Developing A Sustainable, Post Treated, Half Warm Mix Asphalt for Structural Surface Layer

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Abstract

Sustainability and materials recycling have increasingly acquired importance in various aspects of life. It has well known that 95% of roads are paved with hot mix asphalt (HMA), their raw materials require a lot of energy to prepare and lead to the release of a considerable amount of CO_2 into the environment. As a result, developing new technologies to prepare a new sustainable asphaltic mixture that consumes less energy and is eco-friendly becomes a necessity. This research aims to develop a sustainable half-warm asphalt mix by exposing the cold bituminous emulsion mixture (CBEM) to a post treatment using microwave energy technique, as well as utilising crushed glass waste as fine aggregate. The newly developed mix (half warm bituminous emulsion mixture, or HWBEM) is evaluated in terms of two main failure distress (cracking and rutting) using wheel track (WTT) and indirect tensile tolerance index, or cracking tolerance index (CT-index), in addition to the volumetric and durability evaluation in term of air voids content (AV) and retained Marshall stability test (RMS). Tests results regarding mechanical, volumetric, and durability properties indicated that the developed mixture was relatively comparable in some of the properties with referenced CBEM and superior in one aspect. Moreover, the sustainability aspect was achieved successfully by replacing a significant amount of virgin fine aggregate with the crushed waste glass. Based on the results of the test program, it can be said that the newly developed HWBEM incorporated waste glass can work as a structural surface layer.

Keywords: Cold emulsified bitumen mixture; cracking and rutting resistance; crushed glass waste; half warm mix asphalt and sensitivity to moisture damage.

1. Introduction

Global climate change is among the most critical issues we face today. By emitting these gases into the air, the construction sectors also contribute to the problem. Therefore, to minimize the hazardous effects of emissions, production sectors have to follow sustainable approaches by adopting greener technologies, including the asphalt mixture production sectors [1]. Additionally, substantial quantities of solid waste are generated as municipal waste and disposed of every year without any utilization. These materials can also be utilized in producing sustainable asphalt mixtures, alongside reducing emissions this would also reduce the demand for raw materials [2-7].

Currently, the hot mix asphalt (HMA) method is the most widely used road paving technology, despite it being financially and environmentally unsustainable, since it consumes a high amount of raw materials and releases lots of undesirable gases into the air [8, 9]. Hence, in brief, adopting new asphalt production technology that utilises solid waste material and consumes low energy during preparation and laying is necessary for ensuring the environmental and economic sustainability of the construction sector. environmentally and economically friendly, are the most favourable aspects of new technology in the pavement construction sector [10].

The main two components of any conventional asphalt mixture are; more than 90% of graded aggregates and a bituminous binder. This considerable usage of raw materials is considered unsustainable. In the pavement engineering field, many research works have indicated towards the applicability of utilizing solid waste glass materials as a partial replacement for the virgin aggregates of the asphalt mixture and soil embankments [11-13].

Several previous studies have investigated the possibility of utilizing crushed glass waste as a partial substitute for virgin aggregate in various asphalt mixtures, including hot mix asphalt (HMA) [14-17], warm mix asphalt (WMA) [17, 18], and cold mix asphalt (CMA) [3, 15, 19]. The majority of publications highly recommended using crushed waste glass as a fine aggregate in an asphalt mixture with a maximum particle size of about 4.75 mm [20] [21]. In addition, to obtain the best mechanical and durability properties, researchers recommended using an anti-strip agent, such as lime or conventional Portland cement fillers [13, 22-25]. To date, most of the researchers revealed that the desired amount of crushed glass within an asphaltic mix ranges from 5-20% of the total weight of the mixture [15, 23, 26], Researchers have also found that the addition of 10-15% of crushed glass into a wearing course layer may provide the necessary reinvigoration to offer adequate performance [27-30].

Generally speaking, Asphalt mixtures are often categorized according to the temperature at which they are mixed and prepared, including; cold mix asphalt (CMA), half-warm mix asphalt (HWMA), warm mix asphalt (WMA), and hot mix asphalt (HMA). Mixing temperatures for each of these mixtures typically are in the ranges of 0 to 40 °C, 65 to 100 °C, 110 to 140 °C, and 140 to 180 °C, respectively [31-34].

Cold bituminous emulsion mixture (CBEM) is one of the most well-known and reconditioned types of asphaltic mixtures. CBEM is a mixture of a suitably graded aggregate, bitumen emulsion (composition of grade bitumen not less than 50%, waster, and chemicals for longer storage timespan), water, and sometimes additives [35]. All preparation stages in the CBEM technology are performed in ambient temperatures meaning elevating the temperature of components, heating during mixing and heating during compaction are all not required [3, 36-40]. However, although such type provides some environmental, logistical, and economic advantages over other types, it still has some mechanical and volumetric issues, especially during the early stage of life [41-43]. Practically, the CBEM is still restricted for rehabilitation purposes and no trail mixes have been performed to characterize the site's long term performance [44].

For decades, researchers have reported the high percentage of air voids content and weak mechanical characteristics of CBEM rendering it unacceptable to be utilized as a structural surface layer [19, 34, 45]. On the other hand, some have stated that CBEM performance could be used as a surface course if well treated [46]. Comprehensive studies which have attempted to develop CBEMs and overcome such unacceptable properties have used different techniques and methodologies such as incorporating cementitious fillers [47-52], the addition of polymers [41, 53], reinforcing with synthetic fibers [54], or adopting a post-heat treatment method [55, 56]. Moreover, different types of aggregate gradations were used to investigate the potential feasibility to use such mixes in various aggregate skeletons such as dense graded mixtures [3], gap graded [57], and open graded gradations. When post-heating, whether conventional or microwave energy, is applied to a loosen CBEM before compaction, if the process is within a temperature not more than 100 °C, it is called the half warm bituminous emulsion mixture (HWBEM).

HWBEM is a technique for manufacturing asphalt mixes at temperatures ranging from 65 to 100 °C [34, 58-60]. Various types of bituminous binder can produce mixes such as; emulsified bitumen foamed bitumen, and modified bitumen with fluxing oil [3, 45].

HWMA is recently being used increasingly in structural road pavement since its performance is comparable to that of HMA. In contrast to CMA, which is still used for road maintenance and low traffic loading condition [35]. The production of such mixtures can reduce the environmental hazards efficiently by minimizing toxic gases emissions into the air. Also, HWMA presents many technical, ecological, and economical benefits when compared with the HMA, relatively in terms of laying, compacting, and production temperatures. Moreover, the advantages of such mixtures are not limited to what has been mentioned previously, further advantages can be obtained logistically through increasing hauling distance efficiently, and better working conditions by reducing risks during the mixture's laying down and compaction; i.e; safer than HMA [61].

As stated previously, more than one method can be utilized to raise the HWBEM mixture's temperature; i.e; infrared method, induction method, and microwave heating method. Many researchers had reported that the microwave processing technique is the most efficient method among other methods for many reasons, i.e; no direct contact, higher energy saving, being more eco-friendly, higher thermal response and efficiency, and finally its release of controlled energy (phase selecting energy) [62-64]. This method is similar to the radio waves and is based on subjecting an object to electromagnetic waves with frequencies ranging from 0.1 GHz to 100GHz, and wavelengths ranging from 0.003 m to 3 m (lower than the radio's wavelengths). Practically, in terms of asphalt and concrete, several previous researchers had conducted that with the microwave heating technique, higher thermal efficiency, higher heating rate, and homogeneity could be achieved when compared with the other methods [65, 66].

Recently, microwave heating technology has been paid a lot of attention by many researchers. Some researchers approved the efficiency of the microwave heating method in processing the cold mix asphalt mixtures when compared with conventional heating [34].

2. Research Aim and Scope

This research work aims to develop sustainable, half-warm emulsified bituminous mixtures (HWBEM) for a dense graded surface layer purposes by utilising the municipal waste glass as fine aggregate after crushing (FGA). The crushed glass waste was replaced with the virgin limestone aggregate with different dosing ratios starting from 0% to 100%, and 25% step increment. The testing program focused on three aspects; volumetric properties, mechanical properties and durability performance. Volumetric properties investigated were air void content and density. Mechanical properties investigated were indirect tensile strength, CT-index fracture energies, rutting resistance and resistance to plastic deformation (Marshall stability-flow test). Durability performance was assessed from the results obtained from the retained Marshall stability test.

3. Materials Characterization

Karbala city, which is approximately located in the middle of Iraq, has tremendous resources of natural aggregates in its west. The limestone aggregate is considered the leading type amongst other types of aggregates. Therefore, coarse and fine aggregates from virgin crushed limestone were sourced from the local quarries. They were washed, dried, graded, and stored according to the Iraqi general specification for roads and bridges (GSRP) [67]. For fine glass aggregate (FGA), the large glass pieces of various disposal containers, useless window glass, doors, and bottles are collected locally as municipal wastes with different colours and thicknesses. Then, the undesirable types of glass, such as the coloured ones, are eliminated away from other waste glass types, since several previous researchers had stated that the coloured glass has weaker properties than uncoloured ones. It was reported that glass that has been painted, coloured, or has foiling on it cannot be recycled due to the decorative features are not recyclable when mixed with other glass [68].

After that, the waste glass pieces are crushed and sieved to get three types of gradations: passing sieved no.4, passing sieved no.8, and passing sieve no.50, as presented in Figure 1. Tables 1 and

2 presents the physical properties for all previously mentioned types of course and fine aggregates. The cementitious filler component utilised in this study was the ordinary Portland cement (OPC) and sourced locally from the Karbala cement plant. On the other hand, the cationic, medium setting, asphalt emulsion type was supplied from Henkel company, under the commercial name of Polybit, with properties listened in Table 3.

