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http://researchonline.ljmu.ac.uk/id/eprint/12318/

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Al-Merzah, S, Al-Busaltan, S and Al Nageim, H (2019) Characterizing Cold Bituminous Emulsion Mixtures Comprised of Palm Leaf Ash. Journal of Materials in Civil Engineering, 31 (6). ISSN 0899-1561

MT7846

Characterizing Cold Bituminous Emulsion Mixtures Comprised of Palm Leaf Ash

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ABSTRACT

Cold Bitumen Emulsion Mixtures (CBEM's) are a promising substitute for Hot Mix Asphalt (HMA) due to their low environmental impact, cost-effectiveness and low-energy production costs. Nevertheless, conventional CBEM has some disadvantages, mainly related to the long curing time required to reach its full strength and higher susceptibility to moisture. This paper reports the experimental test results of research which aimed to investigate and develop a new CBEM containing a waste biomass material, Palm Leaf Ash (PLA), a waste material produced by burning palm leaves. The new CBEM was compared with a conventional cold mix (CCM) as a control. The tests to assess the mixtures mechanical properties were the Marshall test, indirect tensile strength and wheel track test. Durability was evaluated by water sensitivity and ageing tests. The results revealed noticeable improvements in the mechanical properties of the CBEMs comprising Ordinary Portland Cement (OPC), and raised the possibility of replacing some of the OPC with PLA without compromising said improvements. Results have shown that the new CBEMs with PLA achieved outstanding results in comparison to traditional CBEM, with and without the addition of OPC. There was also a significant improvement in water sensitivity when using PLA. This paper therefore, opens the door for the development of new CBEMs which have outstanding mechanical characteristics when made with biomass ash materials.

KEYWORDS: Asphalt; Cold Bitumen Emulsion Mixtures; OPC; Palm Leaf Ash; Water sensitivity.

INTRODUCTION

Cold Bituminous Emulsion Mixtures (CBEMs) can be created using environmentally friendly technologies which produce reduced CO_2 emissions (Serfass, 2002), at the same time conserving energy as no heat is required during processing, unlike traditional Hot Mix Asphalt (HMA) (Al-Busaltan, 2012; Chavez-Valencia et al., 2007). However, these mixtures have relatively low initial strength meaning they require longer curing times (Ebels, 2008; Brown and Needham, 2000) and are highly susceptible to water damage (Al Nageim et al., 2012; Thanaya et al., 2009). Much research has been carried out to establish the advantages and disadvantages of CBEMs in order to overcome their weaknesses and thus benefit from their obvious advantages (Terrell and Wang, 1971; Head, 1974; Li et al., 1998; Suleiman, 2002; Oruc et al., 2007; Al-Busaltan, 2012; Brown and Needham, 2000; Pettinari et al., 2014; Dondi et al., 2014).

Normally, Ordinary Portland Cement (OPC) is used in the production of CBEMs to overcome low early strength, its subsequent performance the focus of many studies (Oruc et al., 2007; Schmidt et al., 1973; Al Nageim et al., 2012; Oruc et al., 2006; Niazi and Jalili, 2009; Bocci et al., 2011). Researches have examined the incorporation of OPC into bitumen emulsions to control braking behavior, to increase the strength and stiffness of mixtures earlier in the production process and the amount of water released by breaking of emulsion (Niazi and Jalili, 2009; Miljković and Radenberg, 2015; Tan et al., 2013). Others have shown that the addition of cement can reduce the water sensitivity of the mix, this also facilitating the development of its mechanical properties over time (Wang et al., 2014). OPC reacts with the water in the emulsion, this resulting in an impact on the continuous phase of said emulsion, accelerating emulsion breaking (Zhang et al., 2012; Tan et al., 2013). OPC has also been found to decrease the negative influence of free water in mixes and improve the adhesion of the binder to the aggregate (Hu et al., 2009). This occurs because when the cement is hydrated, this increases the rate of coalescence, thereby increasing binder viscosity (Brown and Needham, 2000).

From previous studies, it can be concluded that the addition of OPC to CBEM improves its characteristics. This has encouraged researchers worldwide to use waste and/or by-product materials that have hydraulic or pozzolanic characteristics as alternatives to OPC (Al-Busaltan et al., 2012c; Thanaya, 2007). Incorporating such materials in CBEM provides two benefits: environmental sustainability and economic advantages (Thanaya et al., 2006). Some waste and by-product materials have the potential to work as supplementary cementing materials (SCM), facilitating the absorption of trapped water via the hydration process. The physical and chemical properties of these materials also helps with this absorption (Al-Busaltan et al., 2012b).

