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Mechanical Properties of Cold Mix Asphalt (CMA) Mixed with Recycled Asphalt Pavement

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Abstract: From the perspective of sustainability and environmental concerns, the use of cold-mix asphalt (CMA) and recycled asphalt pavement (RAP) is more advantageous than the use of hot mix asphalt (HMA) and warm mix asphalt (WMA). Some researchers used a mixture of CMA and RAP to improve the mechanical properties of pavement and made it more economical. However, only a few studies have focused on using a high content of RAP—particularly 100% RAP—as the virgin aggregate. Therefore, this study aims to analyse cold-mix asphalt (CMA) using 100% recycled asphalt pavement (RAP) instead of virgin aggregate raw materials and to determine the best mixture for the production of environmentally friendly asphalt. It is necessary to investigate the performance of CMA mixed with RAP in terms of the resilient modulus, indirect tensile strength, fatigue and rutting resistance. In this study, the percentage of bitumen emulsions added is 2%, 2.5%, 3%, 3.5%, and 4%, along with 100% RAP material. The results indicate that the fatigue life of the RAP mixture increased by 49.34% with the addition of bitumen emulsion (BE) from 2% to 4%, while the wheel tracking test experienced a decrease in rutting depth along with an increase in BE dose of 4%, which was 9 mm. The mixture containing 4% asphalt emulsion has the best performance. The results suggested that increasing the BE dosage increases the resistance against rutting and fatigue.

Keywords: cold-mix asphalt; reclaimed asphalt pavement material; indirect tensile strength

Citation: Chegenizadeh, A.; Tufilli, A.; Arumdani, I.S.; Budihardjo, M.A.; Dadras, E.; Nikraz, H. Mechanical Properties of Cold Mix Asphalt (CMA) Mixed with Recycled Asphalt Pavement. *Infrastructures* **2022**, *7*, 45. https://doi.org/10.3390/infrastructures7040045

Academic Editor: Rui Micaelo

Received: 9 February 2022
Accepted: 17 March 2022
Published: 22 March 2022

1. Introduction

The application of recycled and re-usable materials in geotechnical and pavement engineering has been an interest of many researchers (among them: [1–6]). There are different studies that consider different aspects of asphalt testing in terms of major parameters (i.e., rutting and fatigue) (among them [7,8]).

The behaviour of the mixture of the recycled material and aggregate matrix in asphalt specimens is a challenge for new investigations. When waste is added to asphalt or other mixes then more precise testing is required by standards. Cold-mix asphalt (CMA) is a type of asphalt that differs from other asphalt mixtures because it produces low levels of pollution and is more economical because it does not heat aggregates in the manufacturing process [9,10]. According to Jain and Singh [11], road construction often leads to high levels of greenhouse-gas production. The use of CMA can also mitigate the main issue affecting hot-mix asphalt (HMA), which is the environmental impact of greenhouse gases that are produced owing to the high temperatures during the production process. HMA can produce a carbon footprint of 53.6 kg per ton of asphalt [12], with very high production temperatures, reaching 190 °C [10]. In comparison, WMA requires a lower production temperature, of 100–140 °C, so it is a viable alternative to HMA [13,14]. However, the best substitute material is CMA because it requires a production temperature of about 40 °C and is more environmentally friendly. Further, it is more cost-effective because the energy used is lower [15]. In addition, the CO_2 emissions produced are lower, at about 36.1 kg per ton of CMA [12].

The virgin aggregate commonly used in asphalt mixtures comprises 95.55% of the total weight [16]. These materials are directly obtained from mines, which requires significant amounts of energy and harms the environment. Reclaimed asphalt pavement (RAP) can be used as a substitute to mitigate this issue. Asphalt or RAP waste is generated from the demolition and reconstruction of millions of kilometres of road during maintenance, which leads to a build-up of waste in landfills. In 2018, in the U.S. alone, 100 million tons of RAP were collected, the estimated landfill savings for which are 61.4 million cubic meters [17]. Kamariya, Zala [18] found that the increasing use of RAP in asphalt mixtures significantly reduces greenhouse-gas emissions because it does not require fuel to obtain and produce fresh mixing materials. Rahman et al. [19] and Chan et al. [20] determined that the use of recycled aggregates can help overcome issues related to waste disposal into the environment. Using RAP can make the process more economical, as the usage of virgin aggregates is reduced. Furthermore, binder consumption can be reduced through the use of rejuvenating agents to extract old aggregate binders [18]. Therefore, as indicated by Rahman, Imteaz [19] and Wijayasundara, Crawford [21], the use of recycled aggregate can offer both environmental and economic benefits. However, to fully leverage these advantages, the structural performance and durability of the mix should satisfy the requirements of the alternative design [22].

Some researchers have improved the mechanical properties of asphalt mixes and made them more economical through the use of a mixture of CMA and RAP. According to Martinho, Picado-Santos [23], the money spent on virgin aggregate amounted to 16.6% of the total cost of asphalt production. Further, the energy emitted during the production process is only in the form of small-scale destruction and filtration, profiling, and short-haul material-retrieval transportation. The pavement industry also benefits from the utilization of RAP, and previous road-construction materials contribute to 75% of the greenhouse-gas emissions, with an average of 190 tons of CO_2 per kilometre of the road [24].