Figure 1. preparation of waste fine glass aggregates (FGA)

Table 1. The physical properties of virgin coarse aggregate (VCA)

Property	Adopted Specification (ASTM)	VCA	Requirements
Water absorption, %	C127[69]	1.410	-
Bulk specific gravity	C127[69]	2.591	-
Bulk SSD specific gravity	C127[69]	2.601	
Apparent specific gravity	C127[69]	2.618	-
Soundness loss by sodium sulphate, %	C88[70]	7.574	12% max
Percent wear by Los Angeles abrasion test, %	C131[71]	13.5	30% max
Degree of crushing, %	---	93%	90% min
Clay lumps, %	C142[72]	0.080	-
Flat and elongated particles, %	D4791[72]	1.538	10% max

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

Property	Adopted Specification (ASTM)	VFA	FGA
Water absorption, %	C128 [73]	1.810	0.530
Bulk specific gravity	C128 [73]	2.598	2.497
Apparent specific gravity	C128 [73]	2.587	2.471
fine aggregate angularity (FAA)	C 1252 [74]	52.7	87.5
Loss angles abrasion %, D grading	C131 [71]	7.420	31.500
Degree of crushing, %	D5821[75]	87.44	100

* The test conducted for the portion size 4.75-2.36 mm

Table 3. Asphalt emulsion properties

Property	ASTM	Limits	Results
Appearance	----	-----	Dark brown colour
Emulsion type	D2397[76]	Rapid, medium and slow setting	Cationic medium setting (CMS)
Aggregate coating	D6998 [77]	-------	Uniformly coated
Residue %	D6934 [78]	Min 57	61.5
Penetration, mm	D5 [79]	100 – 250	190
Specific gravity	D70 [80]		1.025

4. Mixes Design Procedure

Up to date, no local standard criteria or specifications are developed for CBEMs design [81]. Therefore, to design a cold mix asphalt, the procedure adopted by the asphalt institute in publication (MS-14) [82], was followed herein, with some modifications to meet the Iraqi specifications (as presented in Table 4). Internationally, this method is widely accepted and considered the most well-known procedure to prepare CBEMs. Moreover, the followed design procedure in this research work was detailed in a previous publication by the same authors [3]. Hence, The MS-14 method [67], along with the local specifications of GSRB (as detailed in table 4) [67] are utilized to produce CBEM, and then HWBEM specimens after performing some modifications, as detailed in the flowchart shown in Figure 2. It is worth mentioning that the design procedure of CBEM starts from step 1 till step 7, while the HWBEM starts from step 1 till the last step. In brief, the following points describe the adopted design methodology for both CBEM and HWBEM:

Table 4. GSRB limitation for the surface layer, section R9 [67]

property	GSRB Requirements
Stability, Kg	>800
Retained strength, %	>70
Air Void, %	3-5
Flow, 1/10mm	2-4

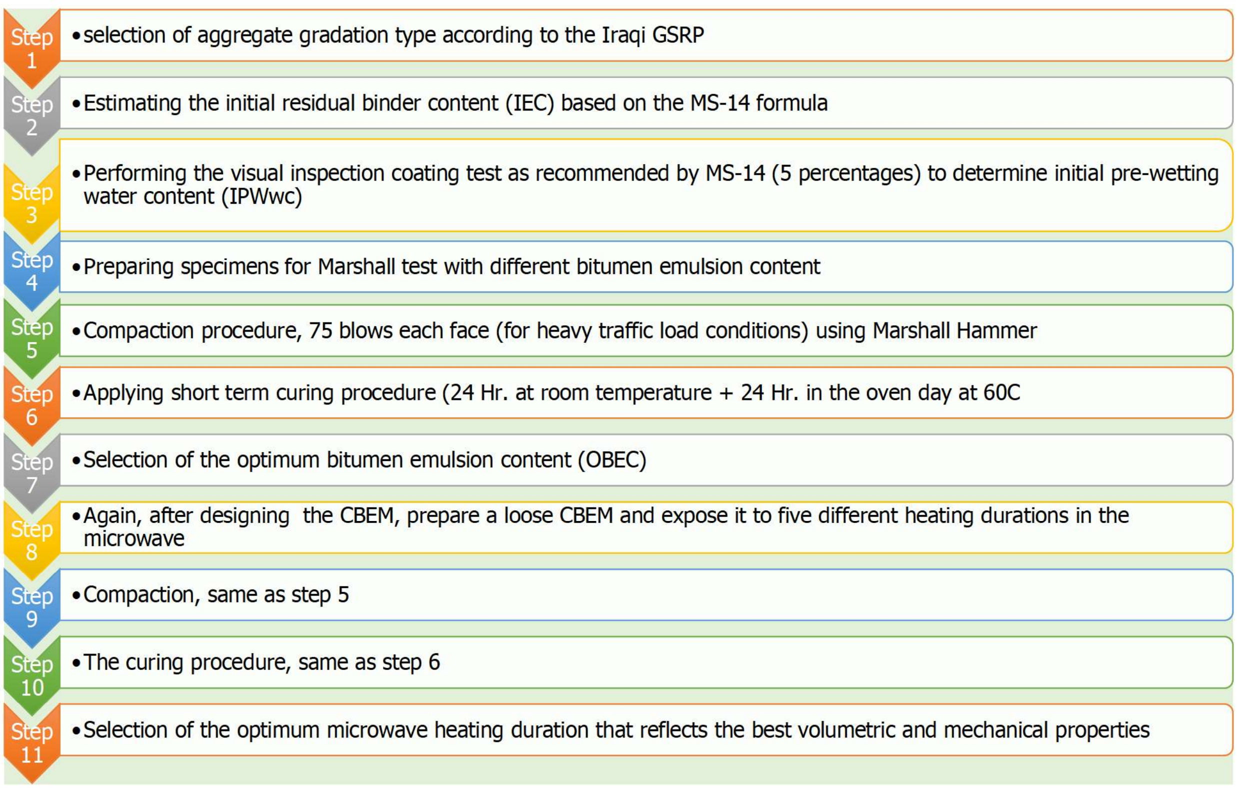

Figure 2. MS-14 manual for producing CBEM and the proposed method to prepare HWBEM.

- Step 1: Adopting suitable aggregates gradation for the mixture. According to the Iraqi GSRP [67], the dense-graded aggregates' gradation for surface coarse purposes (type IIIA) was used as illustrated in Figure 3. Both coarse and fine aggregates were crushed particles, white in colour, of the limestone type with physical properties mentioned previously in section 2.
- Step 2: This step involves the determination of the initial emulsion content (IEC). The proposed empirical formula was recommended by the asphalt instate manual (MS-14) [67] and was adopted to determine the IEC. It is worth mentioning that the MS-14 formula mainly depends on the gradation of the aggregate.

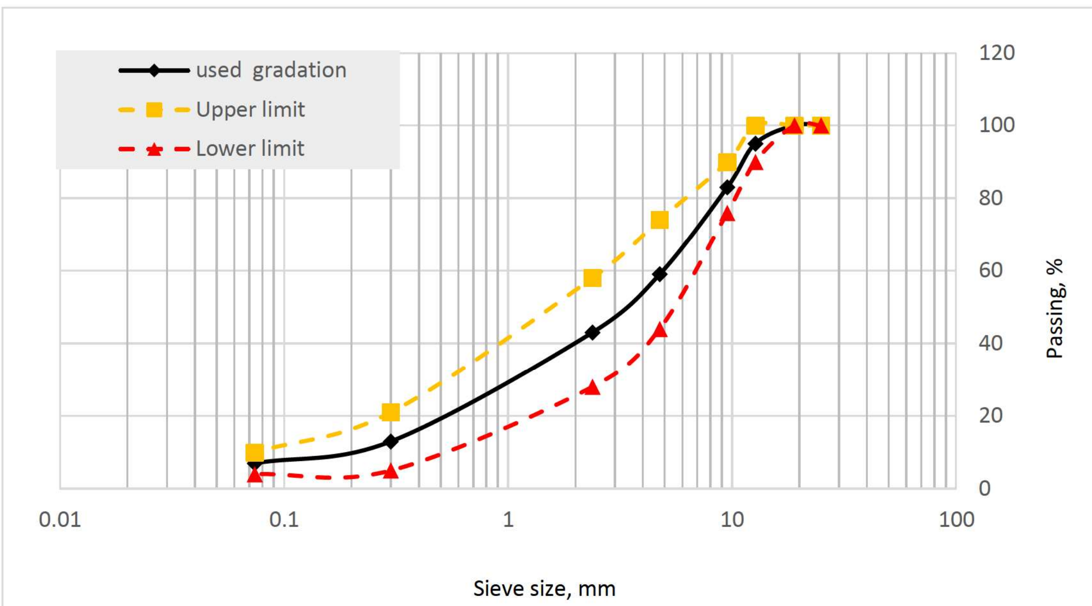

Figure 3. Particle size distribution of type IIIA (dense-graded) for wearing course

- Step 3: Coating the aggregate mix with water. Before mixing aggregate components with the bitumen emulsion, it was highly recommended to prewet aggregates with water, especially for gradation including high materials passing through a sieve of 63 nm. It had been reported that inadequate initial moisture of aggregates causes balling of the bituminous binder with the fine aggregate particles resulting in an unacceptable coating degree [83]. The initial prewetting water content (IPWwc) suggested by the MS-14 manual was adopted in this research work. In the MS-14 it is stated that five different trial percentages should be examined to select the lowest percentage that achieves the best coating state, based on the visual inspection method. Accordingly, the optimum IPWwc value was found to be 3.5%. Figure 4 presents the effect of IPWwc percentage on the overall mixture coating.

- Step 4: Compaction and curing: To simulate heavy traffic conditions, a Marshall hammer was used to compact the cylindrical specimens by applying 75 blows on each face, as recommended by GSRB.

Figure 4. Effect of IPWwc percentage on aggregate coating.

- Step 4: Determination of the optimum emulsion content (OEC). In this step, the Marshall stability-flow test was suggested by the MS-14 manual to determine the OEC [84]. The test was configured according to the ASTM D6927 [85]. In brief, five trail mixes with different bitumen emulsion content were examined. Accordingly, the highest Marshall stability (>800 Kg) corresponded to a flow value within a limit of 2-4 mm, and air void content within a range of 3%-5%. Minimum durability requirements (>70 RMS test) were selected as criteria to decide the OEC value.

- Step 5: Determining the optimum total liquid content (OTLC): the OTLC is the summation of the OEC and OPWwc values that reflects the best mechanical and volumetric results. According to the properties of the materials, test results have shown that the OPWwc, OEC, and OTLC values were 3% and 11 % and 14 % of aggregate masses.
- Step 6: After determination of the mentioned values, the loose CBEM mixture, as illustrated in Figure 5, was conditioned in a home size microwave at full power level (700 watts), with five different durations, starting from 1.5 min to 7.5 min, with 1.5 min time increments. During the microwave heating process, mixture temperatures were measured indirectly using a mountable infrared thermometer device. The proposed method was followed to identify the best post-treatment conditioning duration, which exhibits the highest performance in terms of the volumetric and mechanical properties. Figure 5 illustrates the relation between microwave treatment duration and mixture temperature. It is clear that the relationship is approximately linear, with the maximum reached temperature being 105℃ after 7.5 minutes of conditioning.