Biomass is an organic biological material produced as a result of human animals and plants activities , these materials used in various civil engineering applications (Melotti et al., 2013). Biomass has tested successfully as aggregate, or filler, for concrete construction (Pels et al., 2005), bitumen mixtures (Melotti et al., 2013) and for soil stabilization (Nordmark et al., 2011; Basha et al., 2005).

Biomass Ash has already been mixed with OPC as a filler for concrete mixture production to provide low-cost and more environmental friendly binders (Arum et al., 2013). Biomass Ash has a positive effect on the strength of concrete due to its pozzolanic characteristics. Ash materials such as rice husk, coconut husk, oil palm leaf, bamboo leaf, and peanut shell have been used to achieve this (Arum et al., 2013; Al-mulali et al., 2015; Sargın et al., 2013; Ahmad et al., 2012; Al-Busaltan et al., 2012c). Concrete mixes containing fine Oil Palm Ash (OPA) as cement replacement showed superior strengths, less water permeability and less water absorption. Mortar mixes with 20% replacement of cement by fine OPA exhibited higher compressive strengths than the 100% cement mortar (Aprianti et al., 2015).

There are many benefits of using pozzolanic materials in road construction, especially in CBEMs. Thanaya et al., (2009) reported that the pozzolanic filler is hardened due to the water and cement within the CBEM. Modarres and Ayar (2016) claimed that this material increases the Marshall stability, Indirect Tensile Strength (ITS) and moisture resistance, to acceptable levels for cold recycled pavements. Al-Hdabi et al., improved the mechanical properties of CBEM by using Rice Husk Ash while Al-Busaltan et al., (2012b) found that the hydraulic and pozzolanic effects of Paper Sludge Ash improved permanent deformation resistance and the water sensitivity of CBEMs. Al Nageim et al., (2012) reported that Paper Sludge Ash was better than OPC at enhancing the mechanical and durability properties of CBEMs because of its superior ability to absorb water, Al-Busaltan (2012) and Dulaimi et al. (2015) confirming this finding. Some pozzolanic materials have also been used as secondary binders (Nunes, 1997). Hesami et al. (2013) showed that Biomass fillers increase the viscosity of mastic, the moisture and aging having a significant effect on the viscosity of the mastic because of its particle shape and size distribution. Lundberg et al., (2016) claimed that the reactions between fillers and emulsions are significantly impacted by high specific surface areas.

In this research, Palm Leaf Ash (PLA) is used as a filler replacement for OPC in the production of CBEMs. So, this research work attempt to characterizing the volumetric, mechanical, and durability properties of CBEMs comprising PLA as a filler, partially or totally. PLA is a waste material produced from burning palm leaf, the leaves removed when cleaning the palm trees. According to the Iraq Central Statistical Organization, there are more than 15 million palm trees in Iraq (Central Statistical Organization, 2015), each one producing 25 kg of leaves per annum, meaning that there is approximately 0.375 million tons of palm leaf available, and currently going to waste, each year.

MATERIALS

Aggregates

The fine and coarse aggregates used in this research were sourced from local quarries in Karbala. The binder course gradation was selected according to Iraqi General Specifications for Roads and Bridges, section R9 (GSRB, 2003), Figure 1 illustrating the midpoint gradation and its limits.

Fillers

Three types of fillers were selected: Conventional Mineral Filler (CMF), Ordinary Portland Cement (OPC), and Palm Leaf Ash (PLA). CMF was produced during the crushing process applied to aggregates. The OPC was provided by the Karbala cement plant, the PLA was produced by burning palm leaves. The properties of the fillers are given in Table 1. From this table it can recognize the high surface area of PLA compare with OPC and CMF, this difference in this property will influence the rheology properties of the emulsion at mixing and early stage strength development. Also, the chemical composition of the three fillers (especially the percentages of CaO, Al_2O_3, SiO_3, and Fe_2O_3 percentages) may indicate the hydraulic properties of the OPC, the pozzolanic properties of PLA, and the inert properties of CMF.

