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MODIFICATION IN DIFFERENT PAVEMENT TECHNIQUES USING WASTE GLASS MATERIALS

A Thesis Submitted to the Department of Civil Engineering, University of Kerbala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering (Infrastructure Engineering)

By

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بِسْمِ اللَّهِ الرَّحْمَٰنِ الرَّحِيمِ

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ABSTRACT

Nowadays everything expands rapidly, grows, and develops to meet the demand of communities, including roads networks. The increasing number of cars, with increasing axle loads for modern automobiles, led to accelerating pavement deterioration. The current technology for paving and maintaining roads with Hot Mix Asphalt (HMA) could be the uneconomic solution for future. However, such technology has several disadvantages which are disagreed with sustainable, economics, and eco-friendly to environmental aspects. On the other hand, Cold Mix Asphalt (CMA), or more specifically Cold Bituminous Emulsion Mixture (CBEM) has several environmental and economic advantages over traditional HMA. However, it still has inferior mechanical and volumetric properties at early life compared to HMA if left without treatment. Therefore, the main aim of this study is to offer a new sustainable approach in asphalt technology, by characterizing CBEM with waste material and low energy preparation technique (Microwave technique).

In this study, a trail has been made to develop the mechanical and volumetric properties of CBEM by double enhancement process. The first stage of the development included the developing of CBEM mechanical properties by replacing the Conventional Mineral Filler (CMF) with Ordinary Portland Cement (OPC) with three percentages are, 0, 50, and 100% from filler total weight in the mix. Then utilizing municipal solid waste material (crushed glass was selected) as fine aggregate (FGA) which was incorporated in 5 percentages; namely 0, 25, 50 75, and 100% as a replacement of virgin fine aggregates.

Different mechanical and durability testing methods were performed to identify the variations in CBEM characteristics due to such incorporations; such as Marshall stability (M-S) and flow (M-F), indirect tensile strength (IDT), creep compliance (CC), wheel track (WTT), dynamic stability (DS), and Retained Marshall Stability (RMS).

In terms of mechanical and durability properties, addition of 7%OPC filler to CBEM led to improve overall mix properties significantly. Where CBEM-100%OPC improved by about 2.15, 2.1, 9.28, 13.13, 1.74, 4.88, and 2.1 times of CBEM-CMF in terms of M-S, M-F, rutting resistance, DS, CS, IDT, and RMS, respectively.

While the process of incorporation crushed waste glass (FGA) showed that incorporation of 100% FGA in addition to 7% OPC from aggregates total weight has

made a significant improvement in mixture mechanical and durability properties, but mixture still contains high air voids.

Thus, the second treatment stage was suggested to optimize air voids content in CBEM mixture utilizing low energy post-heating. The new mix of Half Warm Bituminous Emulsion Mixture (HWBEM) showed a novel properties compared to HMA. The HWBEM mix was improved by about 2.2, 8, 9.7, 1.3, and 2.9 times of HMA in terms of M-S, rutting resistance, DS, IDT, and RMS, respectively.

Further, HWBEM incorporated 75%FGA showed a novel mechanical, durable, and volumetric properties, superior (and sometimes comparable) to HMA, and within the requirements of the Iraqi GSRB specification for surface layer, and for heavily traffic conditions. The developed mix called Half Warm Bituminous Emulsion Mixture (HWBEM) since it has prepared at 91 °C temperature

Accordingly, the main aim was achieved, and the newly sustainable asphalt mixture could be comparative to the well-known HMA. Although, this research work is deal with mechanical and volumetric properties characterization, but it worth to say that the new developed mix is cost effective and environmental friendly as it bases on low cost and low energy treatment.

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This thesis is dedicated to:

My parents and my family, brothers, sisters, uncle and cousin for their love and continuous prayers

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Mustafa Amoori Kadhim

CONTENTS

Chapter Five 98

Chapter Six 122

LIST OF FIGURES

LIST OF PLATES

LIST of TABLES

ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
AE	Asphalt emulsion
BEMs	Bituminous emulsion Mixtures
BA	Bottom Ash
BS	British Standards
CMS	Cationic Medium- Setting
CBEMs	Cold Asphalt emulsion Mixtures
CBEM	Cold Bituminous Emulsion Mixture
CMA	Cold Mix Asphalt
CRA	Cold Rolled Asphalt
CBEM-CMF	Conventional Cold Mix
CMF	Conventional Mineral Filler
CC	Creep Compliance
CF	Cellulose Fibers
DGEM	Dense Graded Emulsion Mixture
DS	Dynamic stability
EVA	Ethylene Vinyl Acetate
EAPA	European Asphalt Pavement Association
FHA	Federal Highway Administration
FGA	Fine glass aggregate
FCC	fluid catalytic cracking catalyst
FA	Fly Ash
GSRB	General Specification for Roads and Bridges
GF	Glass Fibers
HWMA	Half Warm Mix Asphalt
HCFA	High-Calcium Fly Ashes
HCM	Highway Capacity Manual
HMA	Hot Mix Asphalt

IDT	Indirect Tensile Strength
IEC	Initial Emulsion Content
IRBC	Initial Residual Bitumen Content
LVDT	Linear Variable Differential Transducer
MF	Marshall flow
MS	Marshall stability
HWBEM	Half Warm Bituminous Emulsion Mixtures
MPR-RI	Ministry of Public Work Republic of Indonesia
NA	Not Available
ND	Not detected
OGBEM	Open Graded Bitumen Emulsion Mixtures
OPWwc	Optimum Pre-Wetting Water Content
OBEC	Optimum Bitumen Emulsion Content
ORBC	Optimum Residual Bitumen Content
OTLC	Optimum Total Liquid Content at Compaction
OPC	Ordinary Portland Cement
OICA	Organization International Des Constructers Automobile
PFA	Pulverized Fuel Ash
RSC	Rapid Setting Cement
RAP	Reclaimed Asphalt Pavement
RBC	Residual Bitumen Content
RMS	Retained Marshall stability
RHA	Rice Husk Ash
SEM	Scanning Electron Microscopy
STR	Scrap Tire Rubber
SS	Steel Sludge
SHRP	Strategic Highway Research Program
SBS	Styrene Butadiene-Styrene
SPS	Styrene Butadiene-Styrene
SBR	styrene–butadiene rubber
VFA	Voids Filled with Asphalt
VMA	Voids in Mineral Aggregate
WCD	Waste Construction Demolition

WMA	Warm Mix Asphalt
WTT	Wheel Track Test
XRF	X-Ray Fluorescence

Chapter One

INTRODUCTION

1.1 Background

Now a days everything expands rapidly, grows, and develops to meet the demand of communities, such as roads networks. Increasing number of cars, with increasing axle loads for modern automobiles, led to accelerating pavement deterioration. The current technology for paving and maintaining roads with HMA could be uneconomic solution for future. However, such technology has several disadvantages that are disagreed with sustainable, economic, and ecofriendly aspects.

From this principle, researchers, regulations, and agenesis have been focused their efforts to introduce a new asphaltic mixture that goes with green construction sides and has superior or at least comparable properties to HMA. Therefore, Cold Mix Asphalt technology (CMA) has been recently introduced as one of the most promising solution to the available asphaltic mixtures since it has many beneficial properties in comparison to others mixes technologies. However, CMA still has unacceptable volumetric, mechanical, and durability properties if it is left without treatment or improvement.

The idea of incorporating waste materials in bituminous mixtures to ensure environmental and economic sides was not new, even with CMA, where e.g., Thanaya (2003) tried to substitute waste materials in CBEM. Further, recycling waste materials in bituminous mixtures are necessary to save raw materials and reduce the impact of such wastes on landfills in most developed countries like Japan, the UK, and the USA as example, a large quantity of wastes are generated annually and disposing of them become complicated and put a huge pressure on landfills.

Cold bituminous emulsion mixture (CBEM), which considers as one type of cold mix technology, is a mixture of suitable graded aggregates with bitumen emulsion and water mixed at ambient temperature (10-60°C). Several countries such as France and the USA have utilized CBEM technology in their roads projects since 1970. At that time, due to its poor strength, CBEM has limited to pavements repairing, reinstatement works in low traffic volume roads, and side works (HAUC, 1992, Choudhary et al., 2012).