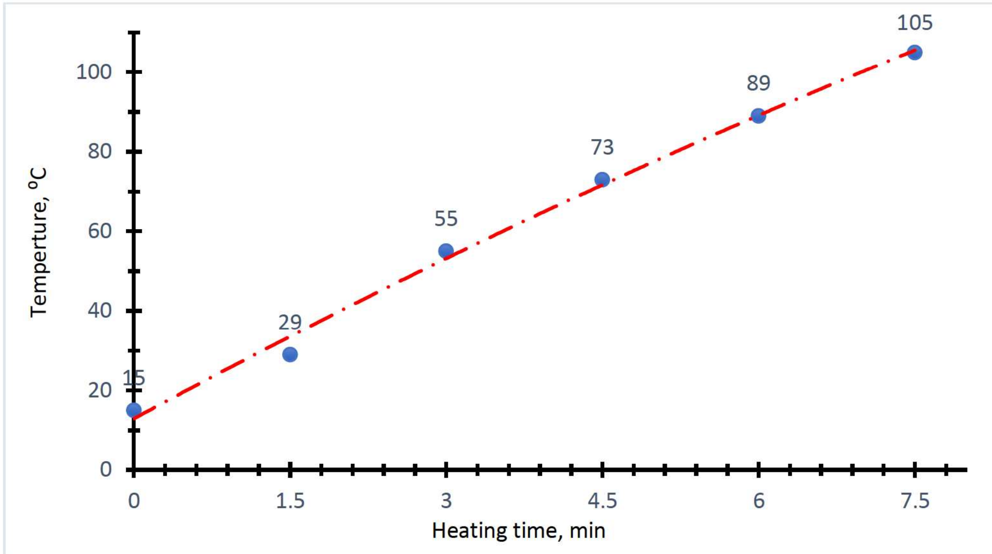

Figure 5. effect of microwave post-treatment duration on the loose CBEM’s temperature

- Step 7: After microwave conditioning, specimens were subjected to compaction using a Marshall compaction hammer with 75 blows on each face of the specimen. It was confirmed that free water was still trapped within the specimen even after conditioning the loose CBEM in the microwave [55]. Hence, as with CBEM specimens, the HWBEM specimens were cured using a specific protocol according to the type of the test, as to be detailed in the following subsection. Figure 6 illustrates loose CBEM conditions before and after conditioning in the microwave.
- Step 8: To achieve greater sustainability, a partial replacement of VFA with the FGA was applied with four different percentages starting from 25% to 100%, with a 25% step increment. Each percentage was substituted equally on three sieves (sieves No.4, No.8 and No.50) while ensuring the same gradation as the virgin fine aggregates.

Figure 6. CBEM loose mixture subjected to microwave heating energy

5. Curing Protocols

Generally, it has been well known that CBEM's mechanical characteristics are time-dependent [86-88]. Also, it requires a long time to reach the mixture's mature strength. Overall, there are two main methods by which the time taken to achieve the required design strength can be reduced, these protocols often adopted by most researchers are illustrated as follows:

1- Short time curing (normal curing): to simulate mixture properties after 7-14 days in place, curing procedures were achieved by: firstly, placing specimens at room temperature for 24 hr, and secondly, 24 hr in an oven at 40ºC. Such protocol was adopted for volumetric and durability tests, Marshall specimens, IDT, and CT-index specimens [88, 89]. Figure 7 illustrates specimens under curing protocol. Such protocol has been adopted by the said researchers [19, 86]. Moreover, adopting a normal curing temperature in this research will stimulate the production, compaction, and placing of such mixtures in field conditions and will also avoid any premature aging of the binder [90]

2- The full strength of the mixture from full curing was simulated by placing compacted samples in the mould at room temperature for 24 hr. then, conditioning them in an oven for 14 days at 40º C as recommended by [91] (see Figure 8). Such protocol was also followed by many researchers to test a mixture's resistance to rutting failure [35, 36, 92].

Figure 7. The curing process of CBEM and HWBEM specimens.

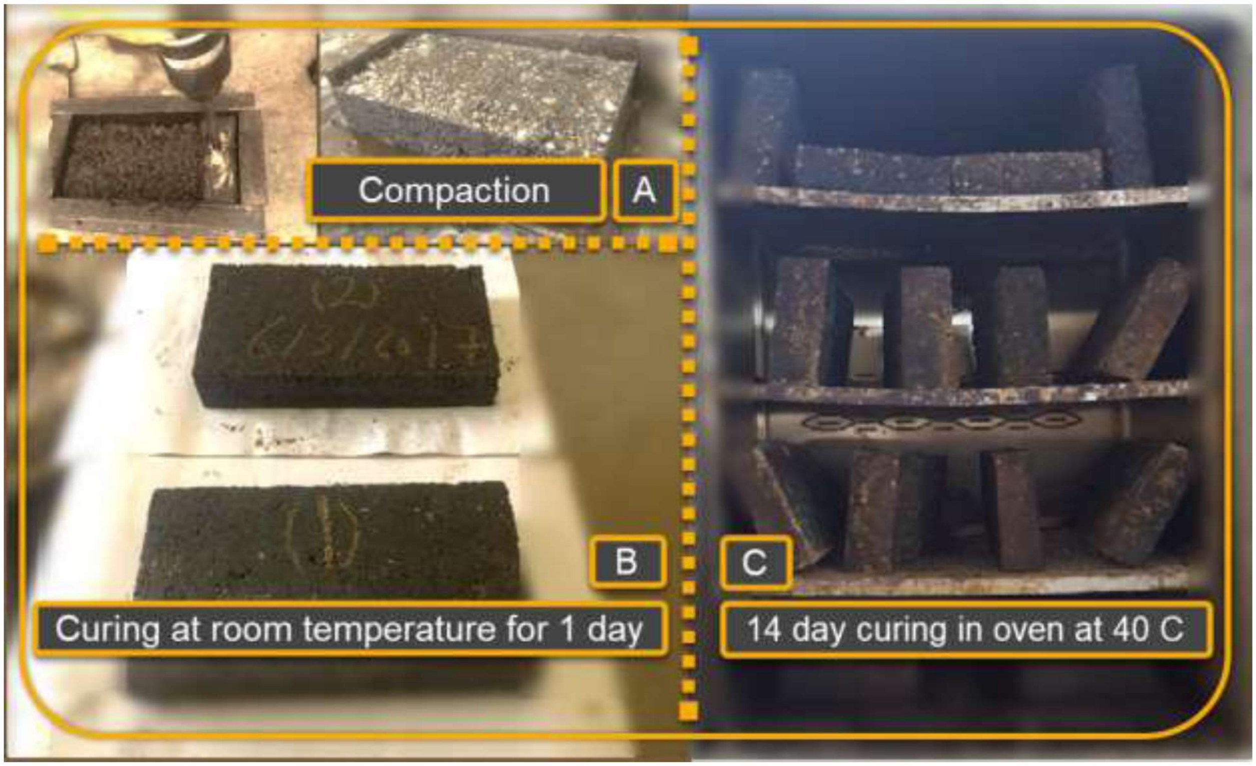

Figure 8. Preparation and curing of rectangular slab specimens for the wheel track test

6. Failure Criteria and Related Testing Methods

Apart from the basic testing methods for asphalt pavement (Marshall test), this study has covered several volumetric (air voids ratio and density), mechanical, and durability tests to cover most pavement distresses and characterise mixture strength as wide as possible. Cracking and rutting are the main mechanical types of failure distress in asphalt pavement layers. Therefore, cracking strength was nominated and identified by three main parameters which are indirect tensile strength (IDT), indirect tensile tolerance index (CT-index), and fracture energy (G_f). At the same time, a wheel tack test was selected to measure the mixture's resistance to permanent deformation (rutting). The durability test in terms of moisture sensitivity to resist cracking was performed using the retained Marshall stability test (RMS), as stated recommended by the asphalt institute (MS-14) and the Iraqi GSRP. The work stages are presented in Figure 9.

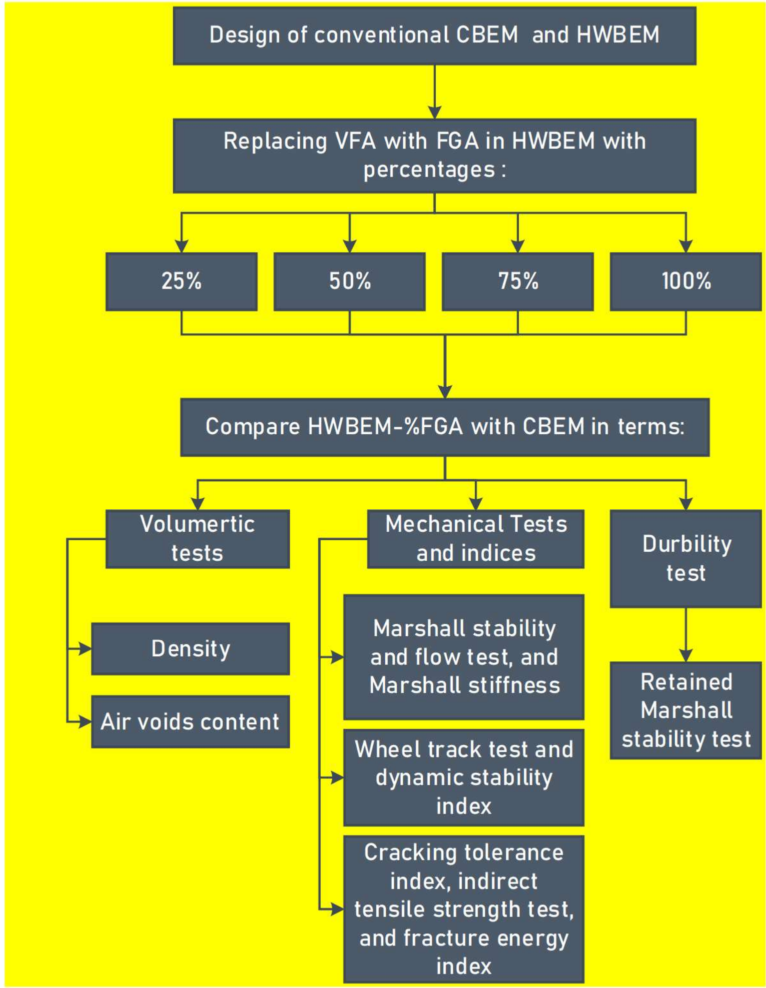

Figure 9. The work's flowchart

6.1 Marshall Testing

Marshall Test is a well-known empirical destructive test that is used to determine the resistance of a mixture to plastic deformation and flow. Marshall test was conducted in this study for both CBEM and HWBEM following ASTM D6927 [85]. Three replicates were performed for each mix type. There are no notable differences in the testing technique between HMA and CBEMs, except for the curing of specimens prior to performing the test. It is important to note that the standard testing apparatus was developed locally to automatically acquire, log, and process data to generate stability-flow curves.

6.2 Cracking Resistance Indices (IDT, CT-index, and G_f)

Cracking failure is one of the most important mechanical distresses to occur when external tensile stress is applied by the traffic load exceeds the tensile strength capacity of the asphaltic layer. As mentioned previously, this study has covered three main parameters to characterize mixture's resistance to cracking which are the IDT, CT-index, and fracture energy (G_f) parameters.

The IDT is a widely used standard test for determining the tensile strength of the asphaltic mixtures. It is carried out by applying compressive forces over the Marshall specimen's diameter using two steel strips, as stated in ASTM D6931[93], see Table 5. The requirements for the IDT test are shown in Table 3, and IDT was determined using Eq. (1).

$$IDT = \frac{2P}{\pi X D \times t} \times 10^{-3} \tag{1}$$

Where, IDT: Indirect tensile strength (KPa), P**:** is max force obtained(N), D: specimen diameter (mm), and t**:** specimen thickness(mm).

Table 5. Testing conditions and configurations for IDT and CT-index tests.