Scanning Electron Microscopy (SEM) was conducted to identify the morphology of each to allow a better understanding of their properties, as shown in Figure 2. These morphology characteristics believed to be very influential in mix properties at early stage after mixing; particles shape, size, the formation of small channels are highly affect the viscosity of emulsion just after mixing with these fillers. Also, the amount of absorb water is highly dependent of surface area and the appearance of tiny channels that increase the suction of water (Al-Busaltan et al., 2012a; Al-Busaltan, 2014).

Bitumen Emulsion

Bitumen emulsion (BE) was supplied by the local market, its properties were determined in lab to ensure their satisfactory according to ASTM D2397/D2397M (ASTM, 2013a). the main properties according to the mentioned properties were measured and compared, as detail in Table 2.

Experimental Program, Test conditions and Methods

The Preparation and Conditioning of Samples

As there is no universally accepted design procedure for CBEM's to date, the design for this work was based on the method detailed in the Asphalt Cold Mix Manual MS-14 (Asphalt Institute, 1989). The Marshall Method for emulsified asphalt-aggregate cold mixture designs was used, with some amendments to meet Iraqi specifications. Specimens of CBEMs were prepared using different fillers as follows:

1. Initially, a coating test was conducted to ensure that an acceptable percentage of aggregates were coated, MS-14 stating that this percentage should not be less than 50, with 75% for base and binder layers, respectively. Aggregates can be highly sensitive to

pre-wetting water content, especially when the gradation comprises a high proportion of fine materials. Different pre-wetting water contents were considered to determine the lowest percentage needed to achieve suitable levels of coating, judged visually, as recommended by MS-14 (Asphalt Institute, 1989), accordingly, the followings were followed:

- Determination of Initial Residual Bitumen Content (IRBC), which was trailed by an empirical formula of dense graded.

$P=(0.05A+0.1B+0.5C)x0.7$ ……..Eq(1)

Where:

P = percent by weight of emulsified asphalt based on dry aggregates

A = present of aggregate retained on sieve (No.8)

B = present of aggregate passing sieve (No.8) and retained on (No.200)

C = present of aggregate passing (No.200).

- The Initial Emulsion Content (*IEC*). value then determined by dividing P by the percentage of the residual bitumen content in the emulsion

$IEC= P/X$ ……..Eq(2)

Where:

IEC = Initial Emulsion Content by mass of total mixture %

X = residual bitumen content of the emulsion, that may be obtained by heating emulsion until whole water content evaporation, then calculation its percentage from total emulsion.

- Coating test after that carried out by mixing all of dry aggregates and filler about 1 minute, and pre-wetted with varied amount of water with *IEC* value obtained from above section. The asphalt emulsion is added later and then mixed for about 2-3 minutes, repeated these steps until adequate coating. The degree of coating was ensure to be not less than 50 % by visual observation.
- Optimum Pre-Wetting Water Content (OPWwc)

The optimum pre- wetting moisture was obtained according to the coating test, which the lowest pre-wetting water content was selected when the coating achieved.

2. Marshall stability tests were used to confirm the optimum pre-wetting water content established by the equation recommended in MS-14 (Asphalt Institute, 1989). According to the characteristics of the selected materials, pre-wetting water contents were 3% for CMF, 3.5% for OPC and 2.5% for PLA.
3. The optimum bitumen emulsion content was determined by using different emulsion contents with optimum pre-wetting water content. The Marshall stability test was used to identify this optimum value as 11.2% for all mixture types, the optimum total liquid contents being 14.2%, 14.7%, and 13.7% for CBEM composed of CMF, OPC and PLA, respectively.
4. For each CBEM variable, three 1,170 g specimens were prepared. Mixing and compacting were carried out at lab temperatures.
5. The materials were mixed in a mechanical mixer; the aggregate, filler and pre-wetting water content added and mixed for 60 seconds. The bitumen emulsion was added gradually, all mixed together for an additional 60 seconds. A spatula used to separate the

mix from the mixer bowl and additional hand mixing was carried out for more homogeneity.

6. The samples were poured into their molds and directly compacted with 75 blows on each side using a standard Marshall Hammer.
7. Finally, the specimens were subjected to curing according to the test procedure requirements.