Several studies on the mixture of HMA or WMA with a high content of RAP have been conducted. Zhao, Huang [25] found that a mix of WMA and RAP—ranging from 0% to 50%—had a rutting resistance and moisture susceptibility better than an HMA and RAP mixture. A study by Lopes, Gabet [26] on the mixture of WMA and 50% RAP showed good performance in terms of rutting resistance but had a higher propensity to fatigue failure in comparison to WMA blends without RAP. However, few studies have been conducted on the use of high-content RAP, particularly 100% RAP, as the virgin aggregate. Likewise, research from Bocci, Graziani [27] regarding the use of cold recycled asphalt base (CRAB) containing 100% reclaimed asphalt (RA) for undercoats for heavy traffic roads in Italy found good construction results. The stiffness moduli value indicates comparable results with the use of HMA. In addition, the indirect tensile strength (ITS) test obtained high results and low air void content from the tested parts. However, this study is only intended for heavy traffic highways located in the Italian region and it cannot be generalized. In another study conducted by Godenzoni, Graziani [28], the complex modulus of cold recycled asphalt (CRA) was investigated incorporating foamed bitumen. The outcome suggested that linear viscoelastic (LVE) of CRA can be characterised the same way as asphalt mixture. Similarly in another study conducted by Graziani, Raschia [29], the application of fine aggregate was investigated into the rheological behaviour of cold recycled materials (CRM). The results suggested fine aggregate matrix (FAM) mortar affected the curing and the thermo-rheological behavior of the CRM mixture. Therefore, this paper aims to develop knowledge on CMA using 100% RAP instead of virgin aggregate raw materials and design the best mixture to produce environmentally friendly asphalt that is also cost-effective and satisfies the structural and durability requirements.

To achieve the aforementioned goals, experimental tests on different asphalt mixtures are conducted, including moisture and optimum moisture content (OMC) tests to determine the amount of bitumen and water that comprise the best mixture. This is followed by resilient modulus, indirect tensile strength (ITS), and rutting resistance tests. These are conducted to determine the best mix proportion, with the highest strength value. According to Meijide [30], the curing time of CMA is, on average, about five days. Therefore, this study selected a curing time for one week to be representative of the initial performance of asphalt mixtures and curing times of 4, 8, and 12 weeks as representative of short-term, medium-term, and long-term asphalt performances, respectively. The curing time has two constraints, namely the drying and soaking times, which reflect the harshest conditions in actual situations. It should be noted that the purpose of this research is to consider the possibility of RAP incorporation, and this paper should be read along with the standards if industry application is required. The objective of this project is to develop knowledge of cold mix asphalt where 100% RAP is used as a complete substitute for virgin aggregate material for Western Australia. Specifically, the optimum mix design will be determined through laboratory analysis. The information obtained will assist and encourage asphalt manufacturers to produce a cold mix asphalt pavement, which incorporates close to 95% recycled materials and carries many benefits as outlined in this report. Although some research was conducted, still in Western Australia due to their different climate and the resultant significant changes in temperature that occur during a day, there is a significant need to conduct this research.

2. Materials and Methods

2.1. Material

The RAP used in this study was obtained from the reconstructed asphalt of a local Western Australian asphalt company. The asphalt was destroyed using a RAP crusher and filtered followed by a particle size distribution test. Particle shape and size have a great effect on the performance of any mixture [31]. This test aimed to ascertain the structure of the RAP material according to the Australian Standard As/Nzs 2891.13.1:2013 [32], which uses 12 sieves. The result is the percentage of matter that passes through each sieve divided by the total mass. Table 1 shows the results for the RAP particle size distribution test. The selected asphalt emulsion was a type of cationic slow set (CSS) because of how it coated the RAP material, which makes it more suitable for CMA.

Table 1. RAP particle size distribution test.

% Passing (Air Dry)	Sieve (mm)
100	13.20
97.0	9.50
81.0	6.70
64.0	4.75
43.0	2.36
28.9	1.18
18.5	0.60
8.1	0.30
2.9	0.15
1.4	0.075

Before further testing, the RAP must be tested for its initial and optimum moisture content (OMC). According to Table 2, the average moisture content of RAP, calculated according to the Main Roads Western Australia WA 110.1-2011 [33] method, is 0.60%. Test results are used to determine the amount of water to be added to the mixture until it reaches the OMC. The OMC of RAP is calculated based on the Main Roads Western

Australia test method number 133.1—2017, with a 5.1% moisture being the OMC. Figure 1 shows the results of the optimum moisture content test.

Table 2. RAP characteristics.

Parameter	Unit	Value
Particle Density	(g/cm^3)	2.32
Bitumen Content	(%)	4.4
Penetration	(10^{-1} mm)	8
Moisture Content	(%)	0.60

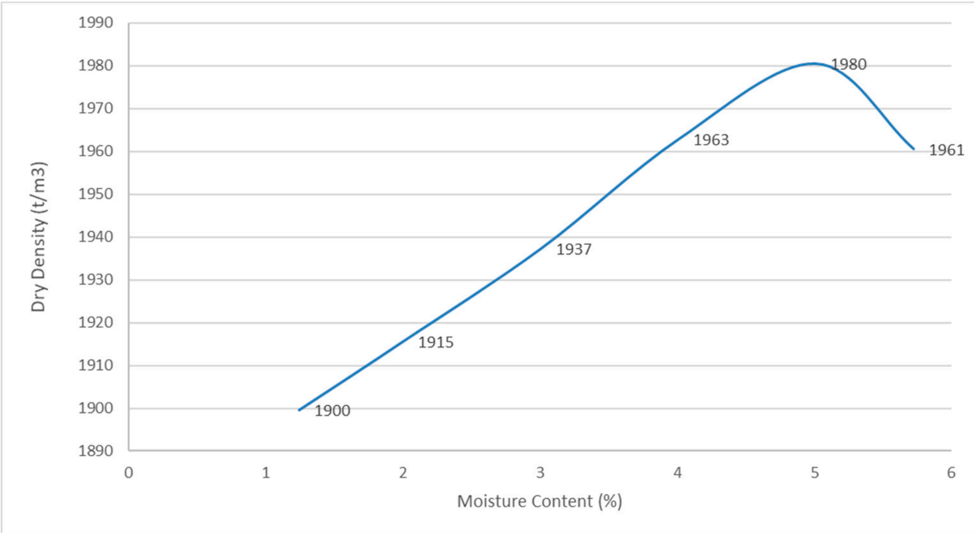

Figure 1. Results of the optimum moisture content (OMC) test.

