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Investigating the Impact of Polymer and Portland Cement on the Crack Resistance of Half-Warm Bituminous Emulsion Mixtures

Muna Al-Kafaji [1], Shakir Al-Busaltan [1], Mustafa Amoori Kadhim [1], Anmar Dulaimi [1,2,3,*], Behrooz Saghafi [4] and Hayder Al Hawesah [2]

[1] Department of Civil Engineering, College of Engineering, University of Kerbala, Karbala 56001, Iraq; muna.f@uokerbala.edu.iq (M.A.-K.); s.f.al-busaltan@uokerbala.edu.iq (S.A.-B.); mustafa.amoori@s.uokerbala.edu.iq (M.A.K.)
[2] School of Civil Engineering and Built Environment, Liverpool John Moores University, Liverpool L3 2ET, UK; h.m.alhawesah@ljmu.ac.uk
[3] College of Engineering, University of Warith Al-Anbiyaa, Karbala 56001, Iraq
[4] Pavement Testing Services Ltd. (PTS), Preston PR2 5AR, UK; behrooz.saghafi@ptsinternational.co.uk
* Correspondence: anmar.f@uokerbala.edu.iq or a.f.dulaimi@ljmu.ac.uk or a.f.dulaimi@uowa.edu.iq

Abstract: Cold mix asphalt (CMA) is emerging as an environmentally friendly alternative to traditional hot mix asphalt (HMA). It offers advantages such as lower costs, reduced energy demands, decreased environmental impacts, and improved safety aspects. Among the various types of CMA, the cold bitumen emulsion mixture (CBEM) stands out. The CBEM involves diluting bitumen through emulsification, resulting in lower bitumen viscosity. However, this process has certain drawbacks, including extended setting (curing) times, lower early strength, increased porosity, and susceptibility to moisture. This study focuses on enhancing CBEM properties through the utilization of low-energy heat techniques, such as microwave technology, and the incorporation of a polymeric additive, specifically acrylic. These innovations led to the development of a novel paving technology known as a half-warm bitumen emulsion mixture (HWBEM). The research was conducted in two phases. First, the study assessed the impact of low-energy heating on the CBEM. Subsequently, it explored the combined effects of low-energy heating and the addition of an acrylic polymer. CBEM samples containing ordinary Portland cement (OPC) as an active filler were utilized in the sample manufacturing process. The effectiveness of these techniques in enhancing crack resistance was evaluated by analysing the results of the indirect tensile strength test. Notably, CBEM samples containing an amount of 2.5% of acrylic polymer and OPC exhibited the highest resistance to cracking. Furthermore, significant improvements were observed in their volumetric and mechanical properties, comparable to those of HMA.

Keywords: crack resistance; cold bitumen emulsion mixture; microwave; polymer modified asphalt

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1. Introduction

Economy, sustainability, and safety carry high profiles nowadays in transportation engineering, and pavements, the inevitable component of most transportation infrastructures, are immediately engaged with all these factors. The majority of pavements around the globe are surfaced with asphalt, and among the different types of which, hot mix asphalt (HMA) prevails in volume [1,2]. However, the use of HMA currently raises a lot of questions due to its environmental costs, as does the matter of sustainability, which applies to almost all types of construction materials [3,4].

The production of HMA consumes a huge amount of energy to heat the two main asphalt ingredients, aggregate and bitumen. Additionally, the process emits pollutant gases, resulting in the categorisation of HMA within environmentally costly products [5].

Therefore, researchers try to alleviate the issues by developing new technologies to reduce production temperature and emittance. Recent works have shown merits in cold bitumen emulsion mixtures (CBEMs), a type of cold asphalt mixture family. The advantage of a CBEM is that it is produced, mixed, and compacted at normal ambient temperature [6]. However, the mechanical properties of CBEM are inferior to those of conventional HMA. CBEMs have a low early life strength and high porosity [7–9]. Such disadvantages result in there being little interest in substituting HMA with a CBEM. Several methods have so far been examined by researchers to develop and advance this technology, including the use of filler types [10–15], advanced polymers [16–19], compaction energy [10,20–22], heating techniques via microwave [23–25], polymers [18,26], and crumb rubber [27,28]. While these methods show a slight modification in volumetric properties, other properties have shown better improvement.

Researchers have been trying to apply affordable techniques, such as heating, to control the porosity of CBEMs in comparison to that of conventional HMA without leaving negative effects on the other improved characteristics of CBEM. Al-Busaltan et al. [23] found that subjecting a CBEM to microwave heating up to 100 °C had a significant impact on the engineering properties of the mixture. The process improved the final product's resistance to permanent deformation while it decreased porosity to an acceptable level. The CBEM's water damage and ageing characteristics were comparable to those of conventional HMA and better fatigue characteristics were achieved. Additionally, Dulaimi et al. [24] concluded that pre-compaction heating led to significant effects such as a reduction in the porosity and mixture sensitivity to water damage and an improvement in the mixture's early life properties.

The term half-warm bituminous emulsion mixture (HWBEM) refers to the technique of applying post-heating, whether conventional or microwave radiation (the process occurs within a temperature not >100 °C), to a loosened CBEM before compaction. Hence, HWBEM is a method for producing asphalt mixtures at temperatures between 65 and 100 °C [24,29–31]. Mixtures such as emulsified bitumen, foamed bitumen, and modified bitumen with fluxing oil can be made using several kinds of bituminous binders [32,33]. According to Van de Ven et al. [34], a HWBEM can provide comparable monotonic qualities at high temperatures in addition to similar fatigue properties in comparison to HMA. The HWBEM offers a variety of advantages due to its lower production, laying, and compacting temperatures, including but not limited to improved working conditions, lower GHG emissions, less energy usage, a longer paving window, and longer hauling lengths [35].

Accordingly, this study is aimed at examining the cracking characteristics of the HWBEM. The improvement in volumetrics post-heating is examined through mechanical properties. The investigation is an attempt to cover the phenomena of expected cracking failure in pavements, which will facilitate more understanding of the HWBEM. To date, this subject is rarely discussed in the literature for the CBEM and HWBEM.

2. Experimental Plan and Sample Preparation

2.1. Materials

The study utilised virgin coarse and fine aggregates obtained from a local quarry in Kerbala. The coarse and fine aggregates from virgin crushed limestone were sourced from local quarries. They were washed, dried, graded, and stored in accordance with the Iraqi general specification for roads and bridges [36]. The coarse and fine aggregates' physical properties are presented in Tables 1 and 2, respectively. The aggregate envelope and the gradation used in the study are depicted in Figure 1. Ordinary Portland cement (OPC) obtained from a cement plant in Karbala was used as a filler material.

Table 1. The physical properties of virgin coarse aggregate.

Property	Adopted Specification (ASTM)	VCA	Requirements
Water absorption, %	C127 [37]	1.410	-
Bulk specific gravity	C127 [37]	2.591	-
Bulk SSD specific gravity	C127 [37]	2.601	
Apparent specific gravity	C127 [37]	2.618	-
Soundness loss by sodium sulphate, %	C88 [38]	7.574	12% max
Percent wear by Los Angeles abrasion test, %	C131 [39]	13.5	30% max
Degree of crushing, %	---	93%	90% min
Clay lumps, %	C142 [40]	0.080	-
Flat and elongated particles, %	D4791 [40]	1.538	10% max

Table 2. The physical characteristics of virgin fine aggregate and fine glass aggregates (FGA).

Property	Adopted Specification (ASTM)	VFA	FGA
Water absorption, %	C128 [41]	1.810	0.530
Bulk specific gravity	C128 [41]	2.598	2.497
Apparent specific gravity	C128 [41]	2.587	2.471
Fine aggregate angularity (FAA)	C 1252 [42]	52.7	87.5
Loss angles abrasion %, D grading	C131 [39]	7.420	31.500
Degree of crushing, %	D5821 [43]	87.44	100

The test conducted for the portion size 4.75–2.36 mm.

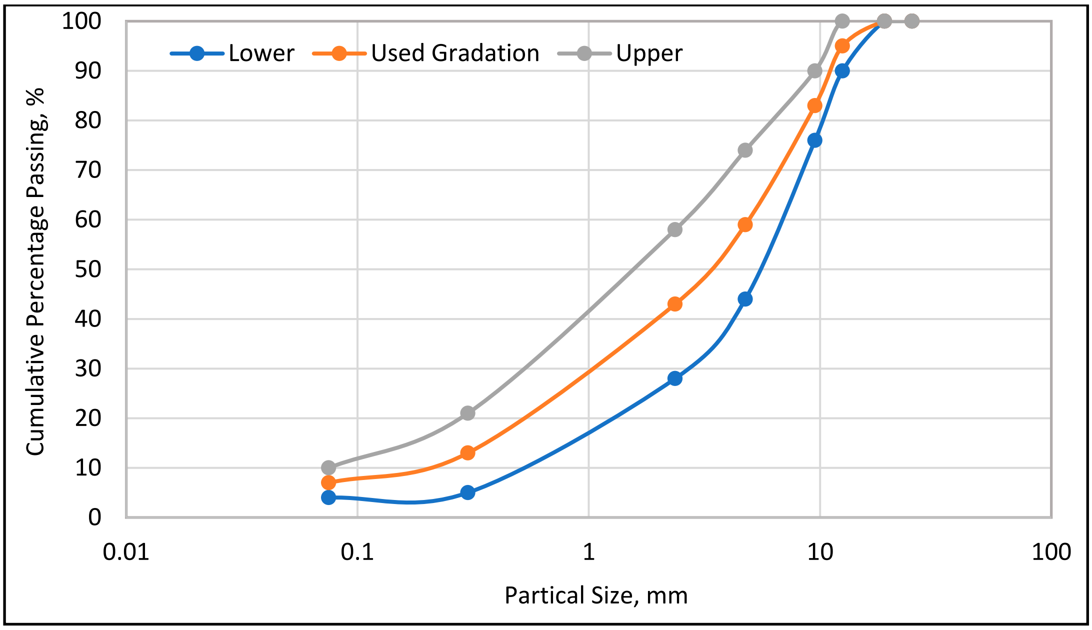

Figure 1. Standard particle size envelope and particle size distribution of the gradation used.

The hard bitumen used in the study had a penetration grade of 40/50 and was obtained from Al-Neisseria Refinery. This bitumen is typically used in Iraq, where hot weather predominates. It meets the specified limits and ranges set by the General Specification for Roads and Bridges (GSRB) [36]. The bitumen emulsion, commercially known as "POLYCOAT", was provided by Henkel Company. The properties of the POLYCOAT emulsion can be found in Table 3. Additionally, an acrylic (AR) polymer, obtained from Conmix Company, was used as a bitumen modifier. The properties of the AR polymer are listed in Table 4.