Other studies demonstrated that developing CMA may produce a suitable material for paving roads layer such as base layer (Jostein, 2000, Shalaby et al., 2014), binder layer (Dulaimi et al., 2017a, Dulaimi et al., 2015, Dulaimi et al., 2017c), and surface layer (Nassar et al., 2016, Al-Hdabi et al., 2013), for roads with low (Anderson and Thompson, 1995) to middle traffic loads (Leech, 1994, Choudhary et al., 2012), and for different aggregates mixes such as open graded, dense graded, and gap graded (Ibrahim and Thom, 1997). While other researchers concluded that such asphaltic mixture could be used as binder course in heavy traffic loads since comparable properties were obtained while developing CMA (Dulaimi et al., 2015). Also, Ibrahim (1998) stated that CMA could be used for all pavement layers in heavy trafficked roads if overlaid with 40 mm HMA layer.

1.2 CMA Technology

The CMA is a mixture of a suitable graded aggregate blend with a bituminous binder (bitumen emulsion or cutback) with or without additives. It can be prepared easily at ambient temperature without heating materials, and with different aggregates such as dense, close, gap, and open-graded mixes. Comparatively to other asphalt mixture technologies, CMA is still under development and requires more studies due to its poor early life properties and long curing time

1.3 Advantages vs. Disadvantages of CMA

Reducing impact on natural environment, saving cost, and provides safety in constructing and manufacturing, which are the most important advantages that are encouraging the use of CBEM instead of HMA. CBEM is the promising alternative for paving roads that respect the environment and compatible with sustainability requirements. The advantages that could be obtained while using CBEM are:

1- Reduce the effect of hazardous gases that harmful to human health and environment, because it does not require any heat during mix production. approximately about 14% of CO_2 gas emission is associated with CBEM production compared to HMA (Kennedy, 1997)

2- No need for aggregate preheating requires before mixing with bitumen, resulting to no dust emission is found during production.
3- As reported by le Bouteiller (2010), the production of CBEM is cheaper than HMA production for many reasons. Firstly, it saves energy, as the energy required for CBEM production is about 13% compared to HMA. Secondly, HMA hauling cost is higher than CBEM since CBEM plants are simpler and can be portable plants.
4- CBEM is safer than HMA and other mixes in term of handling process, since no heat is needed for mixing its components.
5- Since no heat is needed during CBEM production, bituminous material is far from oxidation (AL-Hdabi, 2014).
6- CBEM has logistical benefits over HMA in some cases, as it is unnecessary to use special insulated tracks for mix hauling for a long distance (have longer time span than traditional HMA) (Nikolaides, 1994)
7- CBEM can be produced with recycled aggregates in addition to virgin aggregate, similar to HMA.
8- CBEM eliminates potentials of waste generation as may appear in HMA when losing temperature below a certain limit (AL-Hdabi, 2014).

On the other hand, CBEM has some disadvantages, which can be considered as the statement of the problem. CBEM considers as inferior to conventional HMA, due to some inherent problems related to CBEMs performance while using it as a structural layer for many reasons; the following summarizes such inferiority (Needham, 1996, Thanaya, 2003, Leech, 1994):

1- Weak early life strength because of trapped water action that requires a long time to evaporation.
2- long time to reach mature strength (2-24 months according to mixture climate conditions)(Leech, 1994).
3- High air voids content in the mix, which normally within 10-15% (Thanaya, 2003).
4- Bitumen coating similar to HMA is unachievable as high as 50-70 is reached with the aid of pre-wetting of aggregates (Al-Busaltan, 2012).

1.4 Advantages of Incorporating Waste Material in CBEM

Utilization of waste materials in construction is a modern trend worldwide. Asphalt mix technology in general and CBEM in specific, are not far away from this trend. Thus, the following could be advantages of utilizing wastes in CBEM (Thanaya, 2003, Ellis et al., 2004, Al Nageim et al., 2012, Al-Busaltan et al., 2012b, Dulaimi et al., 2016):

1. Reduce the demand for raw materials and support environmental conservation " sustainability"
2. Some wastes materials have proven their efficiencies in improvements of CBEM.
3. Have economic benefits, as waste materials are normally disposed.
4. Considers ecological benefits.

1.5 Problem Statement

CBEM is a promising technology for paving industry. Although it shows vital advantages, conventional CBEM still has poor engineering properties when compared to HMA, especially if it is left without treatment or development. CBEM is still a new technology and requires extensive studies for development to make its properties stand against heavy repeated loads. Several aspects should be considered in parallel while developing CBEM:

1-Develop the mix design procedures, where the current ones are not comparative to HMA design procedures

2-The main reason of its engineering properties weakness is the trapped moisture between the aggregate and the asphalt film. Thus, continuing development for removing the trapped water is in high demand.

3-Introduce new techniques to improve CBEM volumetric properties also is in high demand, where high air voids associates many defects to pavement layers.

4-Offer a new high-performance technology for the above improvements that considering green sustainable issues also is now-days requirements.

Although these considerations need comprehensive studies, but implement a study to realize the scope of these considerations in M.Sc. study scale is achievable especially for the last three considerations.

1.6 Research Aim and Objectives

This research study aims to improve CBEM weak properties by using the available local municipal solid waste materials. The following tasks have been conducted to achieve the research aim:

1. Select one of the most available local municipal solid waste to perform the development process in term of sustainability.
2. Compare the mechanical, durability, and volumetric properties of new developed CBEM with traditional one and HMA to ensure the feasibility of the development.
3. Optimize the incorporating of waste materials in the new developed CBEM as the percentage of fine aggregates, to reach the best results of such incorporation.
4. Study the effect of low heating energy on new developed CBEM mechanical durability, and volumetric properties, to ensure further development.

1.7 Scope of the Research Work

Within the wide range of conditions, materials, testing methods, and design methods, this research work was achieved under the following scope

1. All materials were local except the bitumen emulsion.
2. Mixtures were evaluated in a lab in terms of mechanical, volumetric, and durability properties. No site evaluation has obtained during research work.
3. All tests were performed at the University of Kerbala (UOK) laboratories.
4. Laboratory temperature ranged between 10°C to 35°C through year seasons.
5. Some testing devise have locally manufactured, including indirect tensile strength test (IDT), creep compliance test (CC), and wheel track test (WTT), except Marshall Device according to standard specifications. Devices were programmed and computerized locally with the help of an experienced programmer.
6. Mixtures were evaluated in terms of volumetric, mechanical tests (i.e. Marshall Stability and Flow, Indirect Tensile Strength, Creep compliance and creep stiffness, Wheel Track test and dynamic stability), and durability tests in term of water sensitivity (Retained Marshall stability).
7. Two types of specimens shapes were used; cylindrical (Marshall Specimens) shape for IDT, CC, and RMS and rectangular Slab specimens for WTT.

8. Specimens were compacted using Marshall Hammer (impact compaction) and vibratory compaction.
9. Two types of curing protocols have adopted for cold and half warm mixtures, which are: short curing (7-14 day) including (24hr@lab temperature in mold+24hr@40°C in oven dry). The former curing protocol was adopted for Marshall Test, IDT, and CC. while the latter was adopted for WTT and includes (24hr@lab temperature in mold+14 day in oven@40°C)

1.8 Thesis Structure

The thesis consists of six chapters to demonstrate the study work outcomes as listed below:

Chapter 1	Introduces the background of the research, its statement of the problem, aim and objectives, scope of the research work, and finally the thesis structure.
Chapter 2	Reviews paving technology, bitumen emulsion, classifications and methods of manufacturing, types of CMA, previous studies for enhancing CBEM properties.
Chapter 3	Describes materials properties that are used in the research, the adopted CBEM design procedure, and the adopted tests to examine mix properties, and finally research methodology.
Chapter 4	Illustrates the results of the study for both the traditional and developed CBEM with comparison to HMA.
Chapter 5	Gives the further development to enhance CBEM volumetric properties by utilizing low energy heating technology. As well as, evaluation of the FGA effect on HWBEM.
Chapter 6	Outlines research conclusions and draw recommendations and suggestions for future studies.

Chapter Two

LITERATURE REVIEW

2.1 Introduction

In general, road pavement can be rigid, flexible, or a composite of both. Rigid pavement system commonly consists of reinforced concrete layer overlaid on subbase unbounded granular layer, which supported by subgrade layer. In most cases, a thin of asphalt concrete layer overlays the concrete layer to improve riding quality and noise reduction purposes, the resulted system then called composite system. Figure (2.1) shows different types of pavement systems.