The RAP bitumen content is obtained using an asphalt extraction tool and centrifuge, as shown in Figure 2, according to the Australia [33] standard Bitumen Content and Particle Size Distribution of Asphalt and Stabilised Soil: Centrifuge Method 730.1. The value of asphalt content is the amount of asphalt content previously left in the RAP and asphalt from added asphalt emulsions.

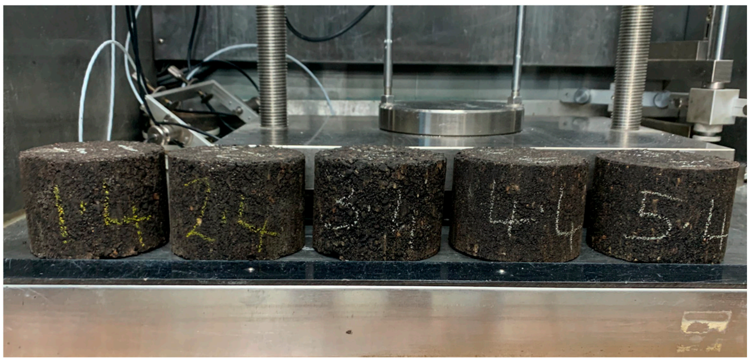

Figure 2. Marshall Compactor samples.

CSS bitumen emulsion, which is used in this study, was obtained from a local Western Australian bitumen supplier. The emulsion characteristics are shown in Table 3. The cationic emulsion was a chemically stabilised system. The slow-setting emulsion was more stable than medium- and rapid-setting emulsions, and was most suitable for applications involving CMA, primarily owing to the way in which it coats the RAP and the way in which it sets. Table 3 presents binder characteristics.

Table 3. Emulsion and binder characteristics.

Emulsion			Binder		
pH	**Setting Time**	**Density Conversion**	**Melting Point of Bitumen**	**Boiling Point**	**Colour**
2.5	>8 min	985 (L/te)	>100 °C	>250 °C	Black

2.2. Mix Design

The amount of bitumen emulsions added was 2%, 2.5%, 3%, 3.5%, and 4%, with 100% RAP. Details regarding the amount of bitumen emulsion and water added to the asphalt mixture are given in Table 4. The asphalt mixture was produced using a Wirtgen WLM 30 pug mill (twin-shaft continuous mixer) because the speed and time could be adjusted to replicate the parameters of asphalt production. Furthermore, the produced CMA was compacted using a Marshall Compactor according to the Australian Standard As/Nzs 2891.5:2015 [32]. and consistent with the Australia Standard test method Australia, M.R.W., 2017 [34]. Each sample was given 75 blows to emulate real-life asphalt conditions. The Marshall samples are shown in Figure 2.

Table 4. Material contents.

Contents					
Bitumen emulsion added	2.00%	2.50%	3.00%	3.50%	4.00%
Bitumen from emulsion	1.20%	1.50%	1.80%	2.10%	2.40%
Total bitumen	5.60%	5.90%	6.20%	6.50%	6.80%
Moisture from emulsion	0.80%	1.00%	1.20%	1.40%	1.60%
Total moisture	1.40%	1.60%	1.80%	2.00%	2.20%
Moisture to be added for OMC	3.70%	3.50%	3.30%	3.10%	2.90%
Marshall sample (kg)	1.5	1.5	1.5	1.5	1.5
Cooper tracker sample (kg)	10	10	10	10	10
Weight of RAP (kg)	23.5	23.5	23.5	23.5	23.5
Bitumen emulsion required (kg)	0.47	0.5875	0.705	0.8225	0.94
Water required (kg)	0.87	0.82	0.78	0.73	0.68

The AGPT-T220-05 test method, designed by Austroads [35], was used for compaction with Cooper slab compactors. Moulds measuring 305 mm × 305 mm × 50 mm were used to obtain the optimal compaction, similar to that of industrial asphalt. The blended design was then cured with four different curing times, i.e., one, four, eight, and twelve weeks, to reflect the mixed design's initial and long-term performance. The mixture was tested under two different conditions, dry and soaked. The sample was soaked for 24 h at a temperature of 25 °C to replicate the mean Western Australian weather conditions.

2.3. Testing Methods

The test methods and procedures are outlined in Figure 3. The first stage in this research is to determine the background and review the literature related to RAP and CMA. Then, identify the characteristics of the materials used and prepare the CSS emulsion. The next step is mixing RAP and bitumen emulsion with variations of 1.5%, 2%, 2.5%, 3.5%, & 4% using the Wirtgen WLB30S tool. After mixing, it was compacted with a marshall compactor and cured. The last stage was a laboratory test consisting of ITS, Dynamic Modulus, Wheel Tracking, and 4-Point Bending Fatigue.