Table 3. Properties of bitumen emulsion.

Property	Specification	Limits	Results
Emulsion type	D2397 [44]	Rapid, medium and slow-setting	Medium-setting (CMS)
Colour appearance			Dark brown liquid
Residue by evaporation, %	D6934 [45]	Min. 57	58
Specific gravity, gm/cm^3	D70 [46]		1.05
Penetration, mm	D5 [47]	100–250	230
Aggregate coating	D6998 [48]		uniformly and thoroughly coated

Table 4. Properties of the acrylic polymer.

Property	Test Method	Standard Limits	Results of Test
Component	-	Single	Single
Form	-	Liquid	Liquid
Colour	-	Milky white	Milky white
Specific gravity	ASTM D1475	1.02 kg/Lit $\pm$ 0.05	1.06 kg/L
Viscosity @ 25 °C	-	100 $\pm$ 50 cps	125 cps
Percent of the solid	-	49.0 $\pm$ 1.0%	49

2.2. Experimental Plan

Four types of specimens were designed:

- Type 1: Control HMA containing OPC as the filler (HMA-OPC)
- Type 2: Control CBEM containing OPC as the filler (CBEM-OPC)
- Type 3: HWBEM containing OPC as the filler (HWBEM-OPC)
- Type 4: HWBEM prepared with AR, including OPC as a filler.

The purpose was to evaluate the impact of incorporating AR on the performance of the HWBEM. The AR used was in the range of 1.25% to 5% of the weight of residual bitumen set at 1.25, 2.5, 3.75, and 5% (HWBEM-OPC-(AR content)%AR). For comparison purposes, the aggregate gradation shown in Figure 1 was used for all the specimens.

2.3. Mix Design, Preparation, and Conditioning of Specimens

The specimens of the CBEM and HWBEM were prepared in accordance with the design methodology specified in the MS-14 Asphalt Cold Mix Manual, Figure 2 [49]. To evaluate the compatibility between the aggregate particles and the emulsion binder, a coating test was performed. This test aimed to assess the ability of the emulsion binder to coat and adhere to the surface of the aggregate particles. This test is highly sensitive to the amount of pre-mixing water used, particularly in cases where the mixture contains a significant proportion of fine aggregate. The test helps determine the effectiveness of the emulsion binder in coating and bonding the aggregate particles, which is crucial for the overall performance of the mixture.

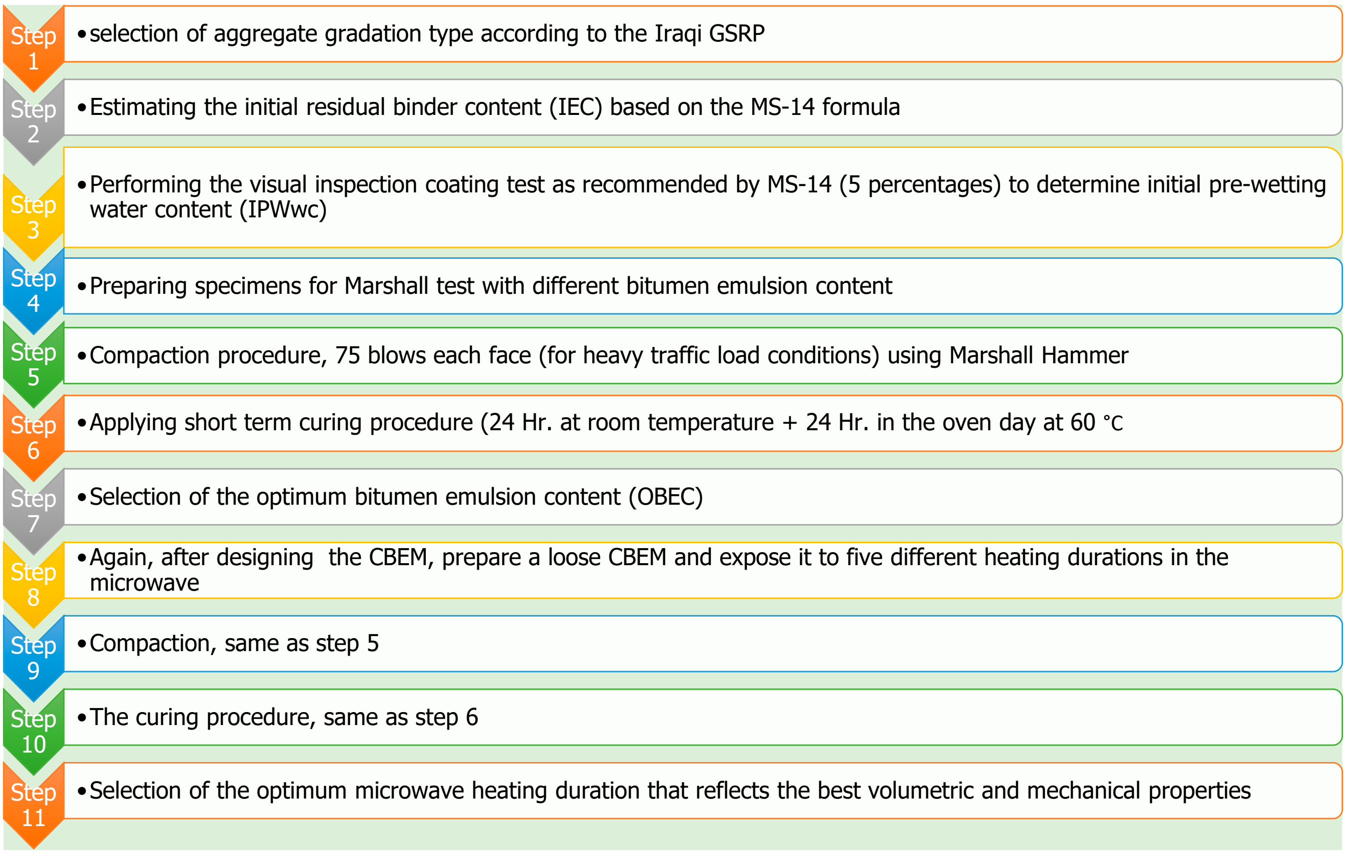

Figure 2. MS-14 manual for producing CBEM and proposed method to prepare HWBEM.

The content of the pre-mixing water was obtained visually through a trial-and-error process described in MS-14. The results suggested the use of 3.5% pre-mixing water for the control CBEM-OPC. The pre-mixing water content was combined with various bitumen emulsion contents to determine the optimal amount of bitumen emulsion that would result in the best volumetric properties and maximum Marshall stability. According to the required marshal mechanical properties, and based on the Iraqi GSRB specifications, the optimum bitumen emulsion content was found to be 12% for CBEM-OPC, and the total liquid content of the mix reached 15.5%.

It is important to note that the formulation and compaction of the samples were carried out at the laboratory temperature range of 20–25 °C. During the mixing process, a stand mixer/blender was utilized to combine the aggregate, filler, and pre-mixing water for one minute. Following this, the bitumen emulsion was gradually introduced while continuing blending for an additional minute. To simulate heavy compaction, the Marshall hammer was used to apply 75 blows on each side of the specimens. This compaction method helps ensure that the samples achieve the desired density and structural integrity [50,51].

To produce HWBEM specimens, some additional steps along with the ones noted above were followed. Following the mixing process, the loose CBEM mixture was conditioned in a microwave oven. Heating durations of 1.5, 3.0, 4.5, 6.0, and 7.5 min were implemented to determine the optimal time frame for achieving the most favourable volumetric and mechanical properties. After the heating process, the loose mixture was promptly moulded and compacted by subjecting it to 75 blows from Marshall Hammer on each side, as previously carried out for unheated samples. All samples were cured under a similar regime.

The temperature of the samples was recorded after the heating process. Changes in sample temperature are shown in Figure 3. The temperature trend during the process indicated that it consistently remained below 100 °C, leading to the introduction of a new technology known as a "half-warm bitumen emulsion mixture". This technology refers to the use of a bitumen emulsion at temperatures lower than those of traditional HMA, while still providing satisfactory performance characteristics. Table 5 shows the GSRB limitation for the surface layer, section R9.

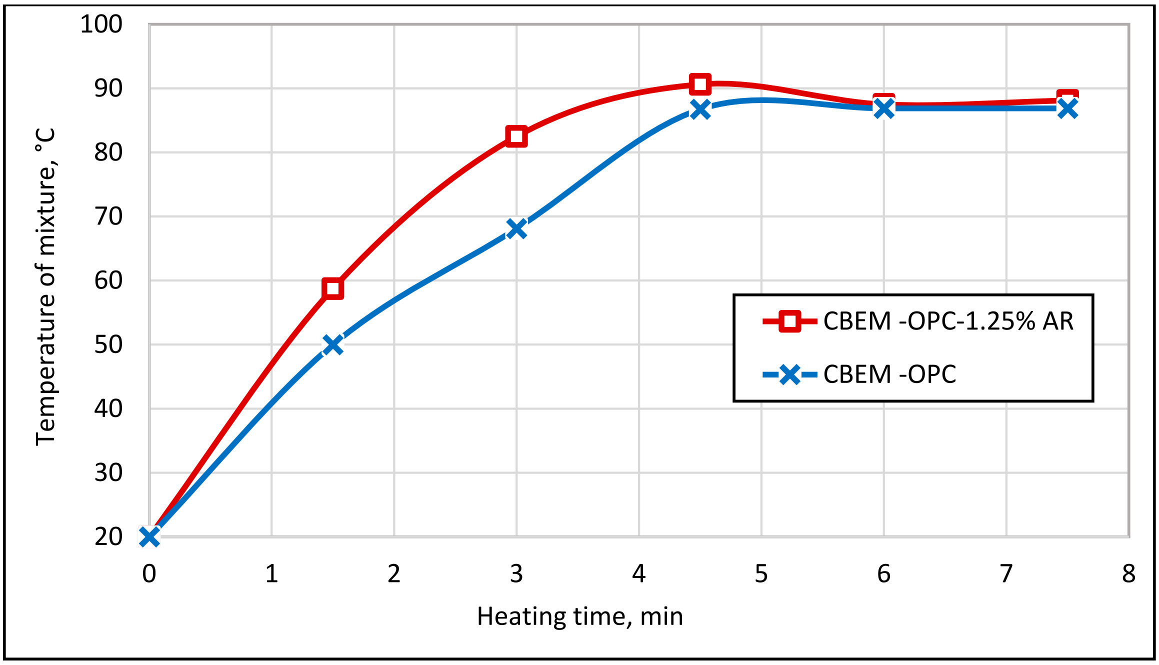

Figure 3. Temperature versus heating time (heating was conducted in a microwave oven).