The other type of road pavement is the flexible pavement system that composes of surface course layer above binder course (each two layer constructed with asphalt concrete), supported by base layer (may be bonded layer such as asphalt concrete or unbounded granular one), which overlays on subbase layer (usually granular unbounded layer to ensure economic aspects). Finally, the subbase layer is supported by the subgrade, as illustrated in Figure (2.1).

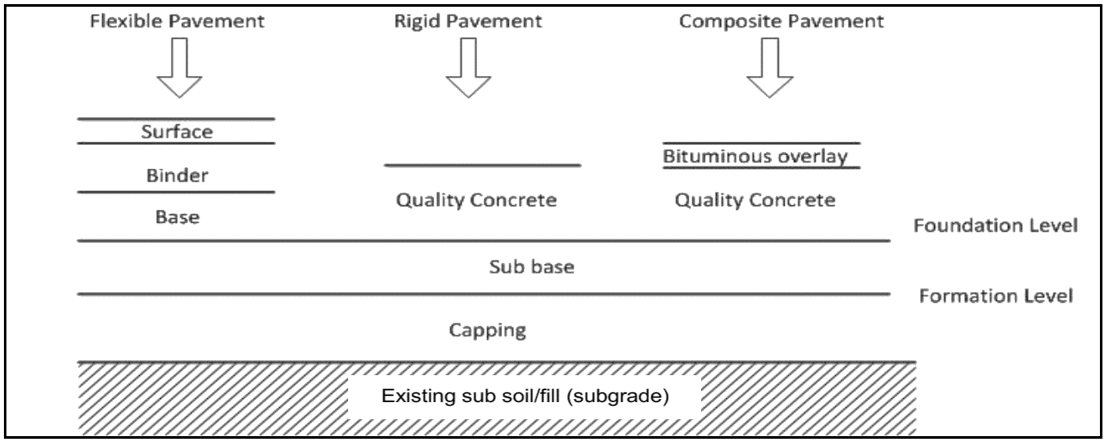


Figure 2.1 Common pavements structure, flexible system on left, rigid system at center, and composite system at the right (Al-Busaltan, 2012).

Large percentage of paved roads and highways networks are constructed with flexible pavement system due to its beneficial properties. It is estimated that more than about 90% of the paved roads are made with the fixable system worldwide (NAPA and EAPA, 2001).

2.2 Technologies Involved in Production of Bituminous Mixtures

Asphalt mixture can be defined as a composite of graded aggregate blended with a bituminous binder. Hot Mix Asphalt (HMA), Warm and Half Warm Mix Asphalt (WMA, HWMA), and Cold Mix Asphalt (CMA) are the three major types of asphalt mixes. Each one differs from others by type of the bituminous binder that is blended with the aggregate and temperature of manufacturing, as can be seen in Figure (2.2). The three mentioned above asphaltic technologies will be introduced in more detail in the following subsections:

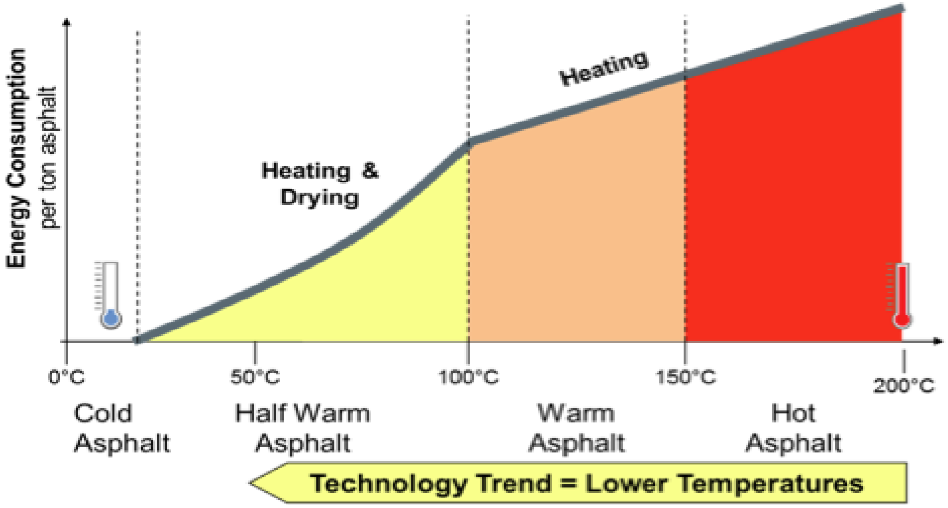


Figure 2.2 Manufacturing temperature of various asphalt mixtures (EAPA, 2014c).

2.2.1 Hot Mix Asphalt (HMA)

To date, HMA technology is the most efficient technology for paving roads. It dates back to the prior of 1875 where the first trial for paving was implemented in the USA in New York city (Roberts et al., 2002). A large percentage of asphalt concrete roads and networks were built with HMA technology, estimated about more 90% worldwide (NAPA and EAPA, 2001). It is working still now perfectly. HMA is produced by blending preheated graded aggregates at temperature above 150 °C with the bituminous binder at ranging temperature of 140°C to180°C (Almeida-Costa and Benta, 2016). It may reach to 250 °C based on the used type of asphalt grade in the mix (NAPA and EAPA, 2001). Such technology requires heat preservation for mix compaction to ensure better workability and gain the target required properties. HMA can be worked with dense graded, open graded, and gap graded according to the final purpose. It was suggested that the temperature mix could be limited to 5°C in temperature reduction for hauling distance purposes. HMA gains strength quickly after mixture cooling. It has to command that such technology does not satisfy the economic side and environmental eco-friendly aspects. Therefore, numerous researchers moved thier focus on developing technologies that satisfy economy and environmental aspects in addition to the engineering requirements.

2.2.2 Warm and Half Warm Asphalt Mixes (WMA/HWMA)

The first trial for developing WMA dates back to the early of 1990 when additives were tested in Germany and Norway to produce foam asphalt (EAPA, 2015). WMA is a technology of blending preheated aggregate with a bituminous binder at a temperature lower than typical HMA by (20 – 55°C) and typically ranging between 100ºC-140ºC (NAPA and EAPA, 2001). This techniques is based on the idea of reducing asphalt binder viscosity to ensure full aggregates coating at working temperature of (100-140 °C) by using organic, chemical additives, or foaming techniques.

WMA has many environmental and application benefits. Several studies concluded that WMA can be at least equivalent to traditional HMA (Capitão et al., 2012). Such technology can be applied perfectly to different asphalt concrete, like dense graded, pours, stone matrix, and mastic asphalt (D'Angelo et al., 2008).

HWMA is the technology of producing asphaltic mixture at temperature not less than 60°C, and not more than 100°C (EAPA, 2014b, Punith et al., 2012). HWMA may be prepared to utilize foamed bitumen technology, asphalt emulsion, or modified asphalt blended with fluxing oil. The production of HWMA at a lower temperature may allow longer time span, in addition to promoting lower compaction effort compared to HMA, and can ideally enhance pavement life in term of its resistance to rutting, low temperature cracking, and moisture damage (USDOT, 2005, Rubio et al., 2012).

2.2.3 Cold Mix Asphalt (CMA)

To obtain low temperature application of bituminous binder, or in other words, to reduce asphalt viscosity, there are several methods: using cut back asphalt, which produced by mixing asphalt with flux oil, or using foaming technology of hot asphalt in addition to cold water, or using asphalt emulsion produced from emulsification process of asphalt emulsion with water (Choudhary et al., 2012).

CMA is a composite of suitable unheated graded (dense, gap, and open) aggregates (virgin or recycled) with bituminous binder and water with or without additives mixed at temperature 0-40°C (EAPA, 2015), or less than 60°C (Speight, 2015). Such bituminous binder that used in cold mix is bitumen emulsion or cutback asphalt (Choudhary et al., 2012). It can be prepared in place or at mix planet. Each type of asphalt is mixed with other components by using special technology at ambient temperature (Thanaya, 2003). This technology has been widely used in different countries for different purposes such as in the USA and France (Read and Whiteoak, 2015).

Cutback asphalt, foamed asphalt, and asphalt emulsion are three common technologies for bituminous binder production. Cutback asphalt , which is produced by blending fluxing oil with bitumen grade using kerosene fluid, has several disadvantages such as high spraying temperature (130-170°C), early life bleeding, dry chippings requirements, and environmental and health issues (Read and Whiteoak, 2015). The second type of bituminous binder is foamed asphalt (will discuss later), is a mixture of hot (170°C) grade bitumen, water, and air. Such technology requires special equipment for production and mixing components which may not be available worldwide (Overby et al., 2004). On the other hands, utilizing bitumen emulsion for cold mixtures has been encouraged by many researchers and regulations since environmental and economic issues can be covered when utilizing such technology as will be discussed hereinafter (Thanaya, 2003).