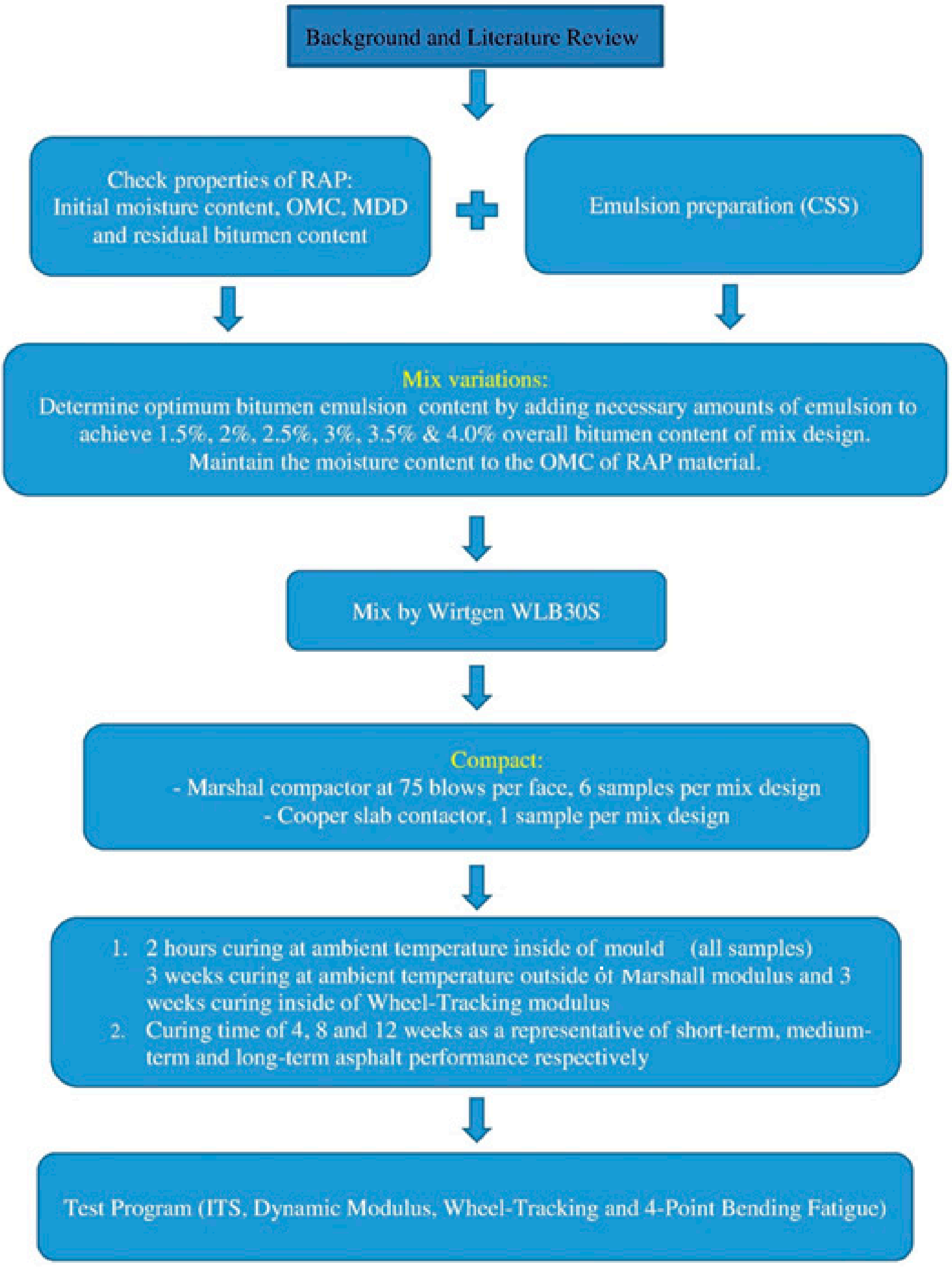

Figure 3. Test methodology.

2.3.1. Indirect Tensile Strength Test

The strength of materials always is an important factor, which affects the stability of the whole mixture [6]. The Indirect Tensile Strength (ITS) test aims to determine the characteristics of the resistance of the mixture to failure. This test referred to Main Roads Western Australia's WA 142.1—2012 standards [36].

The test results for samples with different soaked and dry conditions were compared to the test results obtained by Huan [37], which indicated the ITS of foam bitumen stabilised material. This comparison helps assess the performance of CMA with 100% RAP. The ITS test was conducted at 25 °C with a loading rate of 50 mm/min. For each condition, five samples were constructed and tested.

2.3.2. Resilient Modulus Test

This test referred to the Australian Standard AS 2891.13.1-2013 [38], using universal testing machines (UTMs), and samples tested at a temperature of 25 °C, rise time 40 ms, pulse repetition period 3000 ms, recovered horizontal strain 50 ± 20 macrostrain.

2.3.3. Wheel Tracking Test

Wheel tracking Test refers to Austroads [39] AGPT-T231-6 standard, with a standard sample thickness of 50 ± 5 mm, a vertical load of 700 ± 20 N, a rate of 42 ± 0.5 passes/min, a temperature of 60 ± 1 °C, and a minimum load-pass amount of 10,000. Details of the asphalt mixture performance criteria based on depth are presented in Table 5. The superior category is indicated by a depth of less than 3.5 mm, while a depth of more than 13 mm is categorized as a poor (low) mix. The wheel tracking apparatus used is shown in Figure 4.

Table 5. Mixed performance criteria (AGPT-T231-6).

Superior	**Good**	**Medium**	**Low**
<3.5 mm	3.5–8 mm	8–13 mm	>13 mm

Figure 4. Cooper wheel tracker device.