Table 5. GSRB limitation for the surface layer, section R9 [36].

Property	GSRB Requirements
Stability, Kg	>800
Retained strength, %	>70
Air void, %	3–5
Flow, 1/10 mm	2–4

2.4. Sample Testing

In addition to the volumetric properties, the mechanical properties of the HWBEM were compared to those of the control HMA and HWBEM for quality control.

2.4.1. Indirect Tensile Strength (ITS)

The ITS test showcases the capacity of a bituminous mixture to withstand the development of tensile cracks and prevent stripping. A Marshall specimen is positioned between two stripes on its sides and is loaded radially in accordance with ASTM D6931 [52]. The test resulted in sample failure. ITS test conditions are summarised in Table 6. If the deformation of the sample under loading is recorded, the integration of the area under the curve of the ITS against horizontal deformation will yield the toughness of the bituminous mixture.

Table 6. ITS test conditions.

Item		ASTM D6931	Used Value for CBEM and HWBEM
Number of required specimens		3	3
Rate of the loading, mm/min		50 ± 5	51.3
Device accuracy		min 0.01 N	0.01 N
Test temperature, °C		25 ± 2	23
Specimen diameters, mm		101.6, 150	101.6
Specimen thickness, mm		50.8–65.5	63
Compaction (Marshall Hammer)		75 × 2	75 × 2
Curing		-	24 h @ 25 °C
Specimen conditioning before the test	Oven dry	120–130 min	120 min
	Water bath	30–40 min	Not used

2.4.2. Cracking Tolerance Index (CT-Index)

The indirect tolerance index (or CT-index) is a simple alternative test indicator of the indirect tension test strength that was introduced to evaluate the effectiveness of mixtures in resisting cracking [53]. This newly developed cracking performance index was declared by the Texas A and M Transportation Institute [54] and reflects mode I of fracture mechanism according to the ASTM D 19 testing method [55]. The test has many advantages over other cracking resistance indices since its formula is based on more than one parameter to evaluate the cracking resistance. Moreover, the chase cannot be handled easily at intermediate temperatures. The chase can be performed at an applied loading rate of about 50 mm/min, and it does not require cutting, notching, drilling, gluing, or any additional instrumentation [56,57].

At present, X-ray computed tomography (CT) can be employed for the non-destructive scanning and virtual cross-sectioning of specimens. It enables the intuitive and precise visualization of internal structures and material compositions in both two-dimensional sections and three-dimensional images. This facilitates the analysis of internal structures and the measurement of void content within the specimen [58,59].

The adoption of this approach is based on the recognition that microcracks tend to develop when the load-bearing capacity peak is reached. Microcracks continue growing and propagating after that point and result in a proportional decrease in the mixture's load bearing capacity. The CT-index is calculated via Equation (1), which is developed based on an understanding presented in Figure 4.

$$CT_{\text{Index}} = \frac{t}{62} \times \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{D}\right) \quad (1)$$

where, CT_{Index} refers to the cracking tolerance index (unitless), Gf, t, D, $|m_{75}|$, and l_{75} are: the mode I failure energy (Joules/m^2), specimen thickness and diameter (mm), the post-peak loading slope (N/m), and the strain at 75% of the loading stage, respectively, and can be determined as follows:

$$G_f = \frac{W_f}{D \times t} \times 10^6 \quad (2)$$

where D and t are as described previously, W_f is the required work (in joules) until the failure load (the area under load–displacement curve divided by the specimen's cross-sectional dimensions).

$$\left|m_{75}\right| = \left|\frac{P_{85} - P_{65}}{l_{85} - l_{65}}\right| \quad (3)$$

where P_X and l_x are the loadings with respect to the crack initiation load and displacement values at the specified stage in the post-peak side (for instance, P_{85} is the loading resistance value at 85% of the cacking initiation load and l_{85} means the displacement corresponding P_{85})

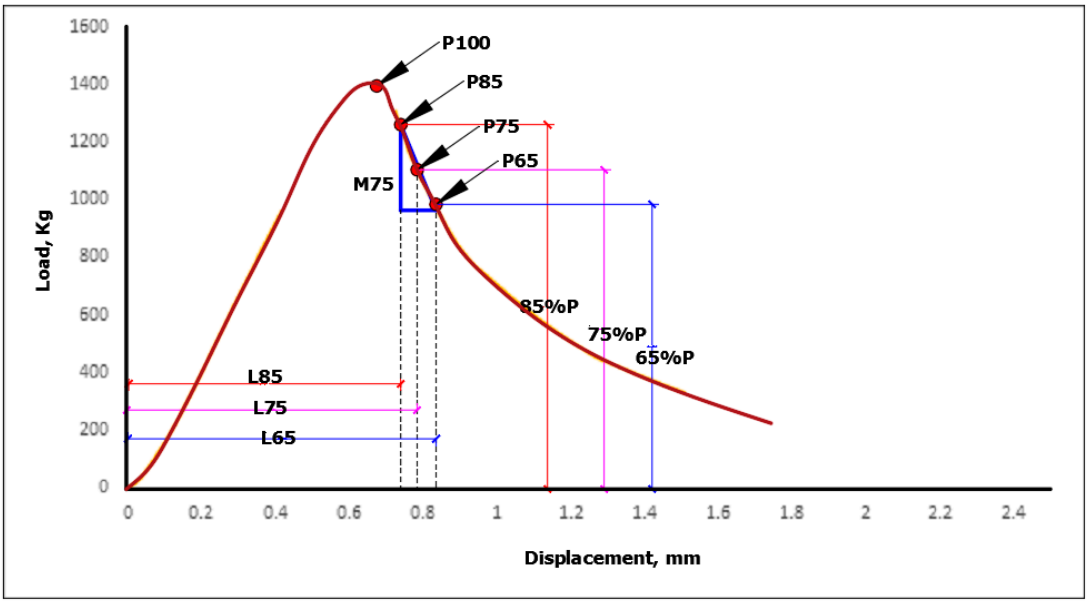

Figure 4. Illustration of CT-index calculation parameters and philosophy [55].

2.4.3. Cracking Resistance Index (CRI)

Another recently introduced mechanical performance indicator for asphalt mixtures is the *CRI* [60]. It is calculated by dividing the fracture energy by the peak load, as described in Equation (4):

$$CRI = \frac{G_f}{P_{max}} \quad (4)$$

where G_f is the failure energy (Joules/m^2), as mentioned above, and P_{max} is the peak load or P_{100} (N), as depicted in Figure 3.

2.4.4. Toughness Index (TI)

The toughness index is simply calculated using the post-peak G_f rather than considering the total area under the curve [61]. Equation (5) will yield the *TI* value where a scale adjustment factor of 10^{-3} is also included.

$$TI = \left(G_{f,\ \text{post-peak}}\right) * (\Delta mdp - \Delta P_{max}) * 10^{-3} \quad (5)$$

where $G_{f,\text{post-peak}}$ is post-peak failure energy, ΔP_{max} is the displacement at the peak load, and Δmdp is the displacement at 50% of the peak load.

3. Test Results and Discussion

Figure 5 shows the density of the studied mixtures. Increasing the AR content in HWBEM samples resulted in some reduction in the density of the HWBEM samples containing AR. These samples contained excess water because this water formed a continuous phase with the AR. This volume of water was released from the mixture during the curing process, leading to a noticeable decrease in the density of these samples if heat was not applied. Likewise, the presence and loss of water had an impact on the air voids in the mixtures, as demonstrated in Figure 6.

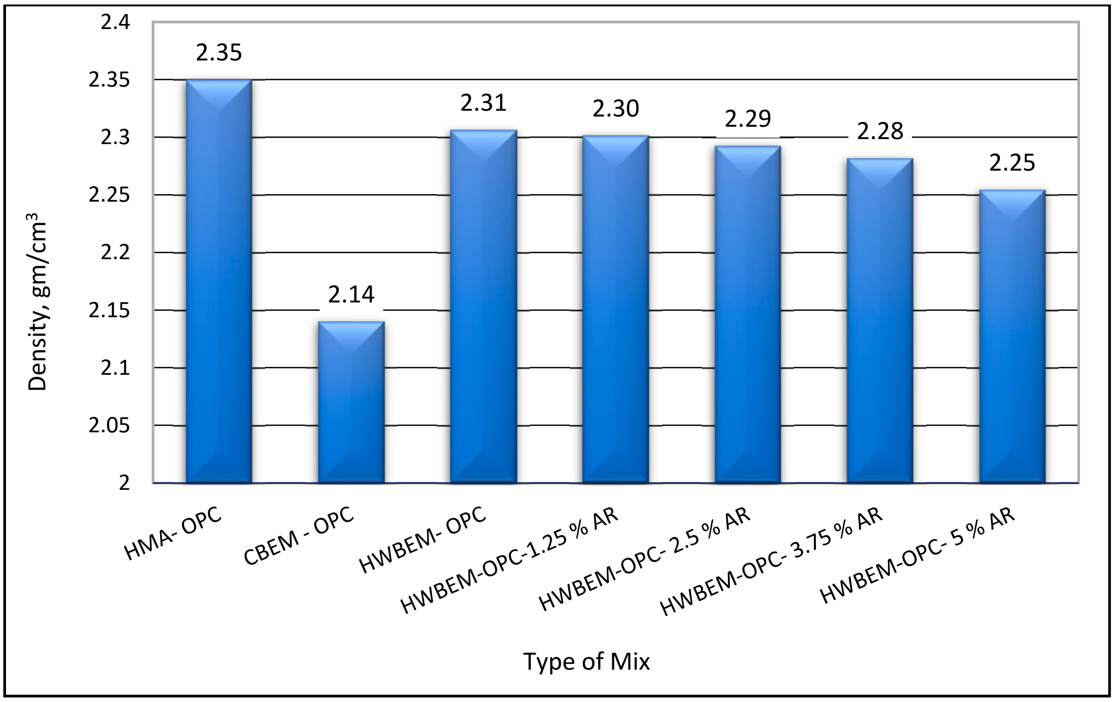

Figure 5. Density results for different mixture types.