Test Conditions and Methods

Because the characteristics which define the strength of CBEM’s are very sensitive to curing time and temperature, sample conditioning occurs in two stages. Stage one is when the specimens are left in their molds at ambient temperature (25 ℃) for 24 hrs. to prevent the specimens from disintegrating when extruded from the mold. Stage two varies depending on the test being applied. The tests used in this study are described below.

On the other hand, to control the potential of the error in the obtained results, at least three specimens were prepared and averaged. In case of an outliers were happened, additional specimen/s prepared and the result averaged to prevent outliers; ±15% of the average was selected to specified the outliers.

Marshall Test

The strength of, and resistance to plastic deformation of a compacted cylindrical specimen of bituminous mixture, is measured when the specimen is loaded diametrically. Table 3 details the arrangement for the Marshall test based on ASTM D6927 (ASTM, 2015a). The stage two curing protocol was conducted by placing the specimens in an oven for 24 hrs at 40 ºC, then applying the test procedure as illustrated in Table 3 below. MS-14 recommends that the Marshall stability for CMA should be conducted at 25℃, but 60 ℃ was adopted in this research to accommodate the high temperatures experienced locally and to explore the potential of the CBEMs. Authors believe that using the standard testing temperature of Marshall test (i.e., 60 ºC) is more realistic then 25 ºC in hot climate water countries.

Indirect Tensile Strength (ITS)

ITS is used to evaluate the potential to resist cracking in bituminous mixtures. The test followed was as recommended by ASTM D6931(ASTM, 2012), the test conditions shown in Table 4. The curing protocols for stage two were 24 hrs at 40 ºC to represent 7-14 days, and 14 days at 40 ºC to represent full curing age.

Wheel Track Test (WTT)

The Wheel Track Test is carried out by placing the compacted bituminous mixture in a reciprocating rolling wheel device. This test provides information about the rate of permanent deformation under a moving concentrated load. A laboratory compactor is used to prepare the slab or cylindrical specimens. The procedure for the WWT is described in AASHTO T324 (AASHTO, 2004), the test conditions summarized in Table 5. This procedure is designed for HMA; in order to apply this to CMA, a modification was made, full curing protocol was used (stage two), 14 days at 40ºC, as recommended by Thanaya (2003), after one day in mold at lab temperature, while such curing is just one day after compaction of HMA. The point is to accelerate the removal of trapped water, whereas higher temperatures than 40 ºC, may change the rheology of asphalt, while lower temperatures could take inappropriate long curing time. This curing temperature is adopted by Asphalt Institute in MS-14 (1989)and many other studies as curing temperature. On other side, the period of 14 days was found to be the appropriate time to remove all trapped water and transfer the compacted mix to a state similar to that under full curing.

Durability Testing

The durability of asphalt mixtures can be described as variation in the ability of the mix to withstand environmental conditions and the impact of traffic during its service life. In this research, durability was determined as a ratio of the ITS of conditioned specimens to those of unconditioned specimens, expressed in percentages. Water damage and deterioration due to ageing, were also used as durability indicators.

Water damage testing of HMA is described by ASTM, D4867/D4867M (ASTM, 2014). The test conditions for water sensitivity are given in Table 6. Water sensitivity for CBEMs can be investigated using the same procedure as for HMA, except that the curing protocol is different in order to ensure the full strength of the specimens. The following curing protocol was followed, in addition to stage one curing, as described previously:

- For unconditioned specimens: 24 hrs. in an oven at 40 °C.
- For conditioned specimens: the same procedure as for unconditioned specimens but with the specimens also placed in a water bath for 24 hrs. at 60 °C.

One of the main concerns about CBEMs is their low early life strength. According to SHRP A383 (Bell et al., 1994), there are two types of ageing; short-term ageing to simulate the mixture's ageing during the manufacturing stage, and long-term ageing simulating the ageing of the mixture on the road during its service life. It is acknowledged that short-term ageing may not be applicable for CBEMs, as no heat is applied during the manufacturing process (Al-Busaltan et al., 2012b). However, to simulate long-term ageing, the method recommended by the SHRP A383 program can be adopted, the testing conditions summarized in Table 7. This procedure was adopted as written for HMA. For CMA, in addition to stage one, the curing times were adopted as follows:

- Unconditioned specimens protocol: 14 days at 40ºC (Jenkins, 2000).
- Conditioned specimen protocol: 14 days at 40ºC +5 days at 85ºC