Table (2.1) illustrates the general comparison between cold and hot asphalt mixtures technologies.

Table 2-1 General comparison between cold and hot/warm mixtures technologies (Taylor, 1997)

Cold Mix asphalt	Hot/warm mix asphalt
Binder storage at refinery in cold state	Binder storage at refinery in hot state
No special transport for binder and mixture requirement	Special tanks equipped with heating system for binder and lagged and sheeted lorries required for mixture transport
Simple storage plant	Heated and lagged storage and pipe work at plant
Mix cold with damp aggregate	Mix hot with pre-dried and heated aggregate. WMA aggregate could be used either damp or pre-dried
Easy to store mixed material	Store need care
Wide time and temperature window for laying and compaction	Narrow time and temperature window for laying and compaction. WMA has wider time and temperature window than HMA

Not affected much by temperature variation within application process, just rain may affected its performance	Hot weather: danger of wheel tracking and over embedment of chippings Cold weather: poor compaction

2.3 Bitumen Emulsion Technology

Asphalt emulsion is a brown liquid composite of grade asphalt, water, and emulsifier agent with or without additives. The idea behind this technology is the ability to use asphalt emulsion for various application at ambient temperature without heating due to its low viscosity at ambient temperature. The production of bitumen emulsion dates back to the early of the twentieth century (Nikolaides, 2014). Currently, around eight million tons are produced worldwide in which the USA produces approximately is about three million tons, which makes it the largest producer of bitumen emulsion worldwide (EAPA, 2014a). The property of low application temperature for asphalt emulsion due to a low viscosity of asphalt emulsion itself make it a preferable alternative to HMA and cutback asphalt in many applications. It is interested to comment that the low viscosity of bitumen emulsion ranges from 0.5 poise to 10 poise at 25-25°C, while the viscosity of asphalt ranges between 100-4000 poise at the same temperature, the reason that make asphalt emulsion can be applicable at low temperature (Read and Whiteoak, 2015). This advantage made the asphalt emulsion as the preferable alternative in many applications over HMA and Cutback asphalt (James, 2006).

2.3.1 Advantages of Bitumen Emulsion

Asphalt emulsion has many advantages in roads constructions and repairing applications (James, 2006):

- Low application temperature due to the low viscosity of asphalt emulsion at ambient temperature when compared to other asphalt binders.
- As a result, it has a credit of saving energy and reduces toxic gas emissions.
- No heating required for aggregate when using asphalt emulsion.
- Asphalt emulsion offers less hazardous effect when compared to hot asphalt.
- With regard to economic and environmental impacts, asphalt emulsion is more economic and ecofriendly than cutback asphalt.

- From eco-efficiency point of view, an environmental impact analysis concluded that some of asphalt emulsion applications (Chip seal and micro surfacing) offers less environmental emissions than a thin hot mix overlay.

2.3.2 Chemical Nature and Components of Bitumen Emulsion

Asphalt emulsion is a composite of two immiscible liquids (phases), in which one dispraised in the other, in addition to some additives. In most cases, water acts as one of the two phases in the emulsion. Emulsion can be produced by two ways: oil in water, in which water considers as the continuous phase and the dispraised phase represented by oil droplets, and water in oil (inverted emulsion) in which the water works as dispraised phase, and the oil works as the continuous phase. In some cases, multiple emulsion phases are also existing, Figure (2.3) illustrates the types of asphalt emulsions. Most of asphalt emulsion, is an oil-in-water type (James, 2006).

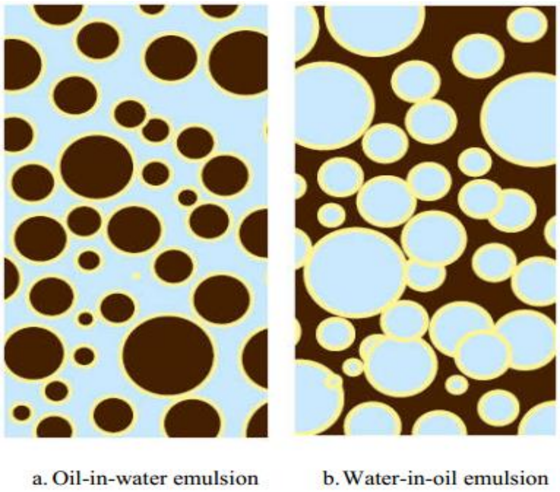


Figure 2.3 Types of bitumen emulsion, A- oil in water and b- water in oil (Wu et al., 2003)

In general, standard asphalt emulsion contains 40-70% asphalt, 30-50% water,0-10% solvents, and 0.2-2.5% emulsifier with some minor component (Salomon, 2006b), as shown in Figure (2.4). The emulsifier is the important component that gives final emulsion charge type. Particle size and particle distribution affect significantly on the physical properties of the emulsion, such as viscosity, and storage stability; larger average particle size lowers the viscosity. In addition, the performance of asphalt emulsion depends largely on particle size of emulsion, whereas the smaller particle size, the best performance of emulsion.

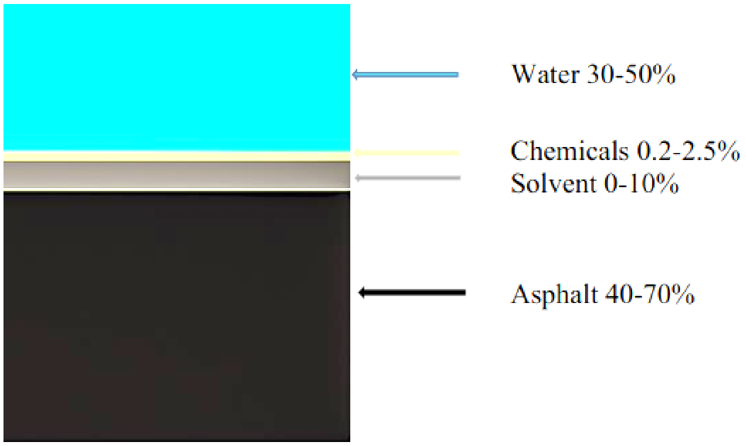


Figure 2.4 Components of asphalt emulsion (Salomon, 2006a).

2.3.3 Classifications of Bitumen Emulsion

Bitumen emulsions can be classified based on (James, 2006):

1. Sign of charge on the bitumen emulsion droplets, or
2. Their reactivates.

The classification of bitumen emulsion sign charge can be subdivided into three types:

- Cationic asphalt emulsion, which has positive sign charge on the surface of the asphalt droplets.
- Anionic asphalt emulsion, which has negative sign charge on the surface of the asphalt droplets.
- Nonionic asphalt emulsion, which has no sign on the surface of the asphalt droplets.

On the other hand, bitumen emulsions can be classified based on their reactivity as follows:

- Rapid setting bitumen emulsion (RS), which has rapidly reactive, and normally used with low surface area type of aggregate application, such as in surface dressing (Chip seal).
- Medium setting bitumen emulsion (MS), which offers less reactivity than RS bitumen emulsion when blended with aggregate that has low surface area property.

- Slow setting bitumen emulsion (SS), which offers no activity with low surface aggregate. For this reason, aggregate used with this type should be an active one (high surface area), such as dense graded mix.

2.4 Cold Mix Asphalt Mixtures

Cold Mix Asphalt (CMA) is a composite of low viscosity bitumen with a suitable graded system of mineral aggregates, which prepared and compacted at ambient temperature. The process of reducing bitumen viscosity may use flux oil with hard grade asphalt to produce cut back asphalt, or by emulsification process to produce bitumen emulsion, or by using foaming process to produce foamed bitumen. Thanaya (2003) listed the most common types of CMAs, namely, cold lay macadam, grave emulsion, foamed asphalt mixtures, and Cold Bituminous Emulsion Mixtures (CBEM).

Open graded emulsified mixtures (OGEM) have been used successfully in the Pacific Northwest since 1966. Also, in the 1960’s and 1970’s, numbers of agencies used cutback asphalt cement as a binder in Dense Graded Emulsion Mixes (DGEM) and utilized a single bin pug mill to mix the material. However, during the early 1970’s, many counties and townships used OGEM and DGEM on their low volume road network. Also, in Ontario, DGEM has been used to improve county roads (Davidson and Eng, 2005).