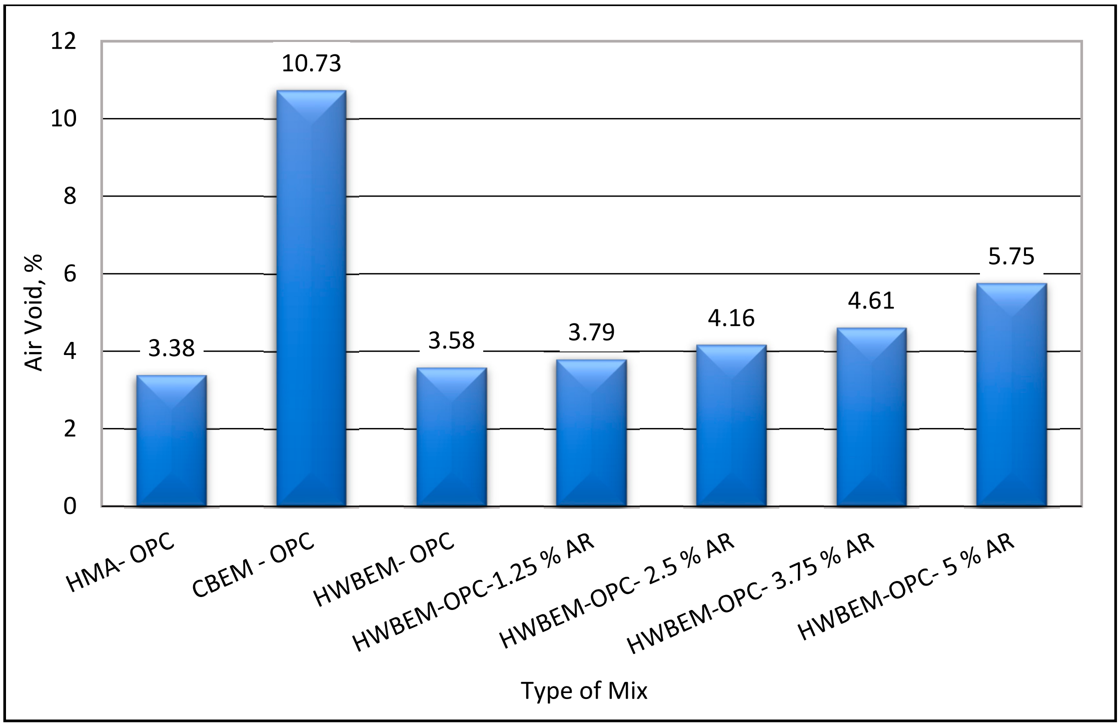

Figure 6. Air void results for different mixture types.

Adding AR to the HWBEM in an amount of up to 2.5% increased the ITS considerably. As shown in Figure 7, even a small AR content of 1.25% led to a higher ITS when compared to that of HMA, and doubling the AR content caused the HWBEM to perform superiorly compared to HMA. However, any further increase in AR caused a cliff fall in the tensile strength of the HWBEM. It is understood that the addition of AR initially led to the development of some interlocking in the aggregate phase of the mixtures. However, a further increase after the optimum point reduced binder–aggregate adhesion at the binder–aggregate interface.

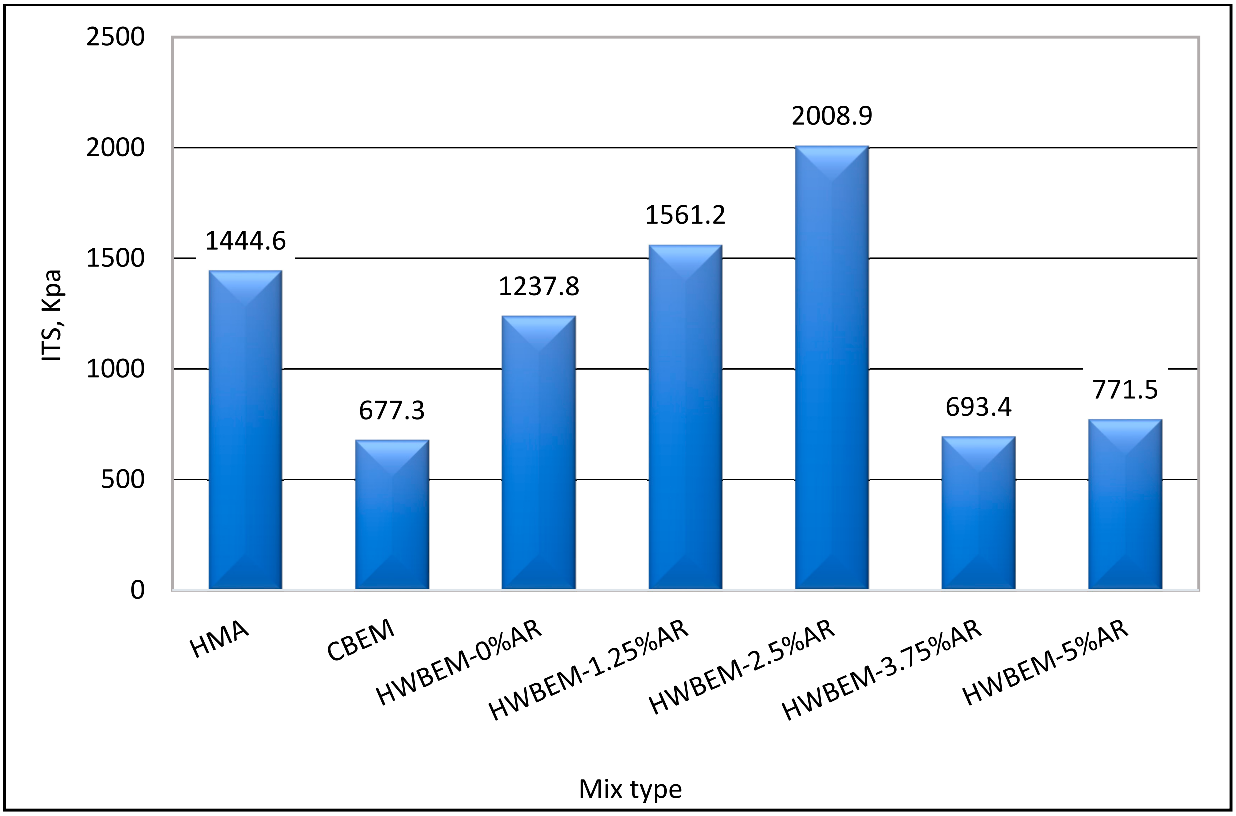

Figure 7. ITS test results for the study mixtures.

Observing the trend of changes in failure energy (Figure 8) confirms the results. Incorporating AR up to the optimal level enhanced the HWBEM's ability to absorb energy before failing. However, any increase beyond this point resulted in mixture failure at much lower energy levels. A higher failure energy level is directly associated with improved material performance under repeated loading conditions.

Cracking, though itself a type of distress, is the onset of future distress usually related to water ingress. Therefore, retarding crack initiation is vital for pavement performance, durability, and preservation. The energy required for the crack initiation (Gf-CI) of the mixtures in the study is presented in Figure 9. Heat treatment certainly improved the GF-CI value, but the inclusion of AR up to the optimum value of 2.5% tremendously enhanced the capacity of the material to absorb energy before crack initiation. As another confirmation of the effect of AR within the HWBEM mixtures, any further addition of AR considerably dropped the energy required before any crack initiation.

Figure 10 shows loading–displacement curves for all the study mixtures. It can be noticed that heat treatment was effective at enhancing the maximum indirect cracking load of the HWBEM when compared with that of the CBEM. Adding AR in an amount up to 2.5% certainly improved the HWBEM's response to loading although it caused the HWBEM-1.25%AR and HWBEM-2.5%AR to be more brittle than HMA and CBEM (associated with the displacement position of P_{max} compared with that of HMA). The viscous phases of HMA were more extensive than those of HWBEMs, possessed an enhanced capacity to dissipate energy and respond to loading, and therefore possessed a higher capacity to retain tensile strength, than that of CBEM.

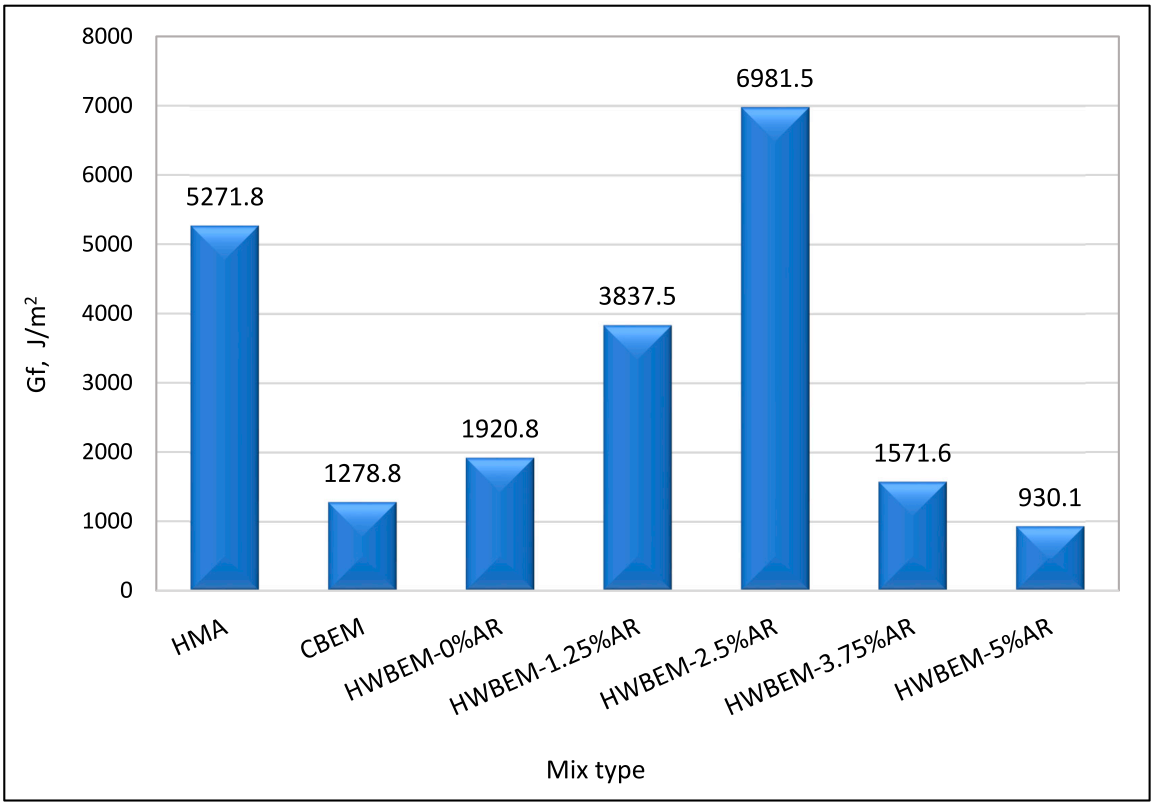

Figure 8. Failure energy values for the study mixtures.