2.3.4. Four-Point Bending Test: Fatigue Test

Four-point bending test was conducted following the AG: PT/T233. The beam for the fatigue testing had a width of 63.5 with ±5 mm, a vertical depth of 50 with ±5 mm, and a length of 390 ± 5 mm. The fatigue beam test samples were cut in all faces and, despite the fact that there was a ±5 mm tolerance for each measurement, ±2 mm was targeted to improve repeatability. The test was conducted in strain control mode, samples tested at a temperature of 20 °C with harvest loading 10 ± 0.5 Hz, to peak tensile strain for the 50th and subsequent cycle = 400), load up to 1,000,000 load cycle or up to load cycles corresponding to 50% of the initial flexural strength.

3. Results

3.1. Resilient Modulus Test

Figure 5 shows the results of resilient modulus testing using different curing times (i.e., 1 week, 4 weeks, 8 weeks, and 12 weeks). Week 1 showed the lowest value compared to other curing times, between 771 MPa when the dose was 2% to 851 MPa using a 4% dose. Meanwhile, week 12 obtained the highest value in the range of 1995–2510 Mpa.

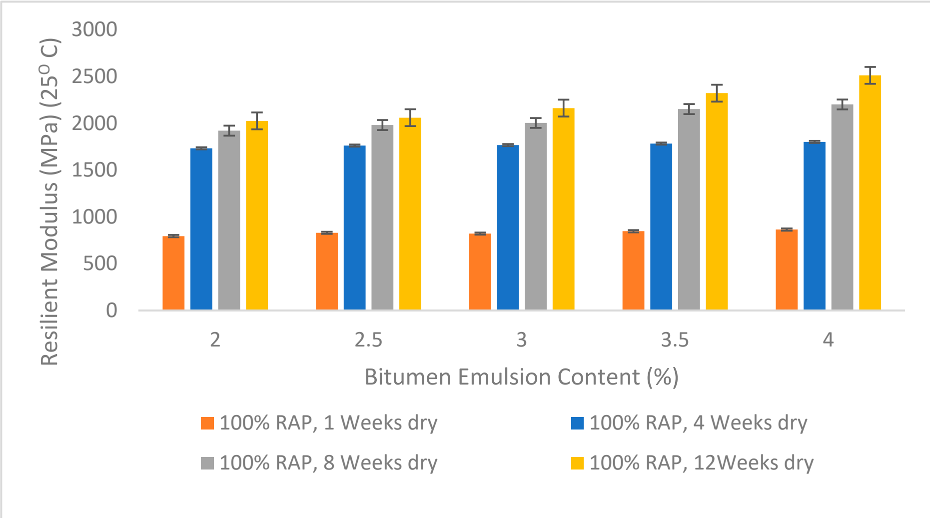

Figure 5. Resilient modulus for 100% RAP in the dry condition after 1, 4, 8, and 12 weeks.

Figure 6 shows a comparison between CMA using foam bitumen stabilised pavement [40] and asphalt using 100% RAP material, based on the results of the resilient modulus test. In comparison to foam bitumen stabilised pavement, CMA has a higher resilient modulus. The highest obtained resilient modulus value was occupied by the mixture with the addition of 3%, namely 576 Mpa.

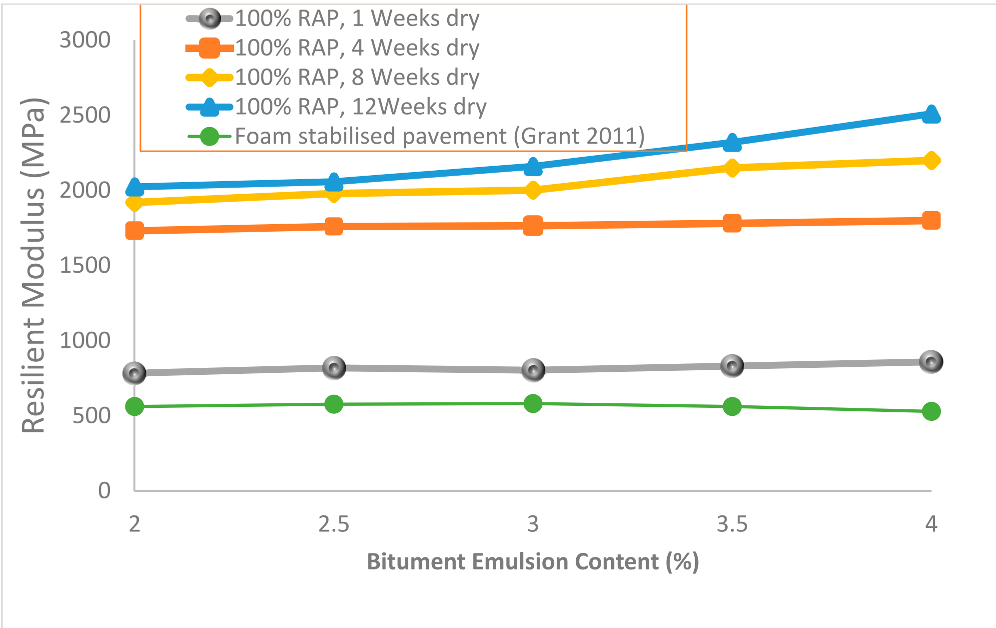

Figure 6. Resilient moduli of different asphalt mixtures.