In France and Eastern Europe, CMA is used in different applications. Britany ,France in 2002 have used 2.5 inches dense graded cold bitumen emulsion as surfacing above two subbase layers (Jorda, 2008).The system has approved its efficiency to resist heavy traffic load despite high air void of 15 % after one month (Jorda, 2008).Also, in the south-east of France, CMA was used as protection and enhancement layer for resurfacing with CMA dense mixture in an industrial park, it showed good performance after 3 years under traffic load (Serfass et al., 2012). Another application in Illinois, in which CMA was frequently used as a base or surface layer on low traffic volume (Anderson and Thompson, 1995). Its performance showed a good resistance to cold climate condition. Also, a recommendation states that CMA can be applied in term of low to medium traffic load conditions, remote area, sidewalk, reinstatement works (Thanaya et al., 2009, Leech, 1994, Read and Whiteoak, 2003). CBEM can be effective and comparable to HMA in case of full curing condition even if no improvements had accrued on mixture (Thanaya et al., 2009).

In rural roads projects in the North Eastern States of India, CBEM was suggested as the alternative solution since it has long time span between mixing planet and laying down and can be laid down in the rainy season (Choudhary et al., 2012).

In the UK, they used CMA for reinstatement works of openings in the highway (Thanaya, 2007). Recently, Nassar (2016) reported in his research on CBEM using different supplementary cementitious fillers that treated mixture as a structural pavement base course or surface course layers. More recently, Dulaimi et al. (2017a) reported the use of CBEM for heavy- trafficked binder course after treating mix with specific binary cementitious fillers.

2.4.1 Cold Lay Macadam

Cold lay macadam is a mixture of aggregate with cutback asphalt (which has prepared by addition solvent or flux oil to hard bitumen). Flux oil should conserve an amount of nonvolatile part that works as a diluent to obtain the required consistency. The quantity of flux oil in cutback asphalt reflects final viscosity of the composition. The setting mechanism of cutback is largely dependent on the type of flux oil and climate conditions. The conventional types of flux oil that used to lower viscosity are: gas oil, kerosene, and white spirit (Thanaya, 2003).

Surface dressings and cold macadam lay are two mixtures in which cutback asphalt is used. These mixtures are normally used as temporary fill materials in reinstatement works to enhance roads convenience and avoid accidents. Cold lay macadam suffers from low stiffness due to the existence of flux oil in the mix. Also, the uneconomic and hazardous effect on soil considerations of cutback asphalt made it unfavorable alternative (AL-Hdabi, 2014).

2.4.2 Foam Bituminous Mixtures

The production of foamed bitumen technology dates back to 1956 when firstly described by professor Csanyi at the university of Iowa state in the USA (Thanaya, 2003). Other researchers mentioned that the production of foam bitumen mixtures dates back to 1928 when the first hot bitumen foaming system was patented (Hailesilassie et al., 2015). Simply, the production of foam asphalt consists of injecting steam to hot bitumen, as illustrated in Figure (2.6A). The huge numbers of tiny hot bitumen bubbles try to trap steam with lead to enhance asphalt consistency. In less than one minute, foam asphalt sets and back to its original condition.

The blending process should be complete within foam state to ensure aggregate coating. In situ, impractical considerations were found in such process since it requires special equipment like steam boilers. As a result, some modifications occurred on the process of production of foam mixture by Mobil oil Australia in 1968, who added cold water instead of steam into hot bitumen to ensure practical and economic aspects (Bowering and Martin, 1976). Due to such development, foamed asphalt is used extensively for highway maintenance. Figure (2.6 B) illustrates the form of the developed equipment for production recycled asphalt mixture with foam asphalt technology.

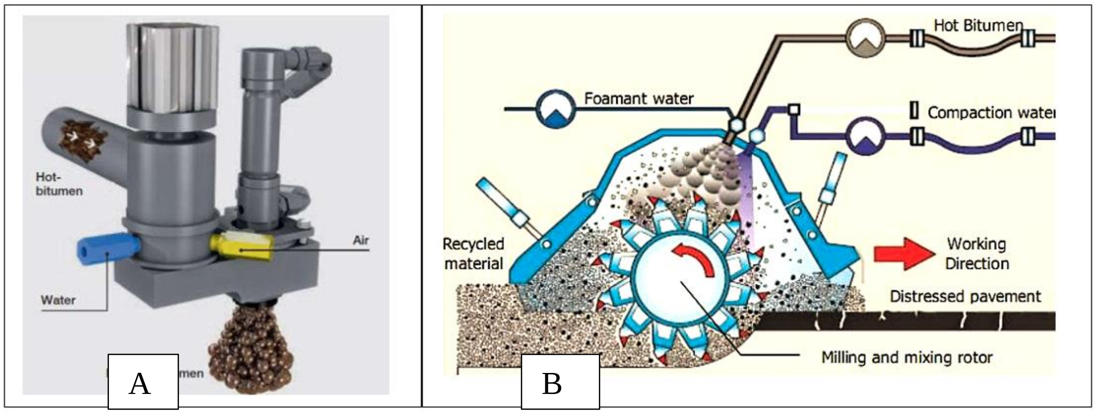


Figure 2.5 Production of bitumen foaming, a: scheme of foam bitumen production process (Wirngton Gmbh, 2001), b: mobile method for production foam bitumen (Ebels, 2008).

2.4.3 Cold Bituminous Emulsion Mixtures (CBEM)

The process of production CBEM includes mixing suitable graded pre-wetted aggregates with bitumen emulsion at ambient temperature with or without additives. It is simple to produce when compared to other mixes (HMA and WMA). Also, it offers several environmental and economic advantages as mentioned previously in Chapter One. As a result, it is considered as an alternative for many applications instead of HMA. The CBEMs suffer from poor early life strength because of the trapped water between the asphalt film and the aggregate surface, resulting in very low engineering characteristics that could not stand against the heavy load application. Therefore, CBEMs utilization is restricted to low and medium traffic loads, repairing, and sidewalks paving (Jenkins, 2000, Choudhary et al., 2012).

Other researchers have proved the opportunity to use CBEMs as a structural layer when some improvements are suggested. (Oruc et al., 2007, AL-Hdabi, 2014, Nassar, 2016, Al-Busaltan, 2012)

2.5 Previous studies for improving CBEMs

Although what mentioned previously about CBEMS advantages, conventional CBEMS is still offering useless properties in the early life and has restricted applications when compared to HMA. Therefore, comprehensive studies have been made to develop such mix technology by various researchers and highway agencies to enhance CBEM to be comparable to HMA.

Various studied have attempted the incorporating of different materials to enhance CMA performance, e.g. reclaimed asphalt pavement (RAP), polymer, active fillers (cement and lime), fly ash, and fibers…etc. Thus, the following sections will describe such attempts:

2.5.1 Improving CBEM by OPC and Lime

Numerous studies revealed the significant effects of active fillers on the performance of CBEMs, such as Ordinary Portland Cement (OPC) and lime (Head, 1974, Needham, 1996, Thanaya, 2003, Ebels and Jenkins, 2007, Poncino et al., 1993, Al-Busaltan, 2012, AL-Hdabi, 2014, Lin et al., 2017, Niazi and Jalili, 2009, Dulaimi et al., 2017a, Al Nageim et al., 2012). Active filler works chemically as a second binder in the mix beside the primary binder (bitumen). Of course, in addition to its origin physical purpose which is a tiny filling material in the aggregate skeleton. OPC can react within mixture because of the existence of water within emulsion composition and premixing water source. Such fillers enhance mixture strength, also, at the early life as the trapped water is absorbed in the hydration process. As a result, they consider as catalyzer agents for bitumen emulsion breaking process (Ebels and Jenkins, 2007).

The incorporation of OPC as a filler in the asphalt emulsion mixture dates back to 1970 (Head, 1974), where it had believed significantly improve the mix properties (Needham, 1996). Head (1974) concluded that Marshall Stability could be increased by about 250-300% if 1% of OPC had substituted. Poncino et al. (1993) stated that incorporation of 2% of OPC filler in CMA with densely graded gradation increases the resilient modulus by 125%, and 66% when limestone filler is used. Furthermore, a study reported that addition of cement to CBEMS increases fatigue life, resulting in high toughness, enhancements in strain energy, and delays in micro cracking propagation (Li et al., 1998).