Item	ASTM D6931 **[93]** and D8225 **[94]**	Selected property
No. of tested specimens	3	3
Loading rate, mm/min	50±5	51.3
Diameter of the specimen, mm	101.6, 150	101
Conditioning temperature, ºC	5-35	25 ± 3
Compaction by Marshall hammer	75 blows on each face	75 blows on each face
Height of specimen, mm	50.8-65.5	55-60
Accuracy	Min.50N	10 N
Conditioning in oven-dry, min	120-130	120
Curing (CBEM, HWBEM)	…….	24hr at Lab temperature+24hr. in oven dry at 40 ºC

The indirect tensile cracking test (CT-index) was developed by the Texas A&M Transportation Institute in 2017 [95] as an advanced and efficient technique for evaluating the overall cracking resistance of mixtures as detailed in ASTM D8225 [94]. It is a novel and quick test where no notching, cutting, or glueing is required to perform the test [96, 97]. Also, compacted specimens are tested at moderate temperature ranges (5°C to 35°C, taking into account the local environment) and exposed to a 50 mm/min loading rate. Unfortunately, our laboratories still lack the availability of Superpave equipment (e.g gyratory compactor), which makes it difficult to compact 150 mm diametric specimens. In the IDT test, both 100 mm and 150 mm specimen diameters can be used for testing. Thus, in this study, Marshall molds of 100 mm in diameter specimens were prepared for the CT-index test, as suggested by Kadhim et al. [98]. Figure 10 demonstrates the setup of the CT-index tests. It is worth mentioning that this device was also used to perform the IDT test.

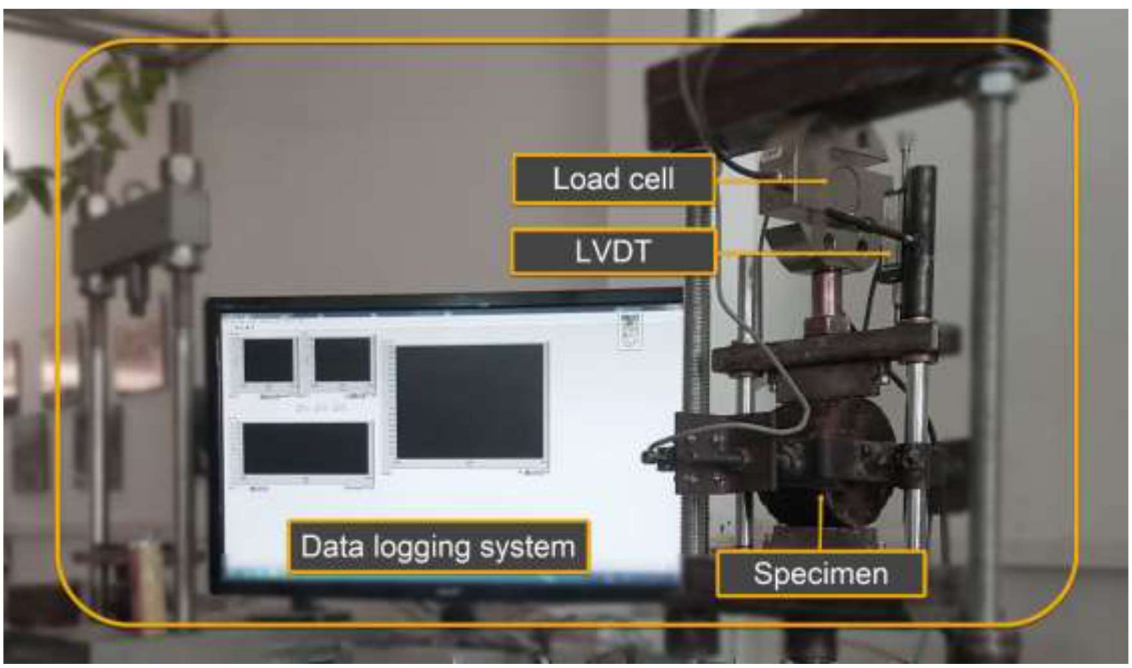

Figure 10. CT- index and IDT testing configuration.

The argument for using this test is that microcracks are initiated after exceeding the peak allowable tensile capacity [99, 100]. With higher external loadings, cracks will be developed and propagated beyond such limit, leading to a corresponding reduction in the specimen capacity, as illustrated in

Figure 11. The govern formula (Eq. 2) was used to determine the CT-index of an asphaltic mixture. It is worth noting that The IDT test cannot capture such effect since it measures the resistance capacity to tensile cracking based on the maximum preserved load. In contrast, the CT-index depends on more than one parameter to characterize mixture tensile strength. moreover, some researchers have reported that the CT index is very sensitive to changes in asphalt mix design composition and this is reflected in the field cracking performance [101, 102]. Generally, Jahangiri et al. [103] recommended a minimum Ct-index value of 65, while the recommended CT for Superpave mixes is 105.

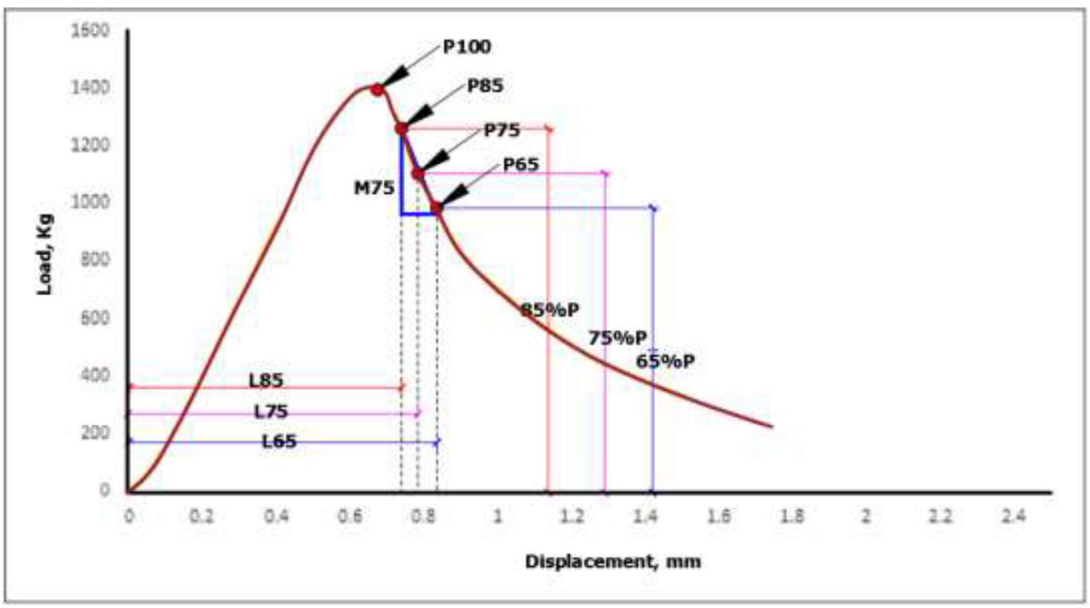

Figure 11. Calculation procedure of CT-index [104].

$$CT_{\text{Index}} = \frac{t}{62} \times \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{D}\right) \tag{2}$$

Where:

CT_{Index} is the cracking tolerance index and is calculated using equation 2. W_f is the work of failure (J) and is found by calculating the area under the load-displacement curve. l_{75} is the fracture energy and is the energy required to create a new unit fracture surface in a specific material body [105]. m_{75} is the post-peak inflection point (N/m) that can be found via equation 3. G_f is the failure energy (J/m^2), it is defined as the energy needed to create a unit area of a crack and can be found using equation 4 [106]. D is the specimen diameter (mm) and t is the specimen thickness (mm).

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

P_{85} and P_{65} are the peak loads at 85% and 65% respectively. l_{85} is the displacement at P_{85} (mm) and l_{65} is the displacement at P_{65}(mm).

$$G_f = \frac{W_f}{D \times t} \times 10^6 \quad (4)$$

W_f is the work of failure (J), D is the specimen diameter (mm) and t is specimen thickness (mm).

Realistically, to achieve the practical characterization of cracking failure phenomena, it is necessary to use a multi parameters index to accurately describe the phases of such failure (cracking initiation and propagation). As mentioned previously, the IDT index identifies the maximum tensile resistance to cracking only. It cannot demonstrate the behaviour of the mixture at a specific phase since it depends on the maximum preserved tensile strength during loading in a static manner. For instance, when two mixtures reflect the same tensile strength capacity, it does not mean that they have the same absorption energy. Moreover, even though the two mixtures have equal fracture energy, theoretically, the comparison level still lacks accuracy. The slope of the degradation curve plays an essential role in reflecting mixture flexibility and demonstrates the pavement layer behaviour at the post-peak cracking phase. Overall, it can be said that CT-index reflects higher reliability for cracking resistance evaluation than the IDT index.

The fracture energy, as defined and detailed previously, was also selected as a parameter for characterising the cracking resistance index, because even if two mixtures have equal total fracture energy, neither of these mixtures has the same fracture energy to dissipate the external cracking initiation energy, nor do they have the same energy absorption to withstand cracking propagation. Therefore, each mixture is characterized by three energies; the pre-crack, post crack, and total fracture energy. The pre-crack absorption energy is calculated by dividing the area under the load-displacement curve up to the maximum load over the specimen's cross diameter (D*t). The post-cracking absorption energy was calculated using the area under the load-displacement curve after the cracking initiation point to the end of the test. The total absorption energy and the fracture energy are the summations of the previously mentioned energies.

6.3 Wheel Track Test (WTT)

Rutting distress, or the Plastic deformation under dynamic wheel loading, considers one of the most common failure types in hot climate regions. It commonly uses the wheel track test (WTT) to describe mixture resistance to rutting or permanent deformation. The WTT indicates mixture stiffness and rate of permanent deformation. It was applied for both CBEM and HWBEM specimens and performed following BS EN 12697-22: 2003 [107]. Table 6 presents the adopted specifications in this study, in which a small device wheel tracker equipment has been utilised as illustrated in Figure 12.

After determining CBEM's and HWBEM's dosing components, a loose mixture was placed in a steel mould to prepare slab specimens for WTT. Then, vibratory compaction was applied under the BS standard [108]. Mixtures were subjected to various compaction efforts to decide the optimum time of compaction corresponding to the target air void content of 7%. Accordingly, three compaction durations were applied for each mixture type (CBEM and HWBEM) to decide the optimum compaction effort (OCE).

Table 6. WTT device conditions

Property	EN 12697-22 **[109]**	Applied conditions
Wheel Diameter, mm	200±5	200
Wheel load, N	700±5	708
Wheel speed, m/sec	26.5	25
Specimens dimensions, mm	50 x 260 x 410	50x130x300
Specimen preloading, cycles	5	5
Compaction duration, minutes	CBEM	3
	HWBEM	4.45
Specimen height, cm	4-10	5-6
Compaction method	Static press, roller compactor, vibrator compactor	Vibratory compactor
Conditioning temperature, ºC	60 ± 2	60 ± 1
Conditioning of conditioning, minutes	120-130	120
No. of tested specimens	3	2

Another indicator of the resistance to rutting of an asphaltic mixture is Dynamic Stability (DS). DS specifically indicates the high temperature stability of the mixture with the test being held at 60 °C. DS is found from the number of wheel passes required to cause a unit rut depth in an asphaltic mixture from 45 to 60 minutes of the test [110]. The test was in accordance with the Chinese Highway Engineering Asphalt and Asphalt Mixture Test Code [111]. DS can be found using equation 5 [111]:

$$DS = \frac{N_{15}}{D_{60} - D_{45}} \tag{5}$$

Where:

DS is Dynamic stability (passes/mm)

N_{15} is the number of the wheel passes after the first 15 minutes of testing (mm).