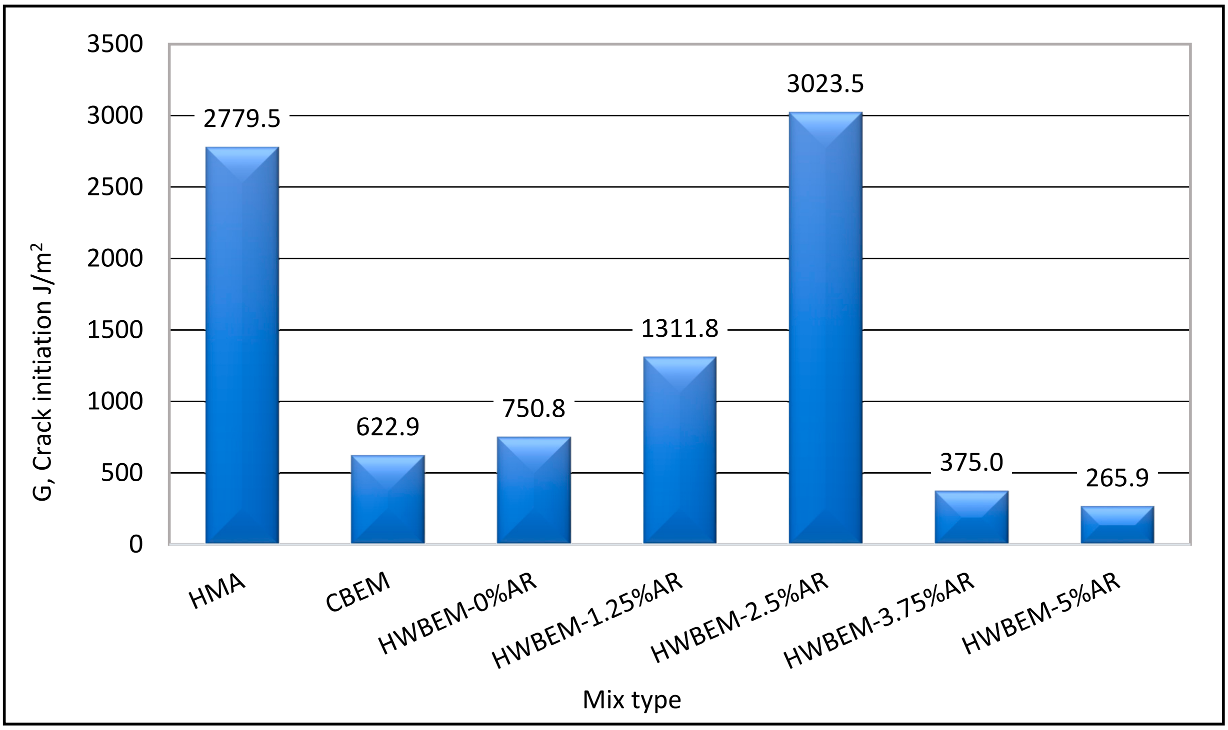

Figure 9. Failure energy required before crack initiation for the study mixtures.

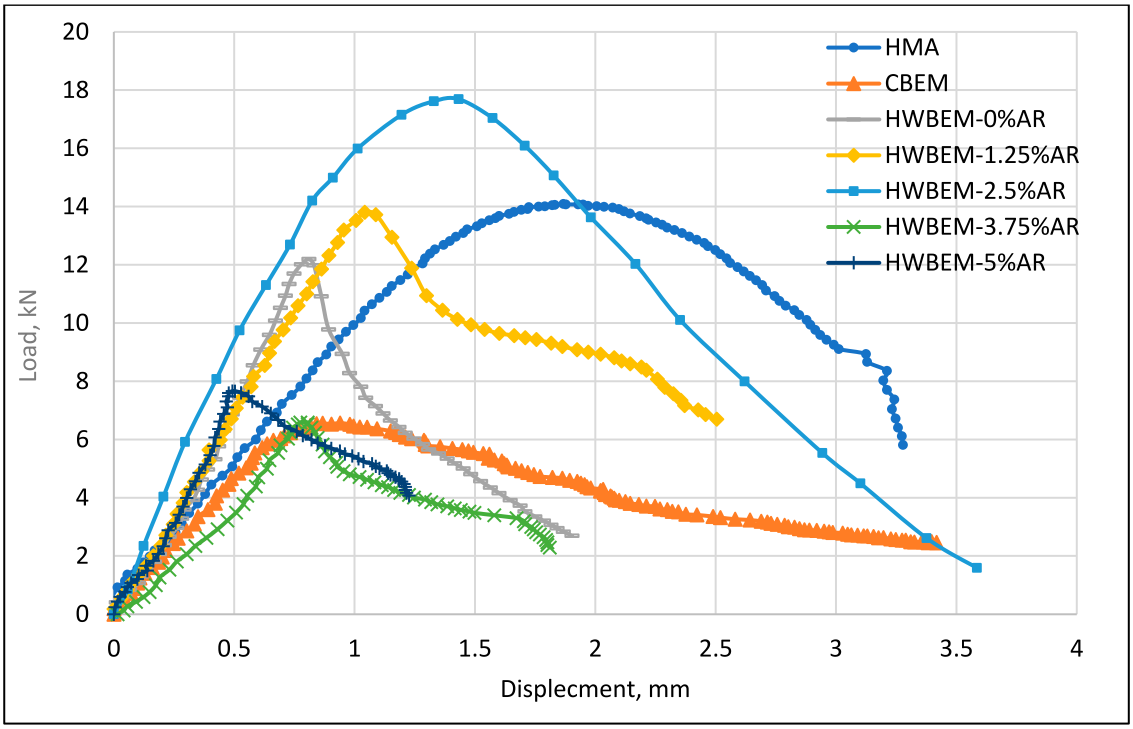

Figure 10. Load–deformation curves for all study mixtures.

Figure 11 reports the CT indices found for the studied mixtures. As expected, the CT_{index} of HMA shows superior characteristics to that of the CBEM. It is known that the CT_{index} for asphalt mixture ranges from 31 to 255 [55]. Moreover, the HWBEM, after being extensively heat-treated, demonstrates a slight improvement in the CT_{index} when compared with that of the CBEM. On the other hand, adding AR in an amount up to led to a continued improvement in the CT_{index}. Now, the criterion for an optimum value for the AR content will need to be discussed. As expected enough now, adding AR in an amount greater than 2.5% caused the mixtures to show a little tolerance to cracking. What is understood from the literature is that the CT_{index} depends on various factors, namely failure energy, the slope of the post-peak inflection point, and the strain value at 75% of the peak load value. These indices are highly affected by the ingredients of the mixture and volumetric properties. Noticeably, in terms of volumetric properties, Figures 4 and 5 demonstrate the lower density and higher air void for the HWBEM containing more than 2.5% of AR. In terms of ingredients, AR extends a reinforced network within the binder (emulsion residue), leading to improved adhesion and cohesion, and ultimately enhancing crack resistance. Inversely, the extra AR predominated the binder materials and affected the role of the binder material, whereas the created networks dispersed the binder, affecting adhesion and cohesion inferiorly.

As mentioned previously, the slope of the curve in the mixture's post-peak behaviour (m_{75}) is one of the factors that affect the magnitude of CT_{index}; theoretically, the sharper the slope, the smaller the CT_{index}. In other words, a sharper slope indicates that the mixture has a weaker ability to tolerate the onset of cracking and less resistance to cracking propagation after the maximum tensile stress is borne. The slope of the mixtures' behaviour in their post-peak stage was studied and is presented in Figure 12. However, the previous claim is correct only when comparing the CBEM with HWBEM-0%AR. Inversely, the remaining m_{75} values results show higher magnitudes. Moreover, some mixtures with a higher CT_{index} are associate with a higher m_{75}, as for example, in the case of HWBEM-1.25%AR compared with HWBEM-5%AR. Therefore, it would lead to fruitless results to use the m_{75} slope index result alone to evaluate the cracking resistance. Its effect must be accommodated inclusively within the CT_{index}.

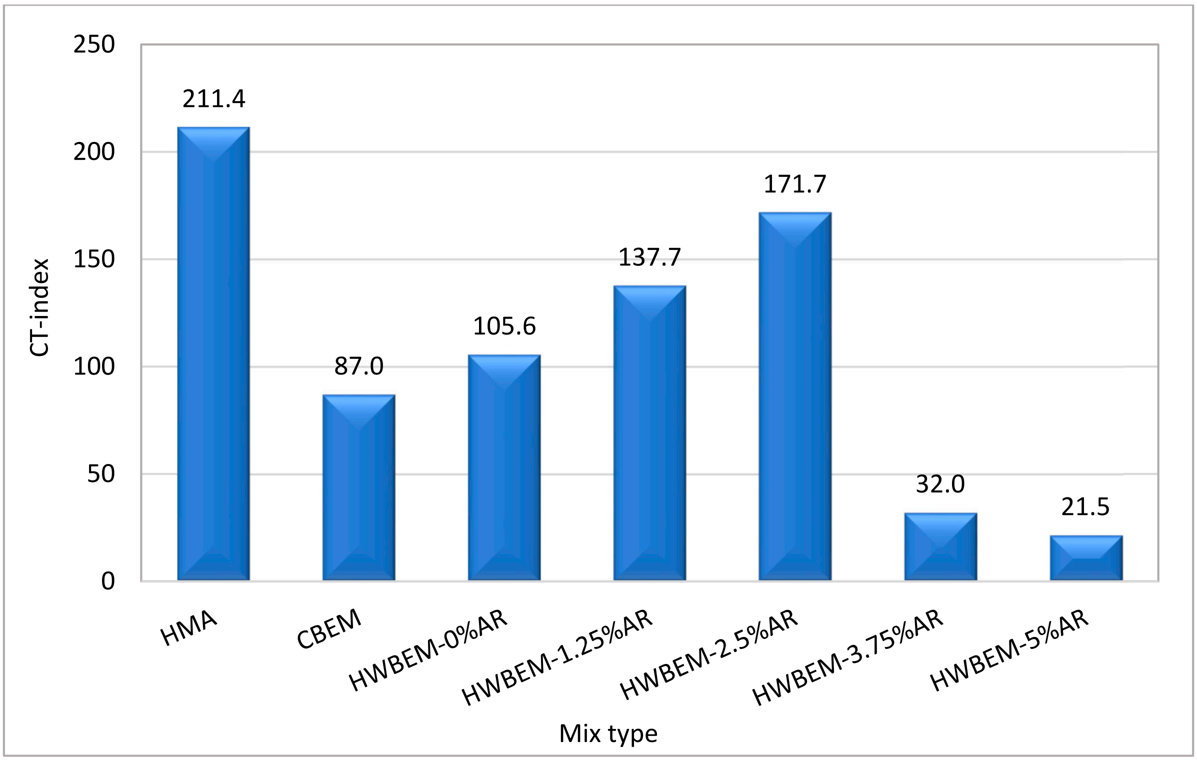

Figure 11. CT-index results for the study mixtures.