Results and Discussion

Marshall Test Results

All CBEMs specimens were tested at a curing age of 2 days. The results are shown in Figures 3 and 4 for Marshall stability and flow, respectively. From these figures, it can be seen that conventional CBEM comprising CMF, shows very low early characteristics; the specification limit is at least 7 KN for stability and 2-4 mm for flow. When CMF is replaced by OPC, the performance of CBEM is significantly enhanced at an early age. This high stability and low flow could be a result of increased binding between particles in the mixture as when OPC is used, curing is faster. The OPC may be acting as a secondary binder in the CBEM, this overcoming low early strength because of the hydration products. The hydration process needs water to start and continue, the water trapped between the aggregates and bitumen film consumed during this process. OPC particles are irregular having angular shapes and an uneven distribution while the CMF particles are more sheet-like, as can be seen in Figures 2 a and b. This may help produce more resistance to internal stresses within the mastic micro scale.

An initial replacement of OPC with up to 25% PLA, resulted in an improvement in the strength of the CBEMs, the strength increasing more than CBEMs with only OPC. The reason for this may be because of the hydraulic characteristics induced by the new chemical phase for each filler in the new blend; i.e. the mix of OPC and PLA (see the chemical composition of the fillers in Table 1). PLA is rich in Ca, Al and Si, these components forming more than 94% of the total solid chemical composition of PLA. This produces different levels of pozzolanic properties, dependent on the relationship between the silicate minerals, calcium oxides and hydroxides. When mixed with existing road materials, these components harden through hydration and carbonation reactions, meaning that the stability of the CBEMs will be enhanced.

Another reason for better performance might be because of physical characteristics. PLA has a high surface area (see Table 1) which allows for a more chemically active surface. More of the water trapped between the aggregate and bitumen films can therefore be absorbed. PLA is also very good at absorbing water, as was seen in the water sensitivity test. PLA also has particles which are angular, as shown Figure 2c. This could also lead to more internal friction between the CBEM particles.

A blend of 0.25PLA+0.75OPC gives more strength than OPC on its own. However, a slight decrease in the strength of the CBEMs was seen when increasing the amount of PLA replacing OPC. Replacements of OPC with PLA up to 0.75PLA+0.25OPC, showed acceptable strength levels, according to Iraqi specifications. Using PLA alone gave low strength because SiO_2 contains little CaO in comparison to OPC where CaO is the main component of the hydration process. This explains the role of the activator for the pozzolanic materials; no hydration activity is expected when mixed with water if there are no activation agent materials, such as the presence of OPC.

Finally, it is worth mentioned that Marshall test at high temperature (i.e., 60 ºC) describes the plastic deformation of asphalt mix. However, different mixes show different behaviours; high rate of plastic deformation is associated with mixture comprising CMF or PLA individually. While the presence of OPC, or the collection of OPC and PLA somehow control the plastic deformation.

This imply that the physical and chemical characteristics of the filler type after hydration process could help in minimize the plastic characteristics of soft asphalt binder.

Indirect Tensile Strength (ITS)

The ITS test specimens were prepared following the same procedure as described for the Marshall test. The main differences are in the curing protocols as mentioned earlier. Figure 5 shows the results for the CBEMs specimens with CMF as a control mixture, OPC and 0.25OPC+0.75PLA.

The ITS of CBEM comprising CMF, had inferior cracking resistance strength at 2 days of curing. This is a result of the water still trapped between the binder and aggregate surface. After 2 weeks, the result improved dramatically, by around 67% in comparison to the early age strength, this clear evidence of the effect of water impairing the mixture at an early age. When CMF was completely replaced by OPC, two features are of note; the OPC acts as an anti-stripping agent for the binder due to the Ca++ present, supplying extra binding and help to grip the aggregates because of the presence of hydration products. There is also around 13% improvement due to improved curing. This can be explained by the removal of trapped water and evolution of the hydraulic products over time.

CBEM with 0.25OPC+0.75PLA showed insignificant drop in ITS. The pozzolanic property of the PLA in the present of OPC and the hydraulic propriety of the OPC itself, are after insignificant change in ITS. At full curing, an 18% improvement was noted because of the curing protocol, the same explanation for CBEM comprising OPC applicable here. Finally, it is worth mentioned that the obtained ITS still non comparative to that for HMA which show a value not less than 700 KPa, therefore further development for crack resistance of CBEM is still in high demand.