D_{60}-D_{45} is the change in rut depth at the last 15 minutes of testing (passes).

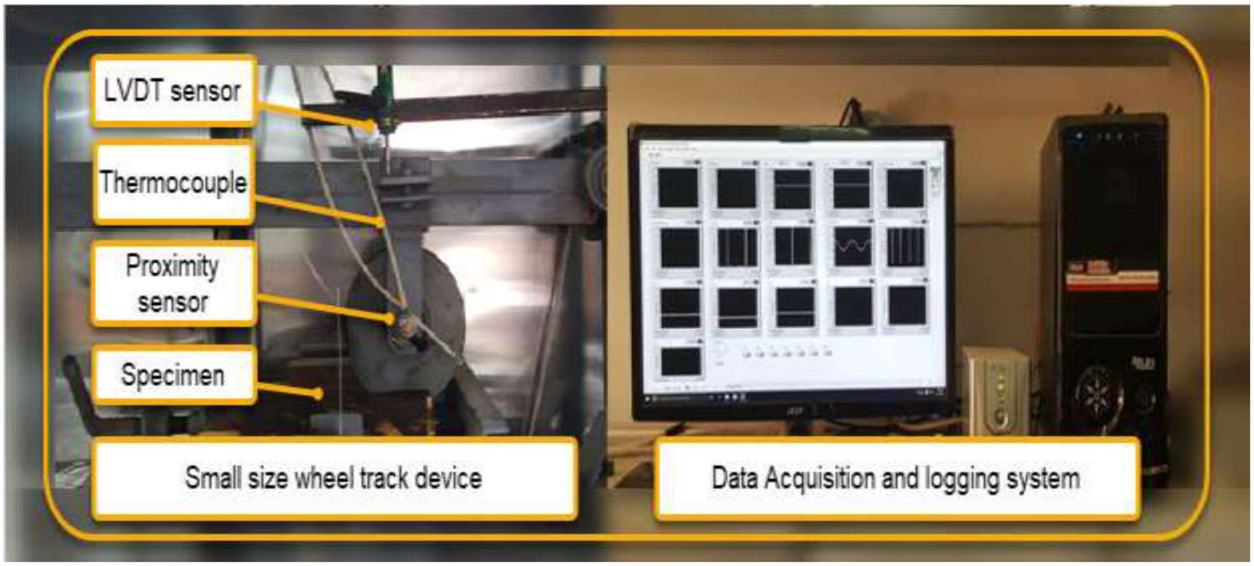

Figure 12. Wheel track device components

6.4 Durability Requirement: Retained Marshall Stability Test (RMS)

Generally, moisture has a detrimental effect on pavement strength and can reduce pavement life severely. The asphalt institute (MS-14) manual suggested using the retained Marshall stability test as a testing procedure for evaluating the mixture's sensitivity to moisture. In short, the Marshall stability index is found by the ratio of the average stability of the conditioned samples over the average stability of the unconditioned samples, the conditioning protocols are outlined in table 7 below. Where, Three replicates were performed for each mix type.

Table 7. Conditioning protocols for RMS test

Unconditioned specimens	Conditioned specimens
24hr in mould @ lab temperature	24hr in mould @ lab temperature
24hr in oven @ 40 °C	24hr in oven @ 40 °C
……………….	24hr in water bath @ 60 °C

The test was performed after curing the specimens in a water bath at 60 °C for 2hr. The RMS index is determined using Eq. 6.

$$RMS\% = \frac{stability\ of\ conditoned\ specimen}{stability\ of\ unconditoned\ specimen} \times 100\% \quad (6)$$

7. Test results

7.1 Effect of Microwave heating duration on the stability and flow results

Tests results have shown significant differences when treating loose CBEMs in the microwave, as demonstrated in Figure 13. It is clear that increasing the duration of the treatment resulted in an improvement in the stability and flow properties. A noticeable improvement in stability values was recorded after 3 minutes of treatment; in other words, about 245% of enhancement in the stability was obtained after six minutes of treatment. It is believed that most of the trapped moisture within the specimens was eliminated at this point. According to the adopted requirements, Although CBEM's stability was acceptable (>800 Kg), the flow property was unfavourable and higher than the specified upper limit (higher than 4 mm). On the other hand, the reduction rate of flow property started after 1.5 minutes of microwave treatment, starting from 6.12 mm with the CBEMs, to reaching the minimum value of 1.943 mm after 7.5 minutes of treatment. The continual increase in temperature results in a reduction of the tapped water that is necessary for the hydration process of the cementitious materials. Thus, the stability after 6 min discloses a noticeable reduction, although the air voids have shown a continuous reduction even after 6 min.

Based on the GSRB requirements, the recommended allowable limit of flow property for the surface layer has been covered from 1.5 minutes to 6 minutes of treatment duration. Therefore, it can be said that the optimum duration of microwave treatment was about 6 minutes, and has been taken as a reference value for treating other specimens. Interestingly, six minutes of microwave treatment at full power level (700 watts) reflected a mixture temperature of about 94°C. Hence, the microwave treated CBEM was then named HWBEM.

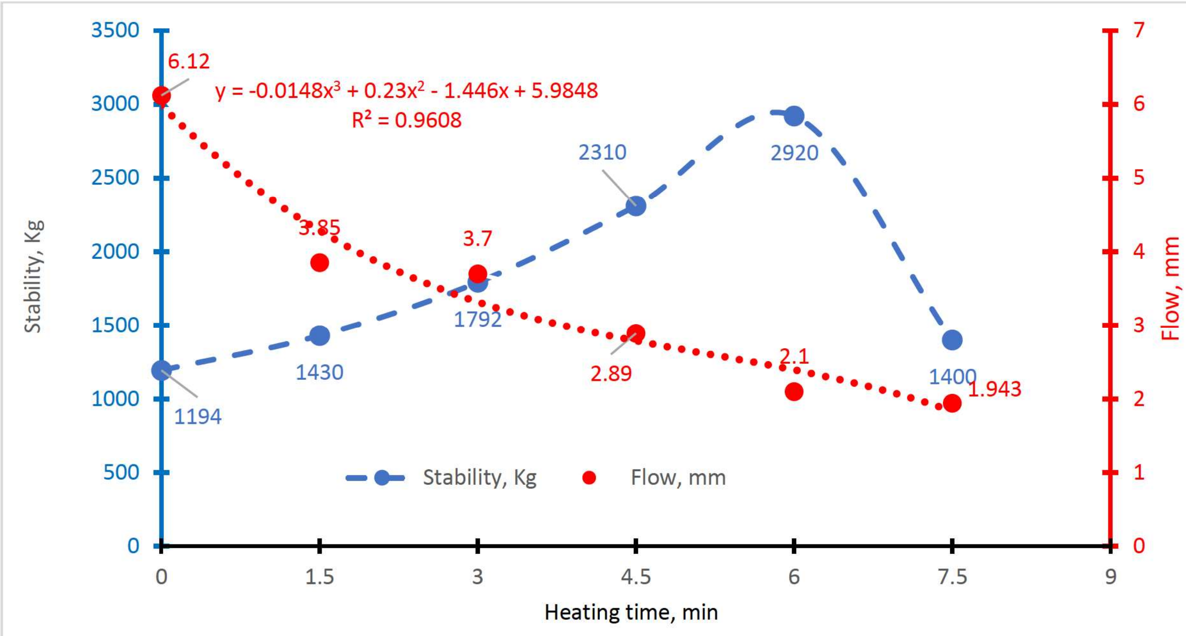

Figure 13. Effect of microwave conditioning on stability and flow behaviour.

7.2 Volumetric performance

The density and air voids content (AV%) results for different mixtures are shown together in Figure 14 From the figure, it can be observed that CBEM has an AV% twice the maximum higher allowable limit (5%) for surface layer conditions, it possessed the highest and lowest AV% and density among other mixtures, respectively. As previously mentioned in the literature, it is often found that it is hard to achieve low AV% of an untreated CBEM within specified limits, because of the high trapped moisture that leaves high voids after evaporation. On the other hand, applying microwave treatment to a loosen CBEM till the optimum value results in an HWBEM mix with lower AV% and higher density when compared with CBEM. It is believed that the free water was eliminated at such a point, resulting in a higher densification process during the compaction stage, and hence lower air voids. Overall, HWBEM possessed the highest density and lowest AV%

among other mixtures, enhanced by about 2.66 times the AV% of CBEM, and within the GSRB specification for the surface layer.

The same Figure also clearly shows that increasing FGA% causes a slight increase in the AV% property and lower density. Generally speaking, all FGA treated HWBEM reflected lower AV% and higher densities than CBEM. Overall, the FGA treated HWBEM AV% values raged between 3.55%-5.89% and were within the limitations of the specification (except HWBEM-100%FGA). FGA aggregate has relatively low water absorption characteristics than the traditional fine aggregate and this leads to the higher moisture content in the mix, which reflects a higher air voids content after evaporation.

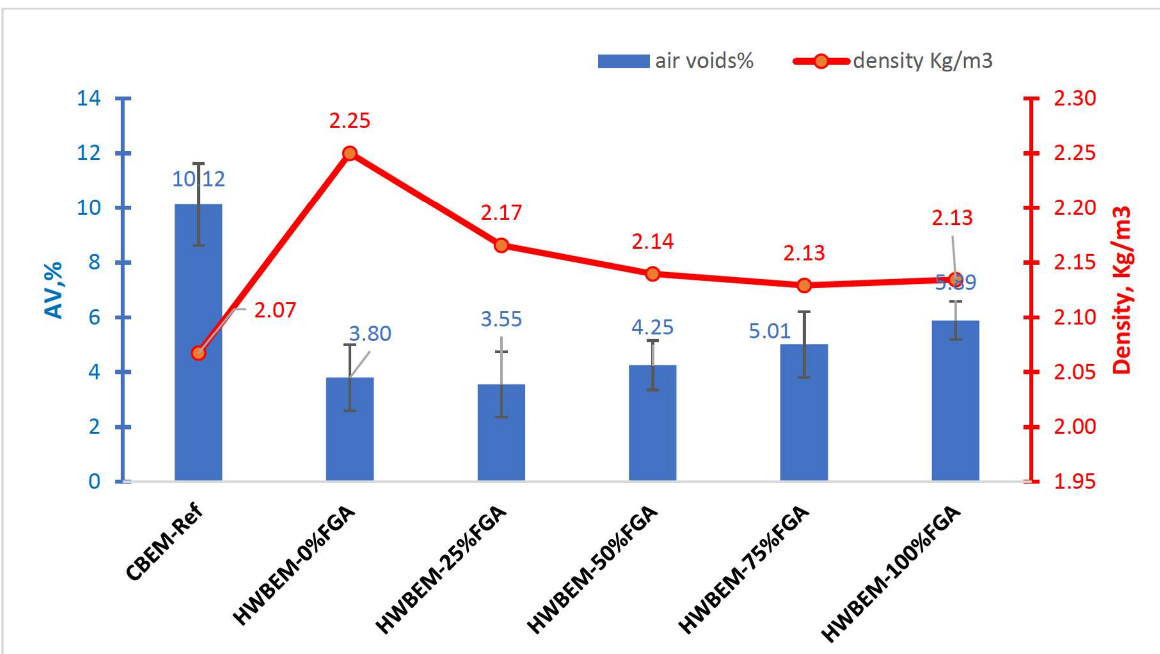

Figure 14. Density and air voids results of various tested mixes.

