurring.

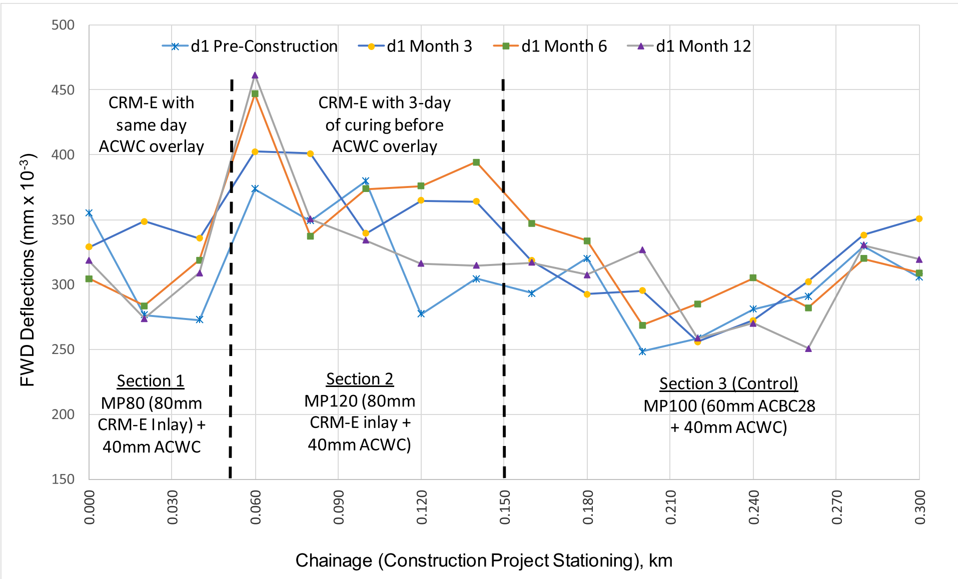


Fig. 11. Comparison of FWD central deflections (d_1) between all phases and sections.

Table 6
50th percentile deflections (x 10^{-3} mm).

Section	Pre-construction		Phase 2 (3 months)		Phase 3 (6 months)		Phase 4 (12 months)	
	d_1	d_6	d_1	d_6	d_1	d_6	d_1	d_6
1	277	83	335	81	304	83	309	84
2	349	82	365	89	376	85	334	85
3	292	73	299	76	307	79	312	77

6.5. Field rutting and cracking measurements

Rutting and surface crack measurements were performed using the Multi Laser Profiler (MLP) test system developed by Australia Road Research Board (ARRB). The MLP system that includes data acquisition and processing toolkits was utilized for Phase 2, 3 and 4. Surface cracks were recorded using the Automated Crack Detection (ACD) cameras attached to the MLP test vehicle. Rutting measurements were carried out using an MLP test vehicle, collecting values every 10 m.

Rutting resistance is considered good when the depth is less than 5 mm according to Malaysian guidelines JKR 2015 [24]. All sections show excellent rutting resistance with an average rut depth less than 2.5 mm after 12 months measured within 3–12 months, as reported in Table 7. Using the average rutting of the section with the highest value of 2.36 mm and adding 2 standard deviations (1.08 mm) means that 95% of the data is expected to have a rut depth of less than 4.5 mm (0.18 in.).

Sections were also visually checked using a straight edge to confirm the absence of rutting.

Surface cracks were measured using Automated Crack Detection (ACD) cameras attached to the MLP test vehicle. The crack detection system software was used to process and interpret the crack data. There were no cracks in any of the sections in any of the phases that could be detected. A visual condition inspection was carried out at Month-12 on the trial sections, which confirmed that there were no cracks.

7. Conclusions and recommendations

A pavement rehabilitation demonstration using CRM-E took place in Taiping, Malaysia on August 25, 2020. The project was divided in three sections to evaluate mill and pave strategies using CRM-E as an alternative to asphalt concrete for the binder course. The wearing course was 4 cm of the same asphalt concrete for the three sections. The difference between Sections 1 and 2 that used 80 mm of CRM-E was to either pave the asphalt concrete 4 h after the CRM-E or to delay its application for 3 days to give additional time to the CRM-E for curing. Section 3 was the traditional mill and pave alternative that consisted of 60 mm of asphalt concrete binder course (ACBC28) followed on the same day with 40 mm of asphalt concrete wearing course (ACWC14). All the sections are along the same lane direction. The overall existing pavement condition was relatively similar based on distresses, FWD deflections, subgrade structural capacity and thickness of the existing pavement layers.

The bitumen emulsion CRM-E was produced at a central plant using 100% RAP fractionated in three RAP stockpile sizes using 1.5% cement and 3.5% bitumen emulsion by weight of dry RAP. The average moisture content in the CRM-E mixture was 4.8% by weight of mixture after the emulsion was added. Satisfactory compaction of the CRM-E sections could be achieved with an average relative density in excess of 97% compared to the laboratory design target density.