3.2. Indirect Tensile Strength Test

The results of the ITS test are shown in Figure 7, and the maximum ITS was found in the addition of 4% bitumen emulsion under dry conditions, with a strength of 561 kPa. It was found that samples with higher total emulsion content had more strength. This is in contrast to samples with lower bitumen content, which collapse along the cracks. Overall, immersion decreased ITS compared to dry samples. These results are shown in Figure 8. As can be seen, at week 4, both the soaked and dry samples had lower ITS values at all BE doses. The mix design containing an additional 4% bituminous emulsion is considered the optimal mix design to achieve the maximum ITS value. The maximum ITS value was

561 kPa for 100% RAP cured for 12 dry weeks. While the lowest value at one week curing time is 230 kPa. Another comparison of results can be seen in Figure 9 with the 1-week dry mixture.

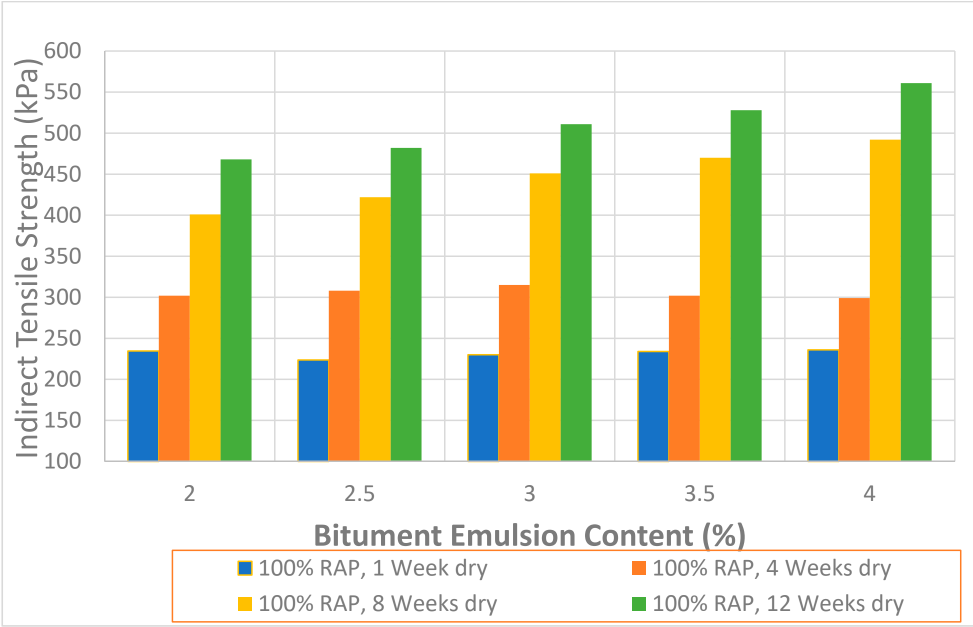

Figure 7. Results for the indirect tensile strength test after 4, 8, and 12 weeks of curing.

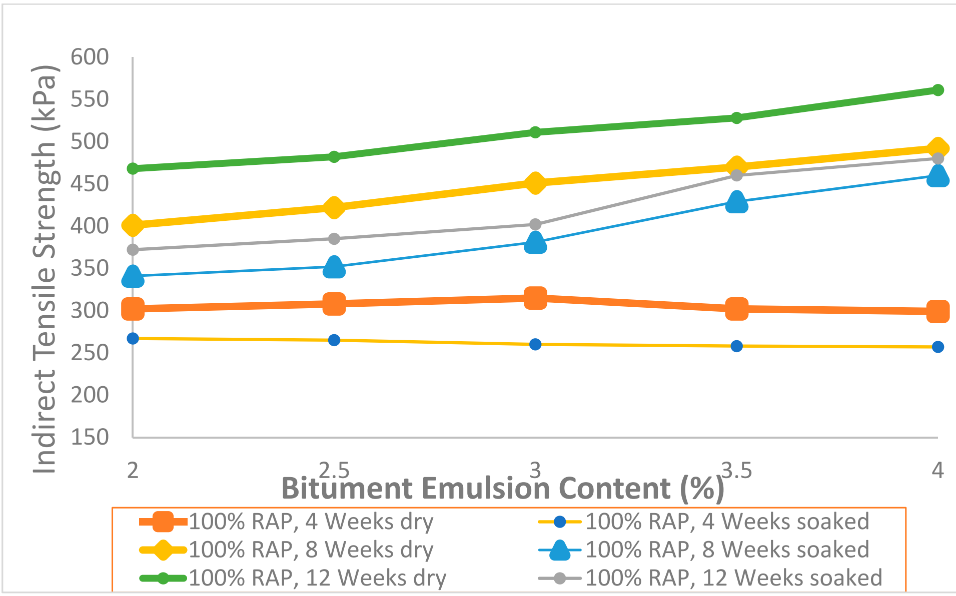

Figure 8. Results for indirect tensile strength test after different curing times in dry conditions.

3.3. Rutting Resistance Test

In Figure 10, it has been found that based on the weight of the mixture of RAP materials, 4% asphalt emulsion shows better resistance to rutting because it helps the asphalt mixture to form uniformly. Figure 11 shows a sample under wheel track test, this phenomenon is known as bleeding and occurs when a sample containing 3–4% is tested. The sample was cured for 5 days before performing the wheel tracking test.