For the WTT slab specimens, AV% results are plotted concerning three different applied compaction durations (3 min, 5min, and 7 min) for both CBEM and HWBEM specimens, as illustrated in Figure 15. In the case of HWBEM, applying 3 minutes of compaction resulted in AV% of about 11.811% and 9.748% for CBEM and HWBEM, respectively. Also, HWBEM reflected a significant reduction in the AV% values after 5 minutes of compaction, which was about 40%. In contrast to the CBEM specimens, where a decrease of about 10.3% was recorded. Till achieving 7 minutes of compaction, the AV% of HWBEM specimens still decreased (56%) with a higher compaction effort, reaching 4.284%. No noticeable reduction was recorded for CBEM; approximately the same reduction percentage and AV% values were observed.

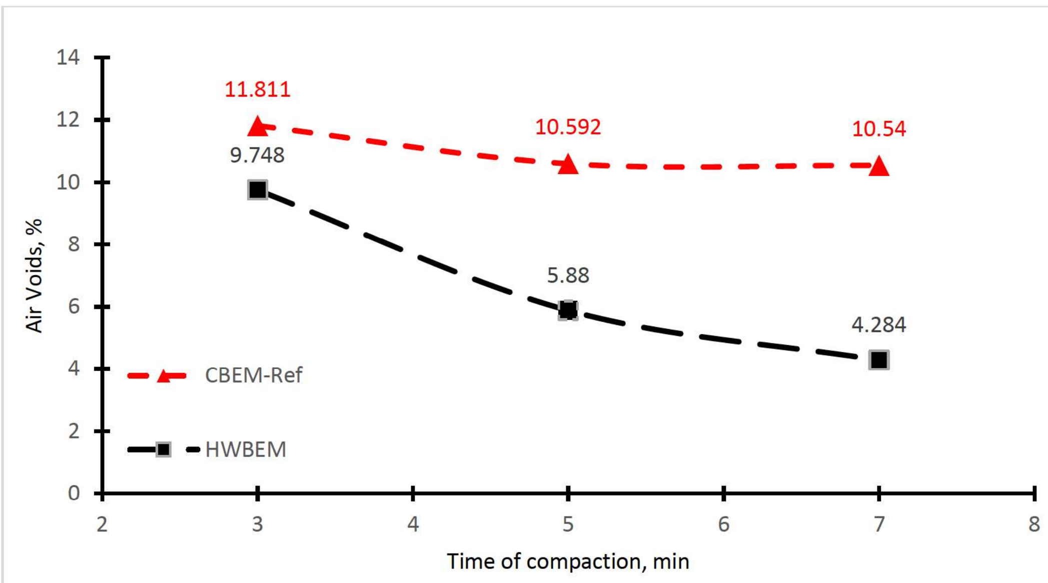

Figure 15. Applied compaction effort duration vs air voids content of CBEM and HWBEMs

7.3 Mechanical Performance

7.3.1 Effect of incorporation of waste glass on the mixture's Stability- Flow performance

The resistance to the static plastic deformation in terms of Marshall stability-flow relation in addition to the Marshall secant stiffness was plotted in Figures 16 and 17. Different mixtures behaviour in terms of the stability-flow curves were noticed as illustrated in Fig. 16. It can be noticed that the CBEM mix has no observable peak stability value in the degradation phase, contrary to the other HWBEM mixes, where the peak stability can be clearly observed. This indicates that applying microwave energy has a significant effect on mix ductility, in other words; heating CBEM mix reflected a new mix with higher stability, higher stiffness and lower ductility or ability of a mixture to retain strength after reaching the peak limit when compared with the untreated CBEM. Also, the maximum stability and stiffness were achieved for the HWBEM mix, which was about 2920 Kg and 2555 Kg/mm respectively. While the minimum achieved stability and stiffness values were about 1194 Kg and 267.5 Kg/mm, respectively for the CBEM mix. Moreover, test results have shown that increasing FGA% content within the HWBEM mix resulted in a noticeable reduction in the stability and stiffness values, but still higher than the CBEM mix and within the Iraqi GSRB requirements for surface layer (>800 Kg). This may be due to the low affinity between the FGA and the bituminous interface (lower adhesion between the composite aggregate and the binder) compared with the virgin aggregates. On the other side, the increase in Marshall stability associated with 100% FGA is related to the angularity characteristics of the FGA in comparison to the normal fine aggregate that improves the mix interlock. In addition, the low absorption capacity of FGA resulted in a higher amount of free water within the mixture which highly affected the mixtures' densities, and hence the low observed stability. On the other hand, it is expected that the higher FGA particle's angularity and degree of crushing compared to the VGA improved mastic stiffness resulted in a rough interaction between the components.

It is worth mentioning that, although the CBEM mix achieved the stability requirements, the flow value was an issue since it was out of the limitations (>4mm). On the other hand, it can be clearly seen that all treated and untreated HWBEM have flow properties within the standards (2-4 mm).

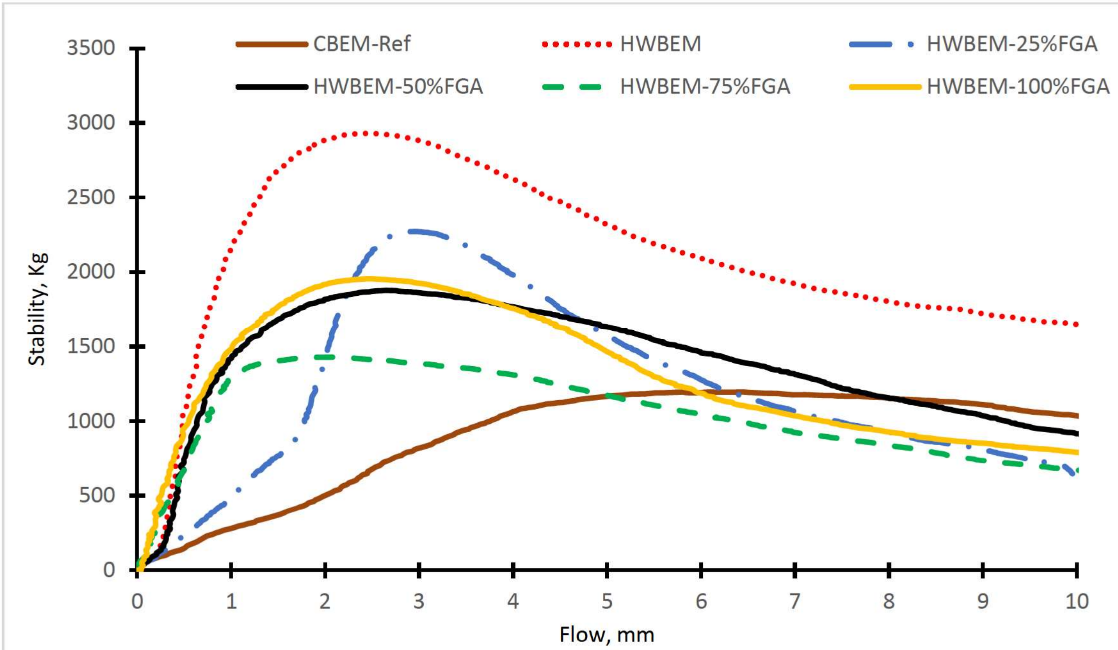

Figure 16. stability-flow curves of various CBEM and HWBEMs

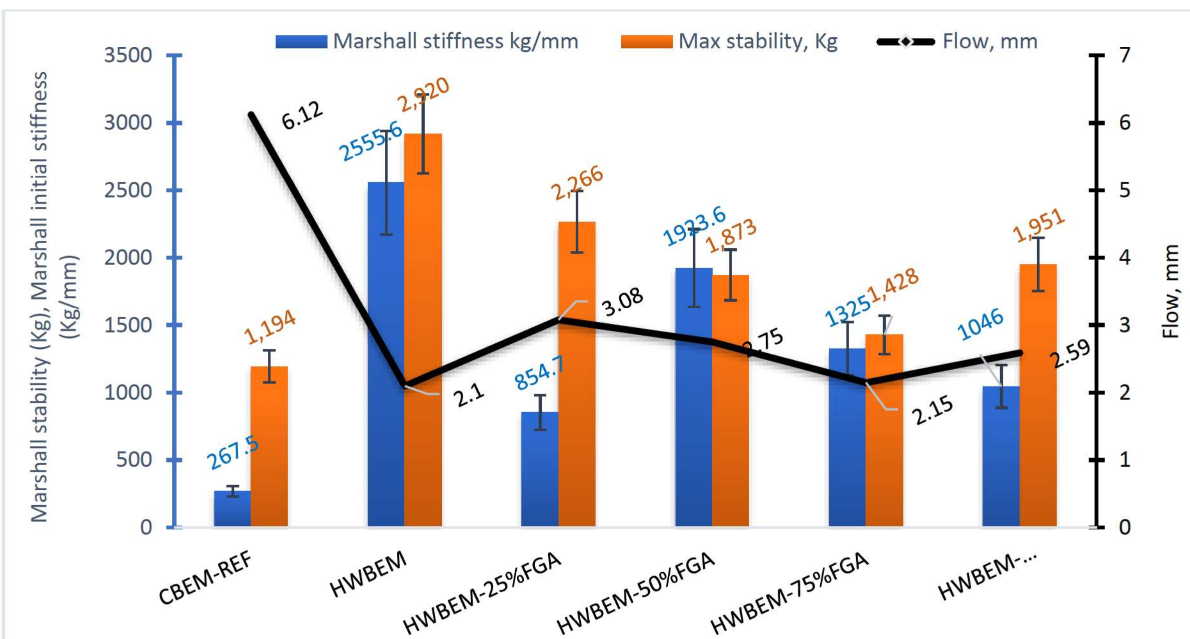

Figure 17. Initial stiffness, Marshall stability and flow results of various mix types.