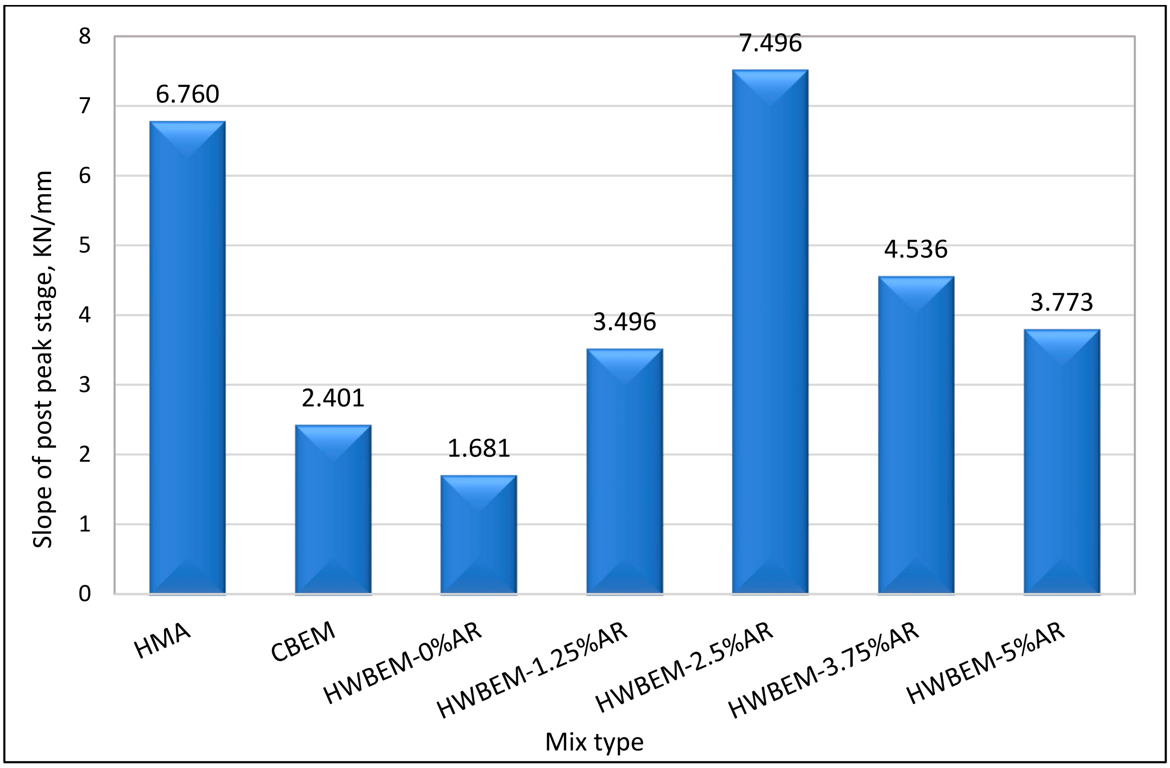

Figure 12. Slope values of the post-peak stage for all the study mixtures.

The strain at 75% of the post-peak load can reflect the brittleness of the asphalt mixture and/or crack initiation, whereas the higher value is associated with ductile material. Results in Figure 13 demonstrate such an indicator, where the hydric filler material in the CBEM produced the secondary binder (hydridic products have brittle characteristics) that controlled the ability of the asphalt binder (primary binder) to be ductile. However, introducing the heat treatment increased the brittleness as a result of extra hydraulic product creation due to the microwave heating process. This is also confirmed by the value of P_{max} and/or ITS, as shown in Figure 6, when comparing the CBEM with the HWBEM with up to 2.5% of AR. Then, the inferior effect of extra AR and volumetric properties works to weaken the mixture with higher amounts of AR. Nevertheless, a controlled dosage of AR of up to 2.5% facilitates there being greater ductility for the mix due to the polymer-created network that reinforces the binders (both primary and secondary binders). Additional conformation can be confirmed through observing Figure 8, where the crack initiation energy is negatively affected by heating but AR inclusion rises to 2.5%.

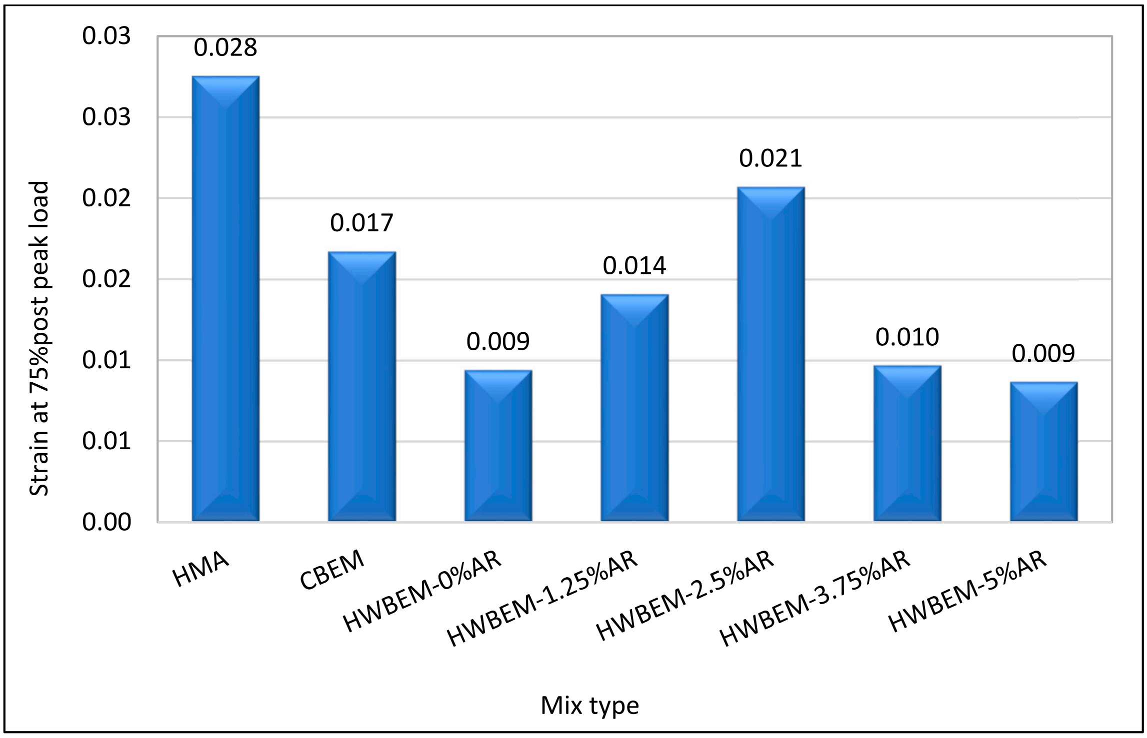

Figure 13. Strain values at 75% of the loading in the post-peak stage.

The CRI-index can reveal the normalization of different mixtures against crack resistance, as it is determined by dividing the failure energy (G_f) over the peak load (P_{max}). Comparing Figure 7 with Figure 14, the same trend can be observed, but there is a noticeable variation in the ratio. An explanation for this would be the difference between these mixtures in their responses to loading. The load–displacement curve provides insights into the characteristics of a mixture. While a mixture might exhibit high peak load resistance, it may simultaneously possess a limited capacity to absorb energy. This relationship becomes apparent when considering the area under the load–displacement curve. However, Figure 14 reveals the significance of AR in extending the energy of failure noticeably with an increase in the peak load with less range, as can be seen with the HWBEM with up to 2.5% of AR.

The toughness index (TI) demonstrates the post-cracking characteristics, or it explains to what extent post-cracking is associated with the total toughness of the material, where the brittle material has a significantly lower value compared with that of the ductile material. However, the highest toughness index obtained for HWBEM-2.5%AR is further proof of the effect of AR (of up to 2.5% in content) in improving the HWBEM's performance, as can be seen in Figure 15. Both 1.25% and 2.5% AR contents caused the HWBEM to demonstrate much higher toughness than that of HMA itself. Furthermore, the heat treatment resulted in a minimization of the toughness index, as can be seen when comparing the CBEM with HWBEM-0%AR.