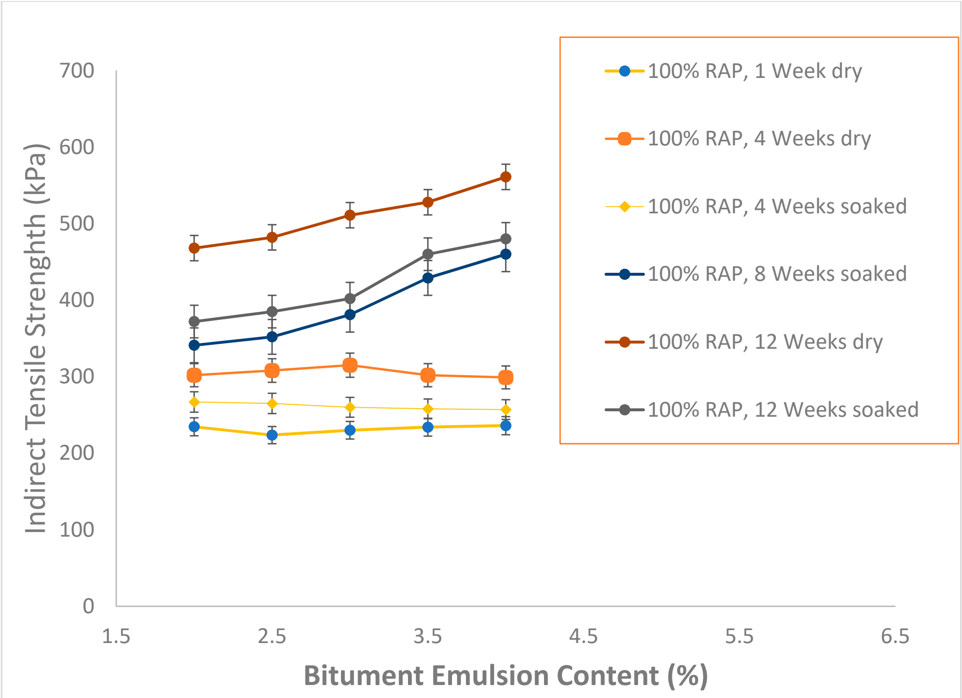

Figure 9. Indirect tensile strength of different asphalt mixes.

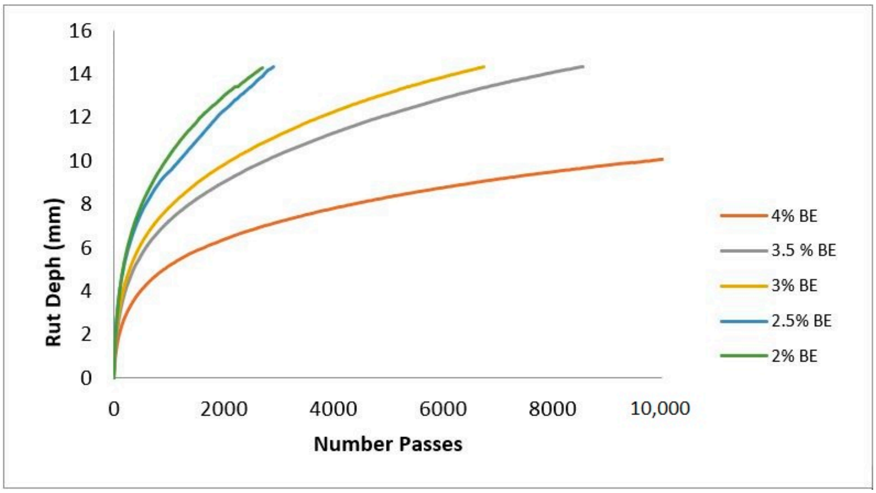

Figure 10. Wheel tracking results.

Figure 11. Wheel track testing sample.

3.4. Four-Point Bending Test

The results for this test are shown that the fatigue life of a sample with 2% BE increased from 102,245 to 152,654 cycles for 4% BE. This trend can be seen in Figure 12. The initial flexural stiffness (IFS) improved by 4% in comparison to 2% BE. The IFS for 2% BE was 4152 MPa, in comparison to 5018 MPa for 4% BE. These results are plotted in Figure 13. Table 6 summarizes the four-point bending test results.

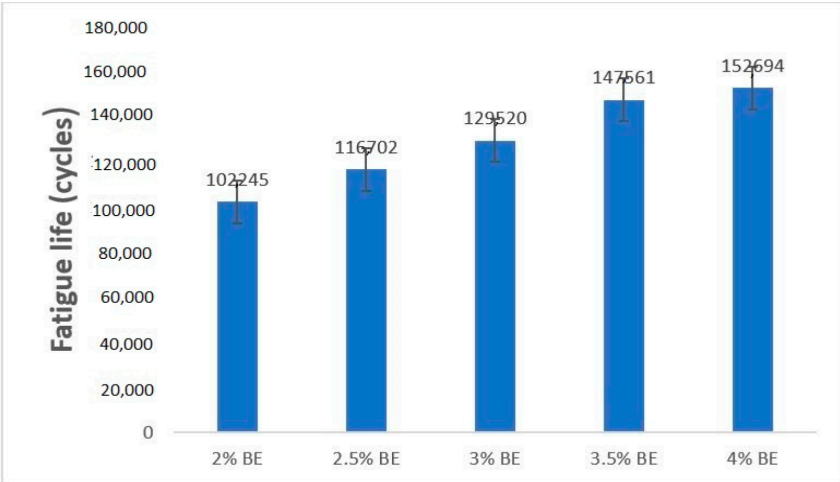

Figure 12. Results of fatigue testing for RAP.