The field performance of the rehabilitated sections was monitored in 4 phases. The pavement monitoring of Phase 1, 2, 3 and 4 was accomplished after 14 days, 3 months, 6 months and 12 months, respectively. Cores were taken during Phase 1–4 to compare ACBC28 and CRM-E layer properties in terms of resilient modulus, dynamic creep and indirect tensile strength. The performance of the sections was assessed based on FWD, field rutting measurements, and cracking distress surveys. The following conclusions can be drawn from this study:

- The average air voids of the CRM-E with same day overlay was at least 1% lower than the CRM-E with delayed overlay when measured on field cores after 14 days, 6 months and 12 months. The heat from the HMA and extra rolling in the early CRM-E strength gain phase is a direct benefit from same day overlay to increase CRM-E density.
- The binder layer resilient modulus of CRM-E and ACBC28 of all sections increased over time. CRM-E largest modulus increase took place within half a year after placement. The CRM-E modulus average values of Sections 1 and 2 at 25 °C were relatively close (within 4%) after 12 months. In other words, immediate or delayed HMA overlay over the CRM-E does not seem to impact the longer-term stiffness development of CRM-E.
- The CRM-E resilient modulus values were greater than ACBC28 when measured at 6 months and remained greater at 12 months. The CRM-E emulsion and cement combination was effective at increasing modulus value as a function of time.
- The finding that in-place modulus values of CRM-E after 6 months and 12 months are greater than ACBC28 supports the fact that ACBC28 (asphalt concrete binder course) could be substituted for CRM-E at the same thickness.
- Dynamic creep was measured on field cores to assess in-place material rut resistance. Both CRM-E sections had less accumulated permanent deformation than ACBC28 after 6 and 12 months.
- Indirect Tensile Strength (ITS) testing of CRM-E and ACBC28 materials from field cores after 14 days, 6 months and 12 months was conducted. The largest increase in CRM-E dry ITS occurred between 14 days and 6 months. CRM-E with same day overlay and CRM-

Table 7
Average rut depth measured using Multi Laser Profiler (MLP) test system.

Section	Rutting depth measured every 10 m, mm					
	Phase 2 (3 months)		Phase 3 (6 months)		Phase 4 (12 months)	
	Average	σ	Average	σ	Average	σ
1 (CRM-E with immediate overlay) Chainage 0 + 050	1.55	0.23	2.36	1.08	1.46	0.12
2 (CRM-E with delayed overlay) Chainage + 050–150	2.24	1.02	2.11	0.75	1.98	0.62
3 (Traditional HMA mill and pave) Chainage + 150–300	1.53	0.47	2.35	0.66	1.91	0.31

Note: standard deviation (σ)

E with 3-day delayed overaly resulted in field ITS values noticeably greater than the design target value after 6 months. This difference can be explained by the fact that unsealed specimens curing in the laboratory during the mixture design process in a forced draft oven at 60 °C is not representative of the field conditions when cement is used.

- Immediate or delayed CRM-E has minimal impact on CRM-E dry ITS after 12 months as average ITS values ended up within 1%. CRM-E ITS is lower than ACBC28 because of air voids differences between the two different mixture types.
- All the binder course mixtures exceeded the minimum Tensile Strength Ratio (TSR) requirement of 70% with values ranging between 85% and 93% on cores obtained after 14 days, 6 months and 12 months. The CRM-E and ACBC28 mixtures had a TSR value in excess of 91% after 12 months, indicating that all the mixtures should resist moisture damage adequately.
- FWD testing was conducted to assess the structural condition of each section over time. The results indicate that all the sections are in a good structural condition after 12 months with average central deflections ranging between 309 and 334×10^{-3} mm. The reduction in average deflection between 3 and 12 months for the CRM-E sections with same day and delayed overlay were 7.8% and 8.5% respectively indicating that the CRM-E layers contribute to improving the overall structural roadway capacity between 3 and 12 months.
- Roadway rutting depth was gathered every 10 m using a van equipped with Multi Laser Profiler (MLP) for evaluation at 3 months, 6 months and 12 months. All sections show excellent rutting resistance with an average rut depth less than 2.5 mm after 12 months with no noticeable increase within the 3–12-month timeframe. Immediate placement of the HMA overlay over the CRM-E had no impact on the field's rutting performance when measured up to 12 months compared to the CRM-E with delayed HMA overlay or the traditional HMA mill and pave options.
- There were no cracks in any of the sections after 12 months.

The following recommendations are made:

- The use of covered RAP stockpiles should be implemented on future projects to have better control of moisture in RAP stockpiles especially in locations with high annual precipitations.
- There are many projects that have been constructed in China in various climatic environments on the expressways in recent years with asphalt concrete binder course replaced by CRM-E at the same thickness with only 4–5 cm of wearing course or SMA overlays placed on the same day over the CRM-E. Follow up of these past projects or new demonstration projects should be undertaken to document the viability of CRM-E and ACBC layer thickness equivalency and same day HMA overlay of CRM-E on heavily trafficked roadways.

CRediT authorship contribution statement

The authors confirm contribution to the paper as follows: Stephane Charmot: Conceptualization, Methodology, Formal analysis, Writing – original draft. Sek Yee Te: Writing – review and editing. Rino Effendy Abu Haris: Supervision, Project administration. Mohd Azli Ayob: Validation, Resources. Mohammad Riad Ramzi: Formal analysis. Dini Dayana Mustaffa Kamal: Writing – Review and editing. Azmi Atan: Supervision. All authors contributed to editing of manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data from this paper is available upon request from the author.

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