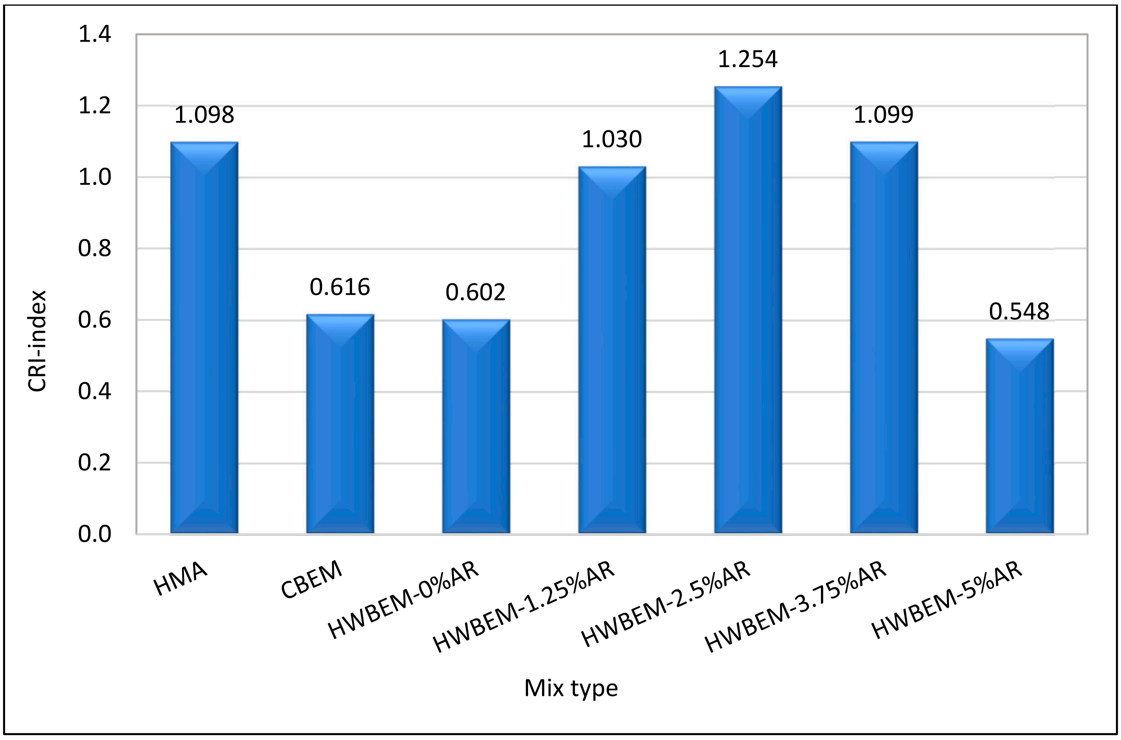

Figure 14. The CRI-index values for the study mixtures.

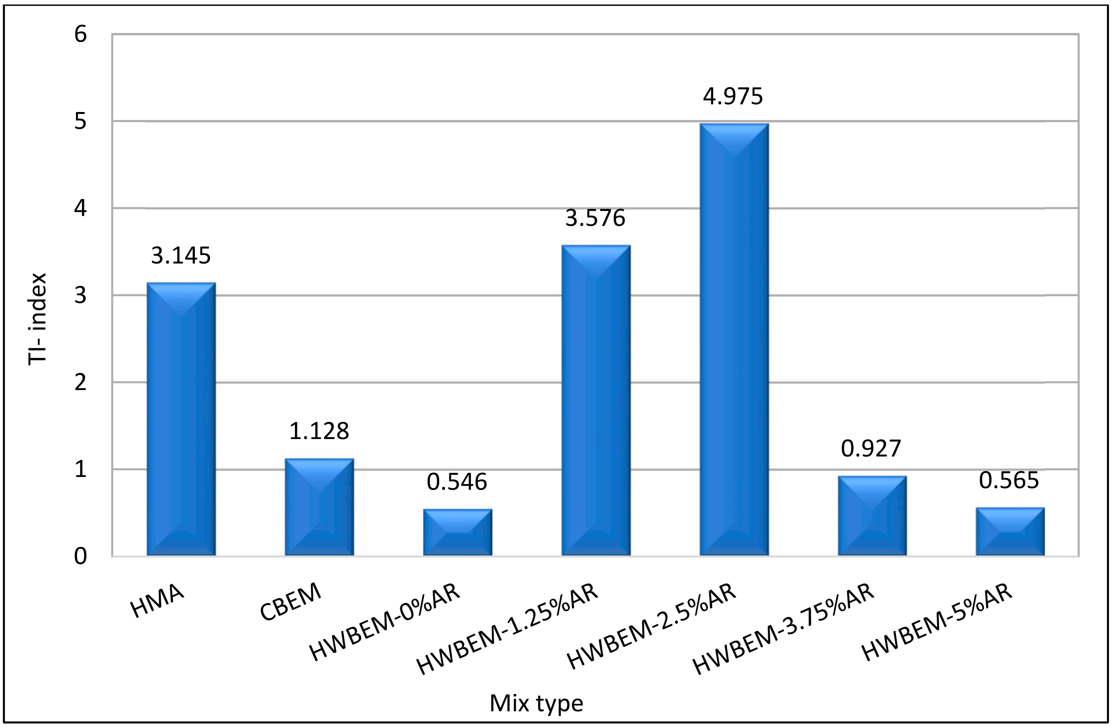

Figure 15. Toughness index for the study mixtures.

4. Conclusions

This research aimed to evaluate the cracking performance of asphalt mixtures that included AR polymer modification, known as HWBEMs. The study investigated how the presence of an AR polymer impacts the resistance to cracking in these asphalt mixtures. It also explored additional cracking indices beyond the standard ITS index. The main finding highlights that the cracking performance of these asphalt mixtures is influenced by multiple phases leading to the final fracture. Therefore, it is essential to use various indices to describe these phases and their significance, as this will improve our comprehension of cracking performance. Considering multiple indices offers a more comprehensive understanding of material behaviour and performance in relation to cracking.

Based on the testing program and analysis of the results, the following conclusions can be drawn:

- Volumetric properties: HWBEMs exhibit superior properties compared to CBEMs. Mixing HWBEMs with 1.25% of AR shows an improvement in AV% that is comparable to that of HWBEMs. Additionally, the density of the treated mixes is slightly higher than that of the CBEM for all AR contents.
- The cracking resistance indices employed in the study demonstrate the effectiveness of the proposed design procedure for preparing HWBEMs. These mixes exhibit a higher tensile strength compared to that of cold mixtures, indicating improved resistance to cracking.
- Relying solely on the ITS value as a criterion to describe pavement cracking resistance can be misleading. This is because certain mixtures with high ITS values may exhibit lower G_f and CT_{index} values in comparison. The crack tolerance index test method, which evaluates the cracking resistance of mixtures considering crack phases, is a suitable approach, particularly for mixtures exhibiting higher brittleness than that of traditional hot mix asphalt.
- Considering volumetric and mechanical performance as well as various cracking indices, it is recommended to utilise an optimal AR content of approximately 2.5%. This content yields higher properties in comparison to those of the reference CBEM and HWBEM.
- It is recommended to consider these indices collectively rather than individually, as each one identifies and describes a distinct phenomenon related to cracking, both before and after fracture.
- The sustainable approach of incorporating microwave post-heating and AR technology in the production of newly developed asphalt mixtures has demonstrated efficiency in terms of various cracking performance indicators.

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References

1. Su, K.; Maekawa, R.; Hachiya, Y. Laboratory evaluation of WMA mixture for use in airport pavement rehabilitation. *Constr. Build. Mater.* **2009**, *23*, 2709–2714. [CrossRef]
2. Ahmadzadegan, F.; Sarkar, A. Mechanical properties of warm mix asphalt–stone matrix asphalt modified with Nano Zeolite material. *J. Test. Eval.* **2022**, *50*, 534–550. [CrossRef]
3. Capitão, S.D.; Picado-Santos, L.G.; Martinho, F. Pavement engineering materials: Review on the use of warm-mix asphalt. *Constr. Build. Mater.* **2012**, *36*, 1016–1024. [CrossRef]
4. Al Nageim, H.; Dulaimi, A.; Al-Busaltan, S.; Kadhim, M.A.; Al-Khuzaie, A.; Seton, L.; Croft, J.; Drake, J. The development of an eco-friendly cold mix asphalt using wastewater sludge ash. *J. Environ. Manag.* **2023**, *329*, 117015. [CrossRef] [PubMed]
5. Rubio, M.D.C.; Moreno, F.; Martínez-Echevarría, M.J.; Martínez, G.; Vázquez, J.M. Comparative analysis of emissions from the manufacture and use of hot and half-warm mix asphalt. *J. Clean. Prod.* **2013**, *41*, 1–6. [CrossRef]
6. Yao, X.; Xu, H.; Xu, T. Mechanical properties and enhancement mechanisms of cold recycled mixture using waterborne epoxy resin/styrene butadiene rubber latex modified emulsified asphalt. *Constr. Build. Mater.* **2022**, *352*, 129021. [CrossRef]
7. Oruc, S.; Celik, F.; Akpinar, V. Effect of cement on emulsified asphalt mixtures. *J. Mater. Eng. Perform.* **2007**, *16*, 578–583. [CrossRef]
8. Thanaya, I.N.A.; Forth, J.P.; Zoorob, S.E. A laboratory study on cold-mix, cold-lay emulsion mixtures. *Proc. ICE—Transp.* **2009**, *162*, 47–55. [CrossRef]
9. Yao, X.; Xu, T. Fatigue fracture and self-healing behaviors of cold recycled emulsified asphalt mixture containing microcapsules based on semicircular bending test. *J. Clean. Prod.* **2023**, *410*, 137171. [CrossRef]
10. Thanaya, I.N.A. Evaluating and improving the performance of cold asphalt emulsion mixes. *Civ. Eng. Dimens.* **2007**, *9*, 64–69.
11. Thanaya, I. Improving the Performance of Cold Bituminous Emulsion Mixtures (CBEMs): Incorporating Waste. Ph.D. Thesis, University of Leeds, Leeds, UK, 2003.
12. Kadhim, M.A.; Al-Busaltan, S.; Almuhanna, R.R. An evaluation of the effect of crushed waste glass on the performance of cold bituminous emulsion mixtures. *Int. J. Pavement Res. Technol.* **2019**, *12*, 396–406. [CrossRef]
13. Raj, A.; Sivakumar, M.; Anjaneyulu, M. Use of rice husk ash-activated fillers on rutting and moisture resistance of cold mix asphalt. *Int. J. PavementEng.* **2022**, 1–13. [CrossRef]
14. Al Nageim, H.; Dulaimi, A.; Ruddock, F.; Seton, L. Development of a new cementitious filler for use in fast-curing cold binder course in pavement application. In Proceedings of the 38th International Conference on Cement Microscopy, Lyon, France, 17–21 April 2016; pp. 167–180.
15. Lu, D.; Wang, Y.; Leng, Z.; Zhong, J. Influence of ternary blended cementitious fillers in a cold mix asphalt mixture. *J. Clean. Prod.* **2021**, *318*, 128421. [CrossRef]
16. Chávez-Valencia, L.E.; Alonso, E.; Manzano, A.; Pérez, J.; Contreras, M.E.; Signoret, C. Improving the compressive strengths of cold-mix asphalt using asphalt emulsion modified by polyvinyl acetate. *Constr. Build. Mater.* **2007**, *21*, 583–589. [CrossRef]
17. Warid, M.N.M.; Hainin, M.R.; Haryati Yaacob, M.; Aziz, M.A.; Idham, M.K.; Abdul, N.A.; Raman, R.M. Effect of Styrene-Butadiene on Rheological Properties of Asphalt Emulsion. *J. Teknol.* **2015**, *77*, 1. [CrossRef]
18. Xu, S.F.X.; Zhao, Z.C.; Xu, Y.; Wang, X.X. Mixture Design and Performance Evaluation of Cold Asphalt Mixture Using Polymer Modified Emulsion. *Adv. Mater.Res.* **2015**, *1065–1069*, 760–765. [CrossRef]
19. Al-Kafaji, M.; Al-Busaltan, S.; Ewadh, H.A. Evaluating the rutting resistance for half warm bituminous emulsion mixtures comprising ordinary portland cement and polymer. *MSE* **2020**, *737*, 012138. [CrossRef]
20. Ibrahim, H.E.-S.M. Assessment and Design of Emulsion-Aggregate Mixtures for Use in Pavements. Ph.D. Thesis, University of Nottingham, Nottingham, UK, 1998.
21. Serfass, J.; Poirier, J.; Henrat, J.; Carbonneau, X. Influence of curing on cold mix mechanical performance. *Mater. Struct.* **2004**, *37*, 365–368. [CrossRef]
22. Huang, W.; Cao, M.; Xiao, L.; Li, J.; Zhu, M. Experimental study on the fatigue performance of emulsified asphalt cold recycled mixtures. *Constr. Build. Mater.* **2023**, *369*, 130607. [CrossRef]
23. Al-Busaltan, S.F.S. Development of New Cold Bituminous Mixtures for Road and Highway Pavements. Ph.D. Thesis, School of Built Environment, Liverrpool John Moores University, Merseyside, UK, 2012.
24. Dulaimi, A.; Al-Busaltan, S.; Sadique, M. The development of a novel, microwave assisted, half-warm mixed asphalt. *Constr. Build. Mater.* **2021**, *301*, 124043. [CrossRef]
25. Wang, Z.; Dai, N.; Wang, X.; Zhang, J.; Guo, H. Laboratory investigation on effects of microwave heating on early strength of cement bitumen emulsion mixture. *Constr. Build. Mater.* **2020**, *236*, 117439. [CrossRef]
26. Carpani, C.; Bocci, E.; Bocci, M. Rheological and performance characterisation of the bitumen recovered from different emulsions for cold mixtures. *Road Mater. Pavement Des.* **2021**, *22* (Suppl. 1), S214–S231. [CrossRef]
27. Dondi, G.; Tataranni, P.; Pettinari, M.; Sangiorgi, C.; Simone, A.; Vignali, V. Crumb Rubber in cold recycled bituminous mixes: Comparison between Traditional Crumb Rubber and Cryogenic Crumb Rubber. *Constr. Build. Mater.* **2014**, *68*, 370–375. [CrossRef]
28. Daneshvar, D.; Motamed, A.; Imaninasab, R. Improving fracture and moisture resistance of cold mix asphalt (CMA) using crumb rubber and cement. *Road Mater. Pavement Des.* **2022**, *23*, 527–545. [CrossRef]
29. EAPA. The Use of Warm Mix Asphalt. 2014. Available online: http://www.eapa.org/ (accessed on 19 December 2016).
30. Punith, V.; Xiao, F.; Wingard, D. Performance characterization of half warm mix asphalt using foaming technology. *J. Mater. Civ. Eng.* **2012**, *25*, 382–392. [CrossRef]