Moreover, other studies stated that OPC filler with CBEM mixture improve the stiffness modulus, reduce susceptibility to moisture damage, improve temperature susceptibility, increase the ability of mixtures to resist creep and permanent deformations (rutting) and make them comparable to HMA (Oruc et al., 2007, Schmidt et al., 1973, Head, 1974) (Thanaya et al., 2009, Fang et al., 2016, Needham, 1996, Al-Busaltan, 2012), as can be seen in Figures (2-6,2-7,2-8,2-9, and 2-10)

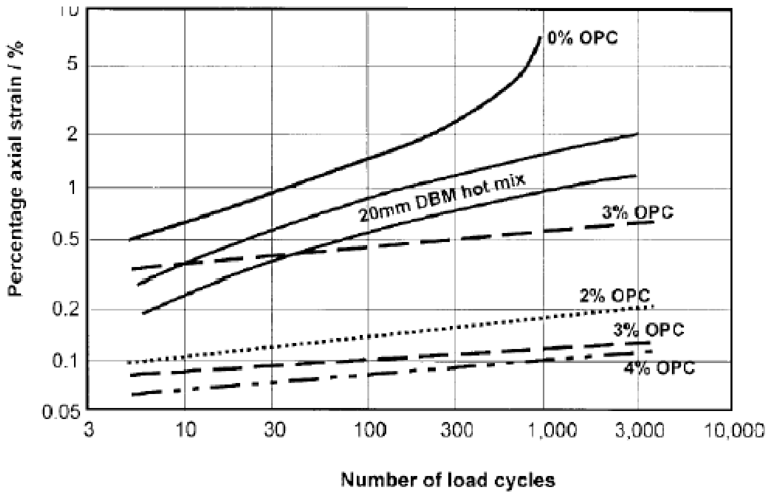


Figure 2.6 Effect of addition different OPC percentages on CBEM permanent deformation (Brown and Needham, 2000)

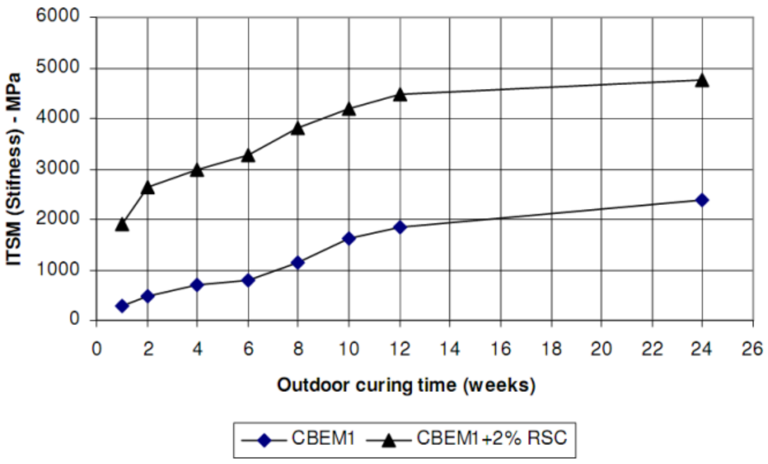


Figure 2.7 Effect of addition 2% RSC on CBEM ITSM performance (Thanaya et al., 2009.

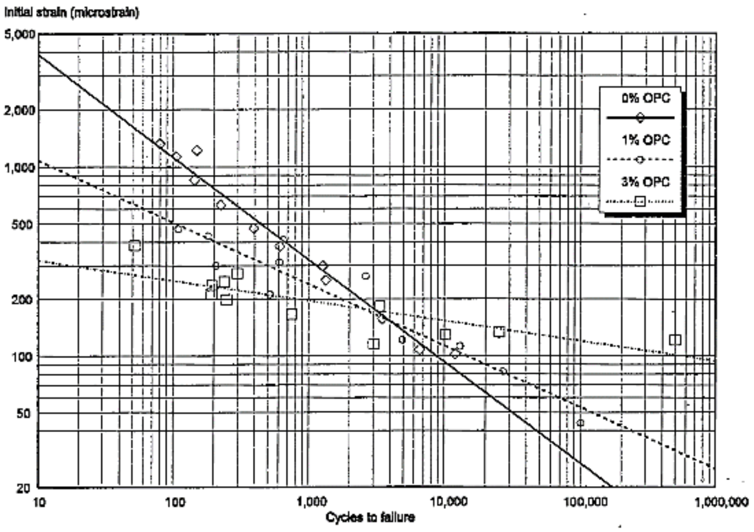


Figure 2.8 Effect of OPC amount in CBEM on fatigue failure(Needham, 1996)

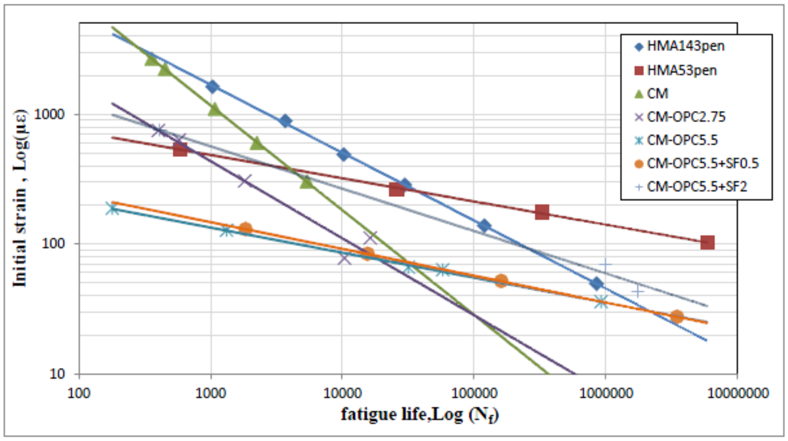


Figure 2.9 Fatigue line for OPC modified CBEM compared with HMA (Al-Busaltan, 2012).

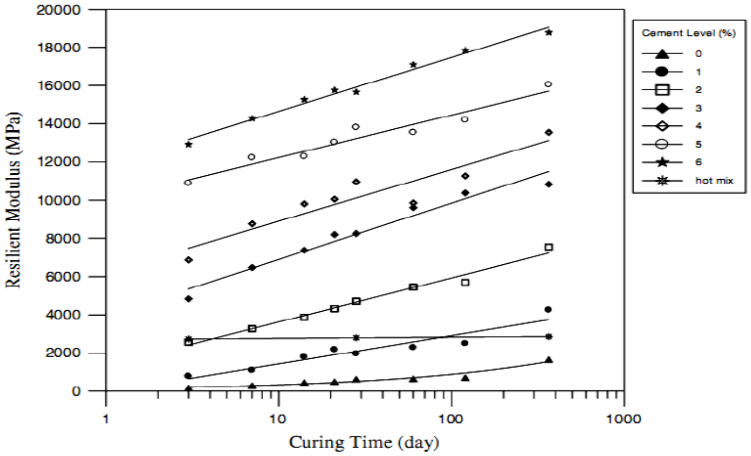


Figure 2.10 Improvement in resilient modulus with increase OPC percentage (Oruc et al., 2007)

Another study concluded by Al Nageim et al. (2012) reported that CBEMs comprising cement can enhance overall mixture properties. Also, the study reported that cement filler produces stiffness properties higher than HMA at long time curing. It also found that full cured CBEMs comprised 2.75-5.5% active fillers offers higher resistance to permanent deformation than traditional HMA

Recently, Yan et al. (2017) investigated the early-age strength and long-term performance of asphalt emulsion cold recycled mixes with various cement contents. They conducted the following points:

- Cement filler promoted higher cohesive strength in term of Hveem cohesion test, and higher raveling resistance in term of raveling test at higher amount of cement content.
- Cement improved mix early strength, and increased resistance to moisture damage.
- Improving high temperature stability and low-temperature cracking resistance. A higher value could be obtained with higher cement content.

Another active filler is the limestone, which has many advantages when blended with CBEMS. It can enhance mixture ability to resist stripping or reduce susceptibility to water damage (Oke, 2011) (Chatterjee et al., 2006).

A study by Niazi and Jalili (2009) stated that when lime is used as a filler with cold in place recycled mix bitumen emulsion, a noticeable improvement occurred in the mix properties such as Marshall stability, stiffness modulus, resistance to water sensitivity, tensile strength, and permanent deformation.

On the other hand, the effect of adding lime as a filler compared to OPC is relatively low, since it has observed by Brown and Needham (2000) that stiffness modulus of hydrated lime treated CMA did not have the same useful improvement, as shown in Figure (2.11).