7.3.2 Cracking resistance performance

Test results in terms of IDT and Ct-index parameters for a mixture's cracking resistance characterisation are illustrated in Figures 18 and 19. It is clear that the CBEM mix has shown a slight degradation slope in the crack propagation phase compared with other mixtures, which would mean better performance and longer life before achieving full crack depth within the pavement layer. On the other hand, HWBEM-50%FGA reflected the highest slope value, which means the mix's resistance to preserve pavement layer strength against cracking propagation decreased faster, and hence, reflected the shorter pavement life. According to the CT-index formula, the sharp slope means a lower CT value and verse versa. Although CBEM reflected the lowest IDT value, it possessed the highest CT-index. On the other hand, all HWBEM mixes reflected higher IDT values than the CBEM mix. Moreover, it can be observed that increasing FGA% content resulted in a noticeable enhancement in the IDT and CT parameters, causing up to 25% FGA blending. Beyond this, the IDT property continuously decreased with higher FGA%. while the CT value started to increase again at 75% and 100% FGA content. Although the Ct index depends on more than one parameter to describe the mixture's cracking resistance, it clearly appears that the degradation slope was dominant, and had the highest influence on the final Ct result.

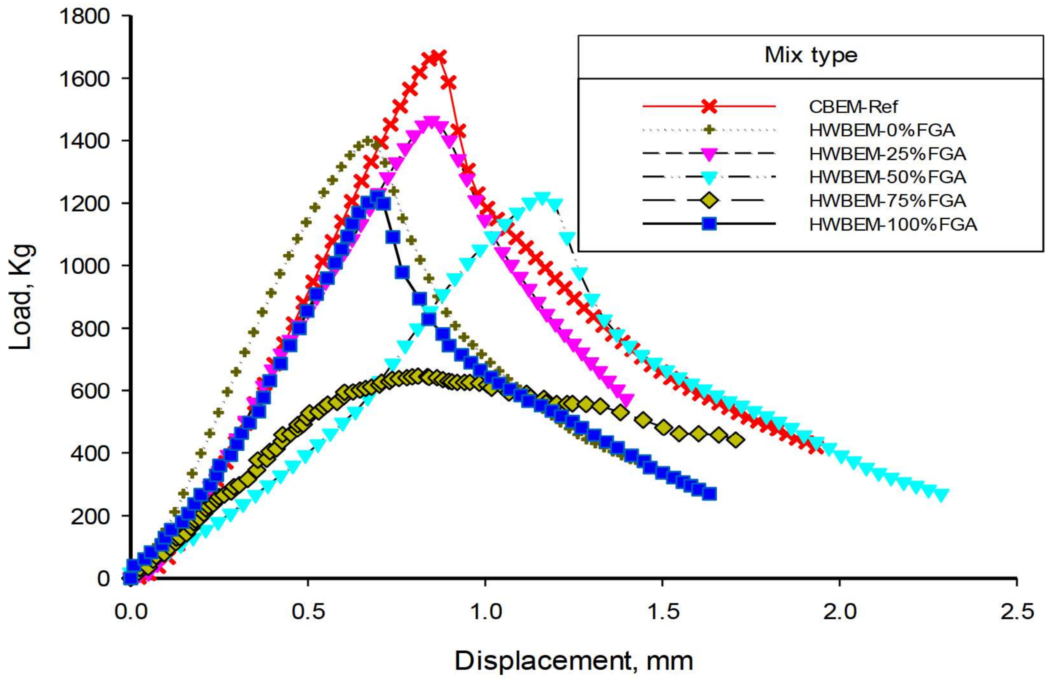

Figure 18. Indirect tensile load- vertical deformation curves for IDT and Ct-index

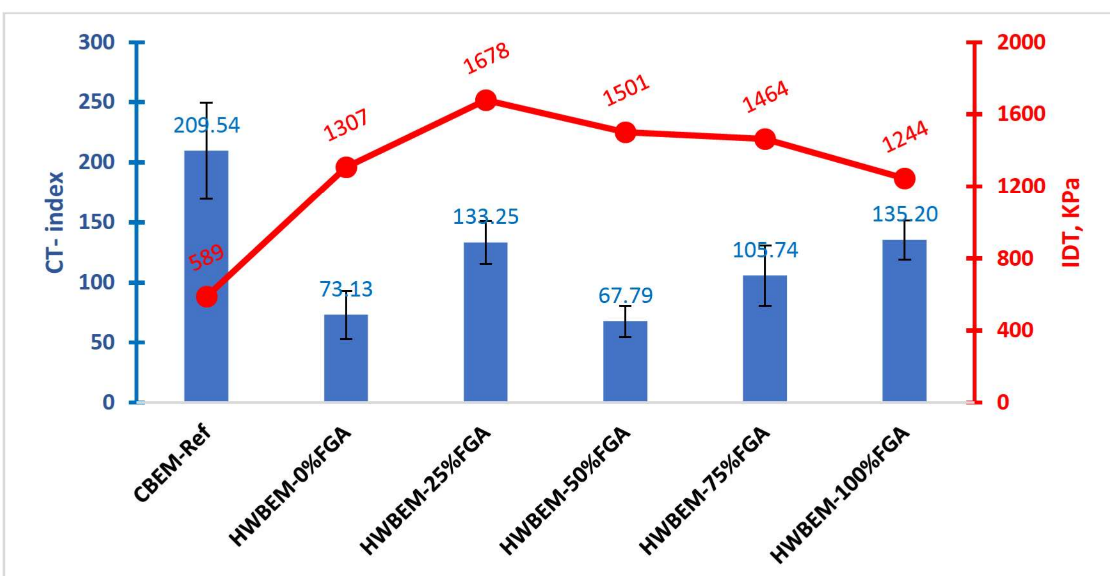

Figure 19. Ct-index and IDT results of various CBEM and HWBEMs.

For mixture absorption energies, as presented in Figure 20, test results have shown that HWBEM-25%FGA specimens have reflected the highest total fracture energy, highest Gf- crack initiation, and highest Gf- crack propagation among other mixtures. In contrast to the HWBEM -0%FGA, which possessed the same value total Gf when compared with CBEB and reflected the lowest values among other mixtures. Generally, the maximum improvement for the total fracture energy, Gf-crack initiation, and Gf-post crack was about 1.5 times, 2.12 times, and 1.27 times, respectively when compared with the CBEM values. Also, it can be observed that most of the mixtures have unequal absorption energies before (Gf-crack initiation) and after the peak carrying a load (Gf-post peak). Apart from HWBEM-75%FGA, most of the mixtures have reflected post peak Gf values higher than the Gf values to initiate the cracks. It is important to notice that some mixtures have a higher total Gf value than others, but have lower G_f to initiate or propagate the cracks, as observed with CBEM HWBEM-75%FGA. Several researchers considered that the capacity of an asphaltic mixture to absorb energy before the initiation of microcracks is a critical portion compared with other absorption energies. For instance, although CBEM and HWBEM-0%FGA have approximately equal total G_f, the latter reflected a higher G_f required to initiate the cracks. Overall, the general trend indicates that increasing the ratio of glass aggregate within HWBEM enhances the Gf- crack initiation portion over the other absorption energy component, and improves the total fracture energy.

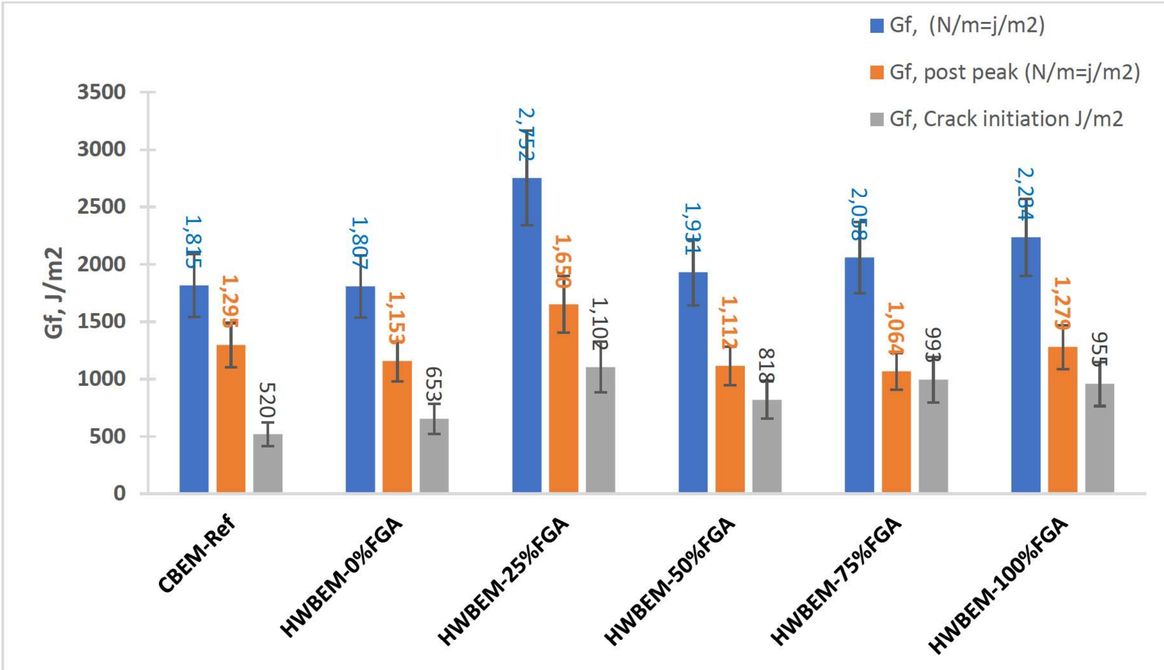

Figure 20. Absorption energy results at different loading stages of various CBEM and HWBEM mixtures.

From the previously obtained results, it is necessary to discuss the behaviour of a mixture's resistance to cracking based on a specified phase and conditions, since some mixtures reflected higher cracking resistance at the crack propagation phase (Gf-post peak), and the lowest value at crack initiation phase (Gf- initiation), and verse versa.

7.3.3 Rutting Deformation resistance and Dynamic stability

Rutting deformation results in terms of WTT are plotted in Figure 18. Test results have shown that CBEM has the poorest resistance to rutting compared with other mixtures, and was about 4.46 after 1000 cycles. In contrast, the resulted rut depth of HWBEM after 1000 cycles was 0.7 mm, which reflected the highest resistance to rutting among other mixtures. By comparing both of the mentioned mixtures, rutting had decreased about 6 times. The small value for rutting is an indication of high mix stiffness and stability under repeated loading and high temperatures.

Furthermore, the high rutting resistance was a result of lower AV% content and density value when comparing HWBEM with CBEM relatively. Moreover, applying microwave energy motivated the bituminous binder to improve the aggregate's coating by lowering its viscosity from the side, and eliminating any water emulsion that could reduce adhesive strength.

For, the HWBEMs with FGA%, the test result had reflected lower rutting resistance compared with HWBEM, but still have higher resistance than CBEM after 1000 cycles. The maximum rutting value was observed in a heated mix with 100% FGA, which was found to be 1.85 mm. Based on the results in Figure 21, the following points can be noticed:

- After 1000 cycles, rutting of HWBEM-25%FGA and HWBEM-50% FGA were higher than the value of HWBEM-75%FGA.
- Rutting values for all FGA% treated mixtures were reduced efficiently as compared with what had been noticed in CBEM.