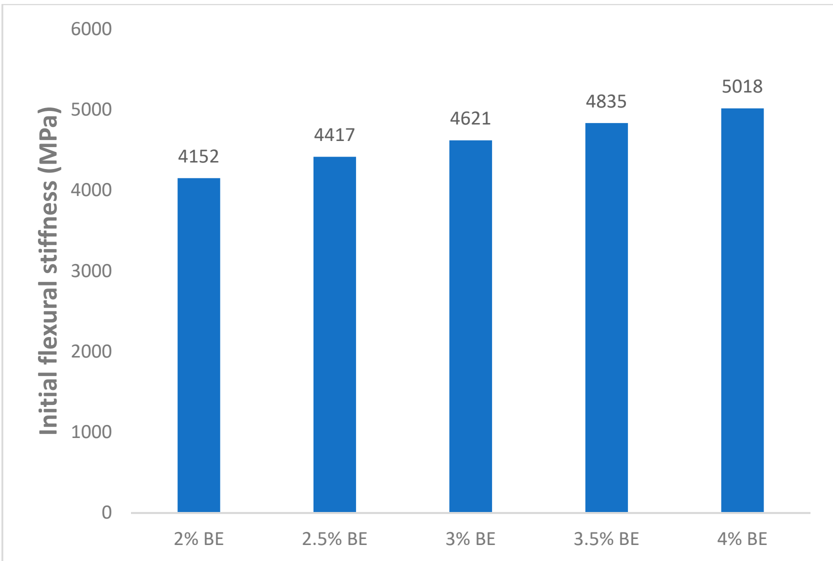

Figure 13. Results for the initial flexural stiffness of RAP.

Table 6. Four-point bending test outcome at 20°C.

Parameter	2% BE	2.5% BE	3% BE	3.5% BE	4% BE
Initial flexural stiffness (MPa)	4152	4417	4621	4835	5018
Fatigue life (cycles)	102,245	116,702	129,520	147,561	152,694

4. Discussion

Stiffness and elasticity criteria are important to consider during pavement design [41,42]; stiffness is reflected by the resilient modulus. A higher resilient modulus indicates that a structure can withstand more vibration caused by traffic without cracking. The selection of pavement-layer thickness depends on the resilient modulus [43]. As can be seen in Figure 5, four weeks may not be sufficient for curing samples that have a higher asphalt emulsion content. Therefore, more time may be required, so the resilient modulus obtained up to week four exhibits steadier behaviour than that at 8 weeks and 12 weeks with changes in emulsion dosage.

From Figure 6, the results clearly exhibit a positive trend with the addition of more emulsion to the asphalt. Further, it is clear that increasing the curing time to 12 weeks improved the effect of the emulsion on the asphalt mix. The resilient modulus test results show that cold asphalt mixtures can be alternative materials for asphalt plants, which allow the control of the products' constituents to reliably achieve the requisite performance.

The ITS value is used to design pavement and reflects the ability of the structure to withstand tensile pressures [44]. Increases in the amount of asphalt emulsion will cause the ITS to increase. This was expected because bitumen is a flexible binder of asphalt pavements. This is also supported by the idea that emulsions have higher curing times and their increased dosage acted as a stabiliser better in asphalt mixes. Overall, soaking decreased the ITS in comparison to dry samples. Both the soaked and dry samples had lower ITS values at all BE dosages. Figures 8 and 9 show that samples with higher bitumen emulsion contents had better performance in dry conditions and higher curing times in terms of ITS values.

The rutting resistance is calculated to assess the phenomenon of rutting, which leads to permanent deformation due to internal pressures that accumulate owing to traffic load [44]. Low levels of asphalt-emulsion addition make the road softer and more susceptible to rutting, particularly 2% emulsion mixtures. While Figure 11 shows due to the increase in the number of passes, the asphalt binder fills the voids of the aggregate when the asphalt is at high temperatures. Furthermore, the results for the four-point bending test are shown in Figure 12, which demonstrate that the fatigue life at 20 °C increased when bitumen emulsion increased from 2% to 4%. The initial flexural stiffness at 20 °C also increased when the BE percentage increased.

5. Conclusions

This research aimed at increasing the breadth of research on CMA using 100% RAP instead of virgin aggregate materials, and at designing the best mixture for the production of environmentally friendly asphalt while achieving optimum performance and workability. A mixture containing 4% bitumen and optimum bitumen content of 6.8% emulsion is the best mixture according to the result. The wheel tracking tests showed that with increasing in BE percentage, the rutting depth dropped. This trend was seen across all samples, which ranged from 2% to 4% BE dosage. The results of 2% BE was 13.6 mm against 4% BE, which was 9mm. Increasing the BE from 2% to 4% results in an increase in fatigue life of the RAP mixtures by 49.34%; the smallest increase is seen when increasing the BE content from 3.5% to 4%, which represents a 3.47% increase. The indirect tensile strength for 4% BE was much higher than that for 2% BE, which was most evident after a 12-week curing time. The dry samples had much higher ITS values than the soaked ones. The resilient modulus values were higher for 4% BE at higher curing times. It was also shown that dry conditions are better than when samples are soaked. The difference between dry and soaked samples indicated a significant gap and highlighted how important sample conditioning could be. The limitations of this study must be acknowledged, therefore the authors provide recommendations for future research that can be outlined as

(a) A longer curing time is suggested for the use of 100% RAP and cold mix asphalt as a reflection of long term use in real conditions.
(b) Variations of RAP mix and cold mix asphalt could be a good point to further consider.

Author Contributions: Conceptualization, A.C. and A.T.; methodology, A.T. and E.D.; validation, A.C., M.A.B. and H.N.; formal analysis, A.C., A.T., I.S.A.; investigation, M.A.B., E.D. and H.N.; data curation, E.D.; writing—preparation of original, A.T., I.S.A. and M.A.B.; writing—reviews and editing,

A.C. and H.N.; visualization, A.T. and I.S.A.; supervision, A.C., M.A.B. and H.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The study did not report any data.

Conflicts of Interest: The authors declare no conflict of interest.

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