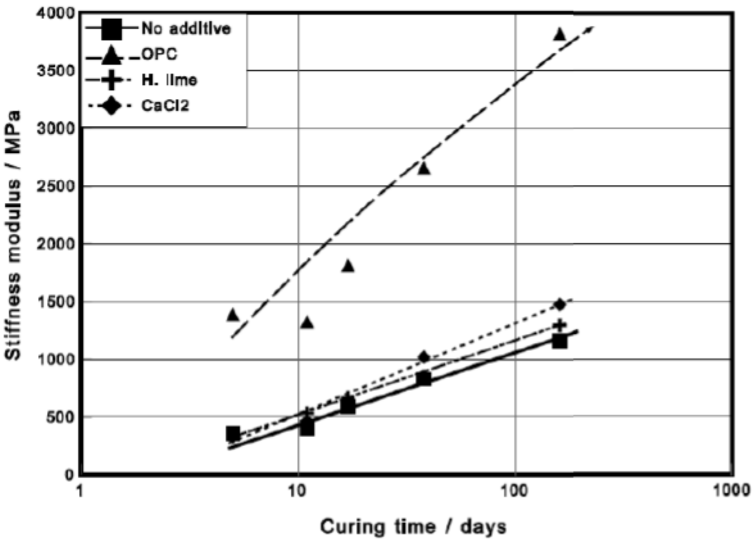


Figure 2.11 Stiffness modulus for cold emulsion mixtures with OPC, Lime, and CaCl$_2$. (Brown and Needham, 2000)

2.5.2 Waste Fly Ash (FA)

Traditionally, fly ashes have been used in a wide range of applications; namely, fill materials, grouting, and soil stabilization (Scheetz and Earle, 1998). Fly ash has also been used in road pavements as a stabilizer for road bases, sub-bases and for sub-grade formation (Kumar and Patil, 2006). Different fly ashes types were evaluated such as Rice Husk Ash (Al-Hdabi, 2016), Coal Fly Ash (Sarsam, 2016), Palm Oil Fuel Ash (Maleka et al., 2014), Sugarcane Bagasse Ash (Zainudin et al., 2016). All these studies reported that such materials have cementitious properties in some instant and can improve the overall mix performance.

Numerous studies investigated the effect of different ashes types on CBEM performance. An early study conducted by Cross and Young (1997) investigated the effect of Fly Ash Type C as mineral filler on cold in-place recycled mixes. The result demonstrated that the incorporation of FA Type C with percentages of 7-11% enhance mixture resistance to water damage and improve mixture behavior in term of its resistance to the action of freezing and thawing. They also concluded that the addition of a high amount of FA Type C makes the mix having brittle fatigue behavior, and enhances temperature of thermal fracture.

Al-Busaltan et al. (2012a) studied the effect of incorporation of waste by product material named Paper Sludge Ash (PSA) with percentages ranging from 0-5.5% of the aggregate mass in close graded cold bituminous emulsion mixtures. They concluded that superior enhancement in mechanical properties of the new upgraded cold mix when incorporating this waste material. Also, they remarked that the treated mix with such materials shows significant improvement and comparable to conventional HMA, as can be seen in Figure (2.12).

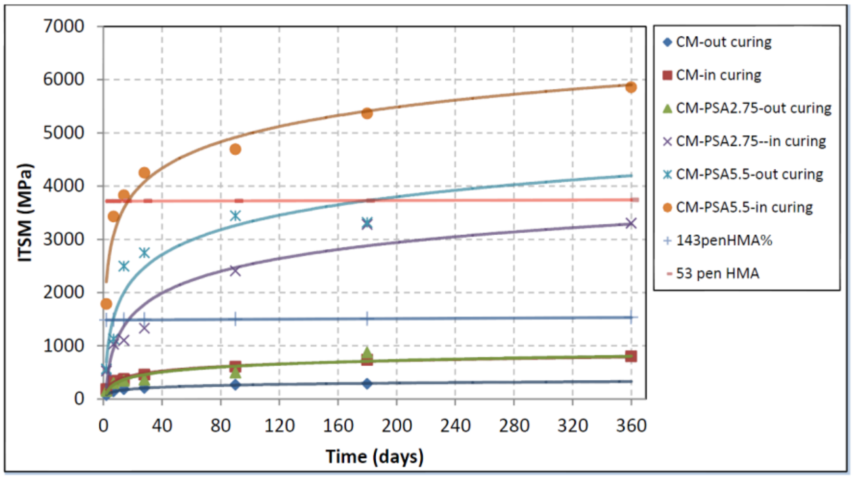


Figure 2.12 Effect of PSA on CBEM stiffness compared with HMA (Al-Busaltan, 2012).

Al-Hdabi et al. (2014b) investigated the effect of waste bottom ash of Rice Husk on Cold Rolled Asphalt (CRA). They concluded that further enhancement could be achieved in term of stiffness modulus; dosages of 2% and 4% with 3% cement as filler in CRA increased stiffness to 160% and 250%, respectively. Also, it increases CRA mixture resistance to water damage in case of stiffness modulus ratio (more than 100%) was recognized. The ash works as an activated agent when added with cement filler.

Recently, Nassar et al. (2016) investigated the effect of fly ash type 450-S as mineral filler on the mechanical and durability properties of dense graded cold bituminous emulsion mixture. They concluded that significant improvements are accrued when FA is added in the mix similar to mixture treated with a high percentage of OPC, and the resulted mixture was comparable to HMA. They remarked that such mixture could be used as a surface layer for roads with low to medium trafficked action.

More recently, Dulaimi et al. (2017c) investigated a new type of fly ash with high amount of calcium called (HCFA) blended with another type of waste fluid catalytic cracking catalyst (FCC) in binder cold emulsion bitumen mixtures. They found that the treated cold mixes were efficient to enhance pavement performance in term of stuffiness (ITSM) as can be seen in Fig (2.13). Also, a resistance to rutting deformation, and water sensitivity have observed. They stated that the new mix has superior properties such as reduced time to reach full curing, and has a comparable stiffness to HMA within three days only. Also, they further reported that the new mix has lower thermal susceptibility compared to HMA, higher rutting resistance than HMA, better resistance to water damage than HMA in term of ITSM.

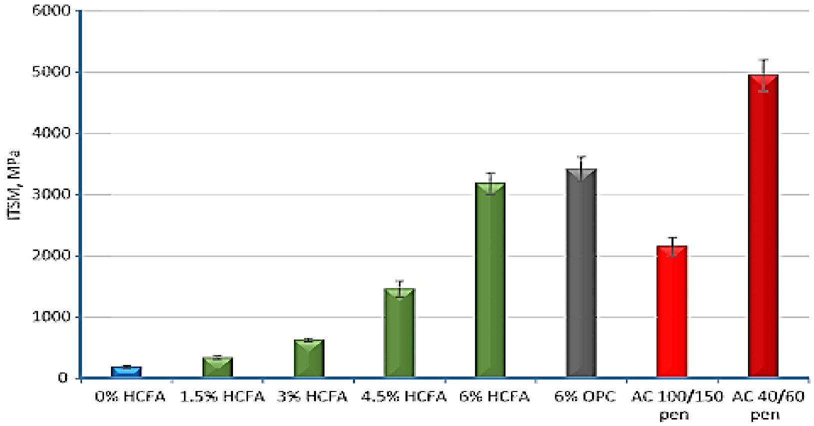


Figure 2.13 ITSM after 3 days for CBEM incorporated HCFA compared with HMA (Dulaimi et al., 2017c).

2.5.3 Utilization of Waste Materials as a Secondary Aggregate in CBEM

Numerous solid wastes materials have been utilized in different civil engineering applications, especially as aggregates in concrete constructions or roads pavements. After a successful research studies, pavements constructions consumed various municipal wastes, industrial wastes, and by-product materials as a partial substitution instead of virgin aggregates. Glass waste, blast furnace slag, concrete and masonry demolition waste, RAP, bottom ashes, roof shingles, scrap tire rubber, and waste plastic bottles all are examples of such materials. However, all mentioned waste materials tried extensively in developing CMA, so the followings are a summary of these extensive researches:

2.5.3.1 Concrete and Masonry Demolition Waste

Large quantities of waste demolition are generated worldwide. Such wastes have been proven their efficiency as recycled material in HMA via various research studies (Shen and Du, 2004, Wu et al., 2013, Qasrawi and Asi, 2016) (Aljassar et al., 2005). Such studies used crushed concrete and masonry as course and fine aggregate in course asphalt mixture. The researchers concluded that such wastes can be used in asphalt mixes and meet the criteria of local specifications in term of rutting, moisture damage, and loss stability.