Wheel Track Test (WTT)

Laboratory wheel-tracking tests were applied to evaluate the rutting resistance of the CBEMs. The mixtures were prepared following the same procedure as described in previous sections; CMF, OPC and 0.25OPC+0.75PLA fillers added to the CBEMs. Figure 6 shows the depth of ruts relative to the number of cycles and loadings in each cycle, Figure 7 showing the creep stiffness.

Under testing, the CBEM comprising CMF failed after 4000 cycles; this might be because of the weakness of the binder and mastic that grips the coarser aggregates. There is less cohesion of mastic materials when CMF is used because it is an in-active filler. However, a significant improvement was achieved when OPC and OPC with PLA were introduced. The addition of OPC to CBEMs created extra binding that helped resist permanent deformation due to cyclic loading. These improvements in rutting resistance were substantiated by the creep stiffness values. It is worth mentioned that the obtained rut depth in contrast to that determined in other research work for HMA is acceptable, especially for CBEMs comprising OPC or OPC with PLA; 2-4 mm as determined in this research work is preferred by highway engineers.

Durability Testing

Durability tests included water sensitivity and ageing tests, Figure 8 illustrating the results for water sensitivity. Because there is an anti-stripping agent in CBEM with added CMF, this mixture exhibited high sensitivity to water. In contrast to this, OPC and PLA act as anti-stripping agents with the binder, creating a chemical reaction with water free Ca++, which prevents stripping. PLA may increase binding by decreasing the viscosity of bituminous materials due to a high surface area. Conditioning therefore helps to upgrade the mechanical properties of CBEM; indirect tensile ratios (ITR) recorded values of 109% and 148.8% for CBEMs comprising OPC and 0.75OPC+0.25PLA, respectively. The materials became more cohesive and more resistant to water damage, satisfying specification requirements; an ITR of at least 70%.

Figure 9 shows the results of the ageing test, these results indicating the superiority of CBEMs composed of OPC, with and without PLA, in comparison to the CMF mixes. This may be a result of the angular shape of both the OPC and PLA particles and the high surface area of PLA lowering the viscosity of the binder, facilitating a thicker binder film and higher resistance to ageing.

Conclusions

Based on the testing program and analysis of the above results, the following can be concluded:

1. PLA has a high surface area that may increase the breaking rate of emulsions.
2. The pozzolanic properties of PLA makes it possible to substitute most of the OPC with PLA. There is the possibility of producing CBEMs which meet specification requirements by replacing the CMF with OPC. Replacing 25-75% of the OPC with PLA can be carried out without any significant drop in the mechanical properties of CBEMs; the developed mix still met specification requirements.
3. Remarkable enhancements can be achieved in early cracking resistance by using either OPC, or OPC with PLA, as a filler instead of CMF. Indirect tensile strength is enhanced

by 78% and 51% when CMF is replaced by OPC, or OPC with PLA, respectively. While, these enhancements are dropped to 20% and 7% after full curing.

4. Conventional CBEM has a high sensitivity to water damage. The addition of OPC, or OPC with PLA, overcomes this issue. PLA with a small amount of OPC, provides very good resistance against water damage and is better than using OPC alone.
5. Conventional CBEM has low resistance to permanent deformation, but replacing the CMF with either OPC or OPC and PLA, overcomes this problem.
6. Almost all CBEMs which had new fillers, had acceptable resistance to ageing.

Acknowledgments

The authors wish to thank the Department of Direct Implementation of the Karbala government, and Karbala Cement Plant for their help and support in this research work.