31. Gulisano, F.; Gallego, J. Microwave heating of asphalt paving materials: Principles, current status and next steps. *Constr. Build. Mater.* **2021**, *278*, 121993. [CrossRef]
32. Saleh, M.F. Effect of aggregate gradation, mineral fillers, bitumen grade, and source on mechanical properties of foamed bitumen–stabilized mixes. *Transp. Res.Rec.* **2006**, *1952*, 90–100. [CrossRef]
33. Al-Busaltan, S.; Al Nageim, H.; Dulaimi, A.; Shanbara, H.K.; Kadhim, M.A.; Al-Kafaji, M. Characterisation of Cold Bituminous Emulsion Mixtures Using Microwave Heating Process. Proceedings of Journal of Physics: Conference Series; IOP Publishing: Bristol, UK, 2021; p. 012239.
34. Van de Ven, M.F.C.; Jenkins, K.J.; Voskuilen, J.L.M.; Van den Beemt, R. Development of (half-) warm foamed bitumen mixes: State of the art. *Int. J. Pavement Eng.* **2007**, *8*, 163–175. [CrossRef]
35. Lizárraga, J.M.; Ramírez, A.; Díaz, P.; Marcobal, J.R.; Gallego, J. Short-term performance appraisal of half-warm mix asphalt mixtures containing high (70%) and total RAP contents (100%): From laboratory mix design to its full-scale implementation. *Constr. Build. Mater.* **2018**, *170*, 433–445. [CrossRef]
36. GSRB. *General Specification for Roads and Bridges, Section R9*; GSRB: Baghdad, Iraq, 2003.
37. *ASTM D2042-22*; Standard Test Method for Solubility of Asphalt Materials in Trichloroethylene. American Society for Testing Material: West Conshohocken, PA, USA, 2015.
38. *ASTM C88-13*; Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate. American Society for Testing Material: West Conshohocken, PA, USA, 2013.
39. *ASTM C131*; Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. American Society for Testing Material: West Conshohocken, PA, USA, 2014.
40. *ASTM C142/C142M-17*; Standard Test Method for Clay Lumps and Friable Particles in Aggregates. American Society for Testing Material: West Conshohocken, PA, USA, 2010.
41. *ASTM C128-22*; Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate. American Aociety for Testing Material: West Conshohocken, PA, USA, 2015.
42. *ASTM-C1252*; Standard Test Methods for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading). ASTM International: West Conshohocken, PA, USA, 2017.
43. *ASTM D5821-13(2017)*; Standard Test Method for Determining the Percentage of Fractured Particles in Coarse Aggregate. ASTM International American Aociety for Testing Material: West Conshohocken, PA, USA, 2017.
44. *ASTM D2397*; Standard Specification for Cationic Emulsified Asphalt. American Aociety for Testing Material: West Conshohocken, PA, USA, 2013.
45. *ASTM D6934*; Standard Test Method for Residue by Evaporation of Emulsified Asphalt. American Aociety for Testing Material: West Conshohocken, PA, USA, 2008.
46. *ASTM D70*; Standard Test Method for Density of Semi-Solid Bituminous Materials (Pycnometer Method). American Aociety for Testing Material: West Conshohocken, PA, USA, 2009.
47. *ASTM D5*; Standard Test Method for Penetration of Bituminous Materials. American Aociety for Testing Material: West Conshohocken, PA, USA, 2015.
48. *ASTM D6998*; Standard Practice for Evaluating Aggregate Coating using Emulsified Asphalts. American Aociety for Testing Material: West Conshohocken, PA, USA, 2011.
49. Asphalt Institute. *Asphalt Cold Mix Manual, Manual Series No.14 (MS-14)*, 3rd ed.; Asphalt Institute: College Park, MD, USA, 1989.
50. Nassar, A.I.; Mohammed, M.K.; Thom, N.; Parry, T. Mechanical, durability and microstructure properties of cold asphalt emulsion mixtures with different types of filler. *Constr. Build. Mater.* **2016**, *114*, 352. [CrossRef]
51. Amoori Kadhim, M.; Al-Busaltan, S.; Dulaimi, A.; Sadique, M.; Al Nageim, H.; Al-Kafaji, M.; Al-Yasari, R. Developing a sustainable, post treated, half warm mix asphalt for structural surface layer. *Constr. Build. Mater.* **2022**, *342*, 127926. [CrossRef]
52. *ASTM 2012 D6931*; Standard Test Method for Indirect Tensile (IDT) Strength of Bituminous Mixtures. American Aociety for Testing Material: West Conshohocken, PA, USA, 2012.
53. Kadhim, M.A.; Al-Busaltan, S.; Nemaa, Z.K.; Abo Almaali, Y.; Saghafi, B.; Al-Kafaji, M.; Al-Jawad, O.; Al-Yasari, R. Evaluating the Cracking Performance Indices of Half-Warm Mix Asphalt Comprising Waste Glass. *Int. J. Pavement Res. Technol.* **2021**, *15*, 1262–1276. [CrossRef]
54. Zhou, F.; Im, S.; Sun, L.; Scullion, T. Development of an IDEAL cracking test for asphalt mix design and QC/QA. *Road Mater. Pavement Des.* **2017**, *18* (Suppl. 4), 405–427. [CrossRef]
55. *ASTM D8225-19*; Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture using the Indirect Tensile Cracking Test at Intermediate Temperature. ASTM International: West Conshohocken, PA, USA, 2019.
56. Bennert, T.; Haas, E.; Wass, E. Indirect tensile test (IDT) to determine asphalt mixture performance indicators during quality control testing in New Jersey. *Transp. Res. Rec. J. Transp. Res. Board* **2018**, *2672*, 394–403. [CrossRef]
57. Chen, H.; Zhang, Y.; Bahia, H.U. The role of binders in mixture cracking resistance measured by ideal-CT test. *Int. J. Fatigue* **2020**, *142*, 105947. [CrossRef]
58. Li, C.; Li, Y.; Han, Z.; Du, Y.; Mohammed, M.A.; Wang, W.; Huang, J. A novel multiphase segmentation method for interpreting the 3D mesoscopic structure of asphalt mixture using CT images. *Constr. Build. Mater.* **2022**, *327*, 127010. [CrossRef]
59. Yao, X.; Xu, H.; Xu, T. Void distribution, interfacial adhesion and anti-cracking mechanisms of cold recycled asphalt mixture based on AFM and X-ray CT. *Appl. Surf. Sci.* **2022**, *606*, 155012. [CrossRef]

60. Kaseer, F.; Yin, F.; Arámbula-Mercado, E.; Martin, A.E.; Daniel, J.S.; Salari, S. Development of an index to evaluate the cracking potential of asphalt mixtures using the semi-circular bending test. *Constr. Build. Mater.* **2018**, *167*, 286–298. [CrossRef]
61. Haslett, K.E. Evaluation of Cracking Indices for Asphalt Mixtures Using SCB Tests at Different Temperatures and Loading Rates. Senior Honors Thesis, University of New Hampshire, Durham, UK, 2018.