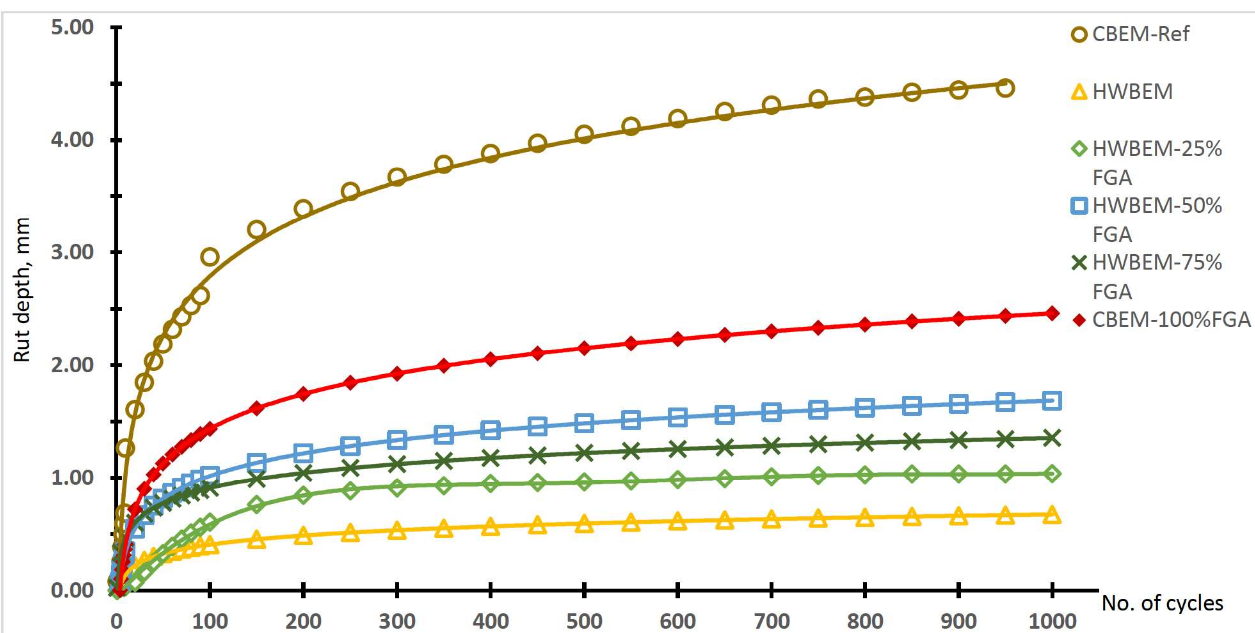

Figure 21. Rutting deformation vs. no of cycles for various types of mixtures

Figure 22 illustrates the dynamic stability (DS) of various treated and untreated HWBEM mixtures. From the figure mentioned, it can be observed that the DS of all HWBEMs has improved significantly compared with CBEM. Raising mix temperature resulted in the elimination of internal moisture, air void content reduction, and as a result, the internal interface between aggregate and bitumen had increased, which had a direct effect on improving bonding and enhancing stiffness. Compared with the CBEM mixture, all HWBEM mixtures reflected superior DS values with an enhancement ratio ranging from 2.4-6.75 times, for HWBEM corresponded for FGA% content from 0%-100%. In general, the trend indicates that increasing the FGA blending ratio resulted in a reduction in the DS index. This may cause a reduction of the interface adherence between the newly composite mastic and the aggregate at higher temperatures.

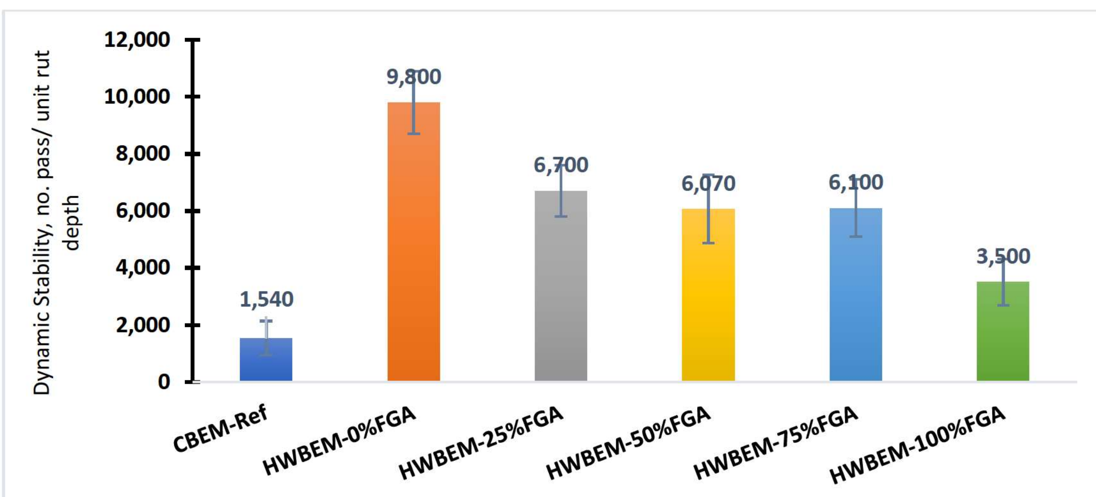

Figure 22. Dynamic stability results of different types of tested mixtures.

7.4 Durability Performance

As seen in Figure 23, HWBEM containing FGA had a higher tendency to maintain its strength than CBEM. RMS values were improved somewhat when FGA content was raised to 75% and then decreased a little when FGA was increased to 100%. To reiterate, HWBEMs have higher RMS than CBEMs. Cement filler plays a critical role in developing mixture strength due to the continuous hydration of cement particles by confined and supplied water from sample conditioning. As a consequence, cementitious materials continue to evolve in order to form bonds with other aggregate particles. Since FGA had a lower absorption capacity than the VFA aggregate, it is believed that the process described had a maximum limit when using a higher FGA percent up to 75% FGA content. Increased trapped moisture resulted in more significant air void content and decreased mixture strength, indicating that increasing the trapped moisture of the combination had reduced the mixture RMS value.

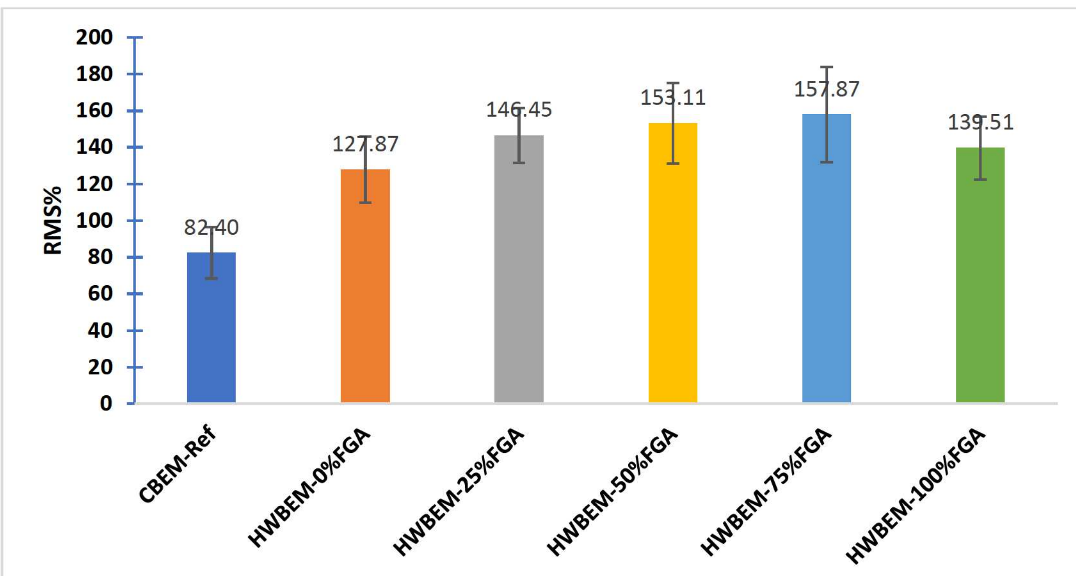

Figure 23. Moisture sensitivity in terms of RMS value of various types of mixes.

8. Conclusions

This study attempted to investigate the overall performance of a newly developed, half warm, emulsified bituminous mixture comprised of waste glass material as a fine aggregate with various incorporation ratios. the testing program had mainly covered the volumetric (density and void ratio), mechanical (rutting and cracking), and durability (moisture sensitivity in terms of retained

Marshall stability). To obtain a better understanding of cracking, more than one cracking performance index was adopted. Performance was determined using a cracking index that was affected by multiple criteria. According to the laboratory scale testing program and relevant scope, the following conclusions were drawn:

1- The volumetric test results have confirmed a superior performance of the newly developed HEBEM in terms of air voids content and density values relatively when compared with the CBEM. The air voids were improved by about 1.8 times the CBEM value when 75% of crushed glass waste was replaced with virgin fine aggregate. Overall, most HWBEM incorporated waste glass reflected better volumetric performance when compared with CBEM.
2- The adopted combination of the asphalt institute method along with the Iraqi GSRB specification and requirements provides an efficient method to produce a sustainable, high performance, half warm mixture for structural surface layer purposes, and meets the local requirements.
3- The sensitivity to moisture damage of most half warm mixtures incorporating waste glass showed higher values than the cold mix asphalt and was within the requirements of the adopted specifications.
4- Regarding the crack resistance evaluation process, results have cleared that depending on one cracking resistance index could be insufficient to obtain a correct characterisation, as cracking is a multi-phase phenomenon. Even the newly developed cracking index (CT-index) could reflect misled values, as noticed with the cold mix asphalt.
5- The absorption energy required to initiate cracks was introduced as an index for cracking evaluation because of its practical importance. In general, the newly developed mixtures

possessed absorption energies comparable to or higher than the cold mixtures. Furthermore, the trend has shown that the addition of waste glass resulted in a noticeable improvement in the absorption of energy to resist crack initiation.

6- According to the testing program and working scope, 75% of waste glass aggregate as partial replacement to the virgin aggregate has been considered as the optimum replacement ratio as it reflected an acceptable value according to the local specification.

7- In terms of resistance to permanent deformation, all half warm mixtures' rutting deformation resistance was lower than the cold mixture. Accordingly, the dynamic stability index values were also the same. Also, the general trend has confirmed that increasing the waste glass ratio resulted in a slight reduction in the mixture's resistance to rutting.

8- According to what has been mentioned previously, the sustainability approach has been achieved successfully through developing a high performance, friendly to the environment, waste glass aggregates recycled mixture. It is worth mentioning that, despite the improved obtained results, it is still a laboratory research scope of work, and requires further investigations to cover all potential advantages and disadvantages of such mixtures.

The study was laboratory-scale work, meaning work on a construction site was recommended to identify challenges in the field. Portable industrial microwaves can be suggested as the primary processing tool for on-site production, similar to those used for sidewalk deicing.

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