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Table 1: Properties of the fillers

Physical Properties			
Property	Filler type		
	CMF	OPC	PLA
Specific surface area (m^2/kg)	225	410	932
Density (g/cm^3)	2.61	2.987	2.011
Chemical compositions (XRF), %			
SiO2	34.54	24.910	66.643
Al2O3	5.67	2.324	8.548
Fe2O3	2.85	1.125	1.870
CaO	47.1	64.148	18.902
MgO	4.35	1.326	1.412
K2O	1.125	0.760	3.0407
Na2O	0.285	1.714	2.052

Table 2: Properties of bitumen emulsion

Property	Specification	Limits	Results
Emulsion type	D2397(ASTM, 2013a)	Rapid, medium and slow-setting	Medium- setting (CMS)
Color / appearance			Dark brown liquid
Residue by Evaporation, %	D6934(ASTM, 2008)	Min. 57	54.37
Specific gravity, g/cm^3	D70(ASTM, 2009a)		1.05
Penetration, mm	D5(ASTM, 2015b)	100-250	230
Ductility, cm	D113(ASTM, 2007)	Min. 40	42
Viscosity, rotational paddle viscometer 50 ℃ , mPa.s	D7226(ASTM, 2013b)	110-990	220
Solubility in Trichloroethylene, %	D2042(ASTM, 2015c)	Min. 97.5	97.7
Emulsified asphalt/job aggregate coating practice	D244(ASTM, 2009b)	Good, fair, poor	Fair
Evaluating Aggregate Coating	D6998(ASTM, 2011)		uniformly and thoroughly coated

Table 3: Marshall test conditions according to ASTM D6927 (ASTM, 2015a)

Item	**range**	**Used**
Number of required specimens	3	3
Rate of load application, mm/min	50 ± 5	50
Measuring device accuracy	Min. 50 N	0.01 N
Test temperature, ºC	60 ± 1	60
Specimen diameters, mm	101.6-101.7	101.6
Specimen thickness, mm	63.5 ± 2.5	63.5
Compaction	Marshall 75x 2	75x2
Specimen conditioning before test in water bath, or an oven	30-40 min. 120−130 min.	30 min.
Iraqi roads design requirement for Marshall test of binder course		
Marshall Stability kN, Min. Marshall Flow, mm	7 2-4	

Table 4: Test conditions of ITS

Item	**range**	**Used**
Number of required specimens	3	3
Rate of load application mm/min	50 ± 5	50
Measuring device accuracy	Min. 50 N	0.01 N
Test temperature ºC	25 ± 2	23
Specimen diameters mm	101.6, 150	101.6
Specimen height for selected diameter mm	50.8-65.5	63.5
Compaction	Marshall 75x 2	75x2
Specimen conditioning before test	2 hr.	2 hr.

Equation formula

$$ITS = \frac{2P}{\pi\ t\ D}$$

Where:

$ITS = \text{indirect tensile strength}$, MPa

$P = \text{maximum load}$, N

$t = \text{specimen hieght immediatly brefore test}$, mm

$D = specimen\ diameter$, mm

Table 5: Test conditions for Wheel Track Testing for HMA

Item	**range**	**value**
No. of required specimens	2	2
Diameter of rubber wheel	203.2 mm	203.2 mm
Wide rubber wheel	50 mm	50 mm
No. wheel passes per min.	50 ∓5	50
Speed of wheel	Max. 0.305 m/s	0.305 m/s
Load on the wheel	705∓4.5 N	705.5 N
No. of cycles	10,000	5000
Specimen thickness	38 - 100 mm	63.5
Test temperature ºC	25-70 ºC	40 ºC
Specimens type	Rectangular or Cylindrical	Cylindrical
Specimens diameter	150 mm	150

Table 6: Water damage testing conditions

Item	**range**
Number of required specimens	3
Rate of load application, mm/min	50
Specimen diameters, mm	100
Specimen height, mm	63.5± 2.5
Compaction	Marshall 75x2
Test temperature, ºC	25 ± 1

Calculate the tensile strength ratio

$TSR = \frac{S_{tm}}{S_{td}}$

$TSR = tensile\ strength\ ratio, \%$

$S_{tm} = average\ tensile\ strength\ of\ the\ moisture - conditioned\ subset, kPa$

$S_{td} = average\ tensile\ strength\ of\ the\ dry\ subset, kPa$

Table 7: Test conditions for ageing

Item	**values**
No. of required specimens	3
Test temperature, ºC	25
Specimen diameter	100
Specimen thickness	30-75 mm
Compaction	Marshall 75x2
Specimen temp. conditioning	2 hr. before testing

Calculate the tensile strength ratio

$TSR = \frac{tensile\ strength\ aftrer\ ageing}{tensile\ strength\ before\ ageing}$

where

$TSR = tensile\ strength\ ratio, \%$;

Tensile strength after ageing, kPa

Tensile strength before ageing, kPa