For CMA, Thanaya (2010) studied the effect of waste construction demolition (WCD) in CBEM. He used concrete and clay masonry wastes that generated from construction demolition works as partial substitution instead of virgin aggregates in a dense graded mix. He concluded that CBEM incorporated WCD requires a higher estimated amount of bitumen emulsion of about 12% optimum bitumen residual as can be seen in Figure (2.14). He confirmed that such aggregate combination is satisfied the specification of the Ministry of Public Work-Republic of Indonesia (MPW-RI, 1990) with stability more than 3 KN and retained stability was 85%.

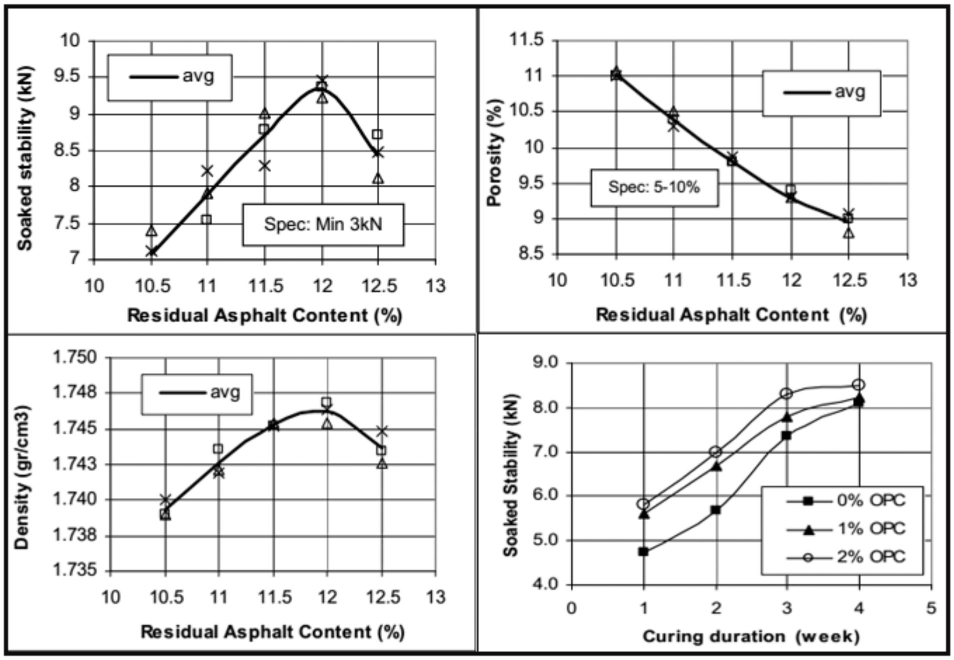


Figure 2.14 Effect of WCD on CBEM Soaked Stability, porosity, and density (Thanaya, 2010).

Also, Gómez-Meijide et al. (2015) investigated the possibility of incorporating of recycled aggregates from construction and demolition waste in cold bituminous emulsion mixtures. He reported the following points

- Cold mixtures with recycled aggregates have lower specific gravity, absorbs water about 3times more than conventional mixes, and required bitumen emulsion more than cold mixes with virgin aggregate, which resulted in higher air voids content.
- Mixtures with recycled aggregates are more stable for temperature change, or in other words less susceptible to temperature change, which may be more resistance to low-temperature fatigue cracking.

2.5.3.2 Steel Slag

Steel slug is a by-product material, which results from processes of stainless steel making. A large amount of such by-product is generated while producing steel, whereas approximately 1 ton is produced for every 3 tons of steel (Jamshidi et al., 2017). Steel slug is used instead of virgin aggregate in different civil engineering applications since it offers high strength and durability properties (Proctor et al., 2000). however, problems could appear if a higher amount of steel slug is substituted since it has the ability to shrink when mixes are exposure to water action, resulting in many cracks in specimens skeleton (Kneller et al., 1994).

Steel sludge was evaluated in HMAs as coarse aggregate by Ahmedzade and Sengoz (2009) or as fine aggregate by Kandhal and Hoffman (1997). Also, in different asphalt mixes as the whole gradation; namely, stone mastic asphalt (Wu et al., 2007), dense graded and gap graded mixes (Oluwasola et al., 2016). The mentioned researchers reported that steel sludge improves mechanical mix properties.

While in case of CMA, Thanaya (2003) studied the effect of substitution steel sludge as coarse aggregate in CBEM. He found that incorporation of steel sludge was unfavorable and may be risky on mix due to cracking of specimens at 40°C curing protocol. It was believed that cracks development were caused by a volumetric change in steel sludge itself because of moisture existence in the mixture. Therefore, the idea of replacement steel sludge as aggregate in CMA is still invaluable unless the volumetric change can be controlled.

2.5.3.3 Reclaimed Asphalt Pavement (RAP)

RAP material is obtained by pulverizing the old asphalt pavement layer to use it as a secondary aggregate in new asphalt layer. In most cases, the recovery process of RAP is accomplished by milling resulting in an aggregate material for maintenance and rehabilitation of roads. The use of RAP as an alternative to new virgin aggregate materials is gaining a worldwide attention as it could be a sustainable, economic, widely available, and environmentally friendly option (Cooley, 2005).

RAP was evaluated in term of HMA by several researchers (Huang et al., 2005, Copeland, 2011, Shirodkar et al., 2011, Arshad and Ahmed, 2017) whom conducted that good properties had been observed when incorporation RAP with virgin aggregates.

RAP was also utilized in cold mixtures by several researchers during their studies. Thanaya et al. (2014) studied the effect of old road pavement as an aggregate and rice husk ash as mineral filler in CBEM (cationic slow setting type) with different compaction efforts. They stated that incorporation of 72% of RAP as aggregate in CBEMs could meet the specifications (3KN min Marshall Stability and 5-10% target porosity). They further concluded that minimum stability of 3 KN could be reached in case of 2 days curing at the temperature of 20-30°C.

Also, Ojum (2015a) investigated the effect of high substitution percentages of RAP up to 100% with virgin aggregate on CBEM behavior in addition to the effect of compaction temperature of the treated mixture. He concluded that incorporation of RAP with percentages 50 and 85% with 1% OPC filler, can improves mixture stiffness by 32%, and he noticed that the stiffness was improved about 89% when incorporated RAP is 95%.

Recently, Lin et al. (2017) investigated the effect of 100% RAP content in cold cement treated bitumen emulsion mixtures. They revealed that the new mix compared to traditional HMA has the following properties:

- New mix has viscoelastic properties, but weaker than reference HMA;
- Higher stiffness in term of dynamic modulus compared to HMA and can be used as surface layer, and it has better rutting resistance at 60°C;
- Lower fatigue resistance at an early life, but still meet the criteria, and it increases with curing time, as can be seen in Figure (2-15).

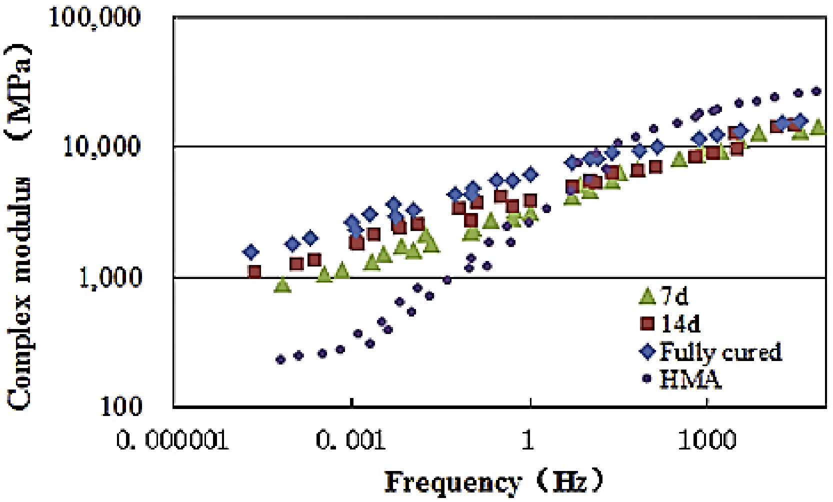


Figure 2.15 Master curve of cold recycles CBEM compared with HMA at different curing time (Lin et al., 2017).

2.5.3.4 Scrap Tire Rubber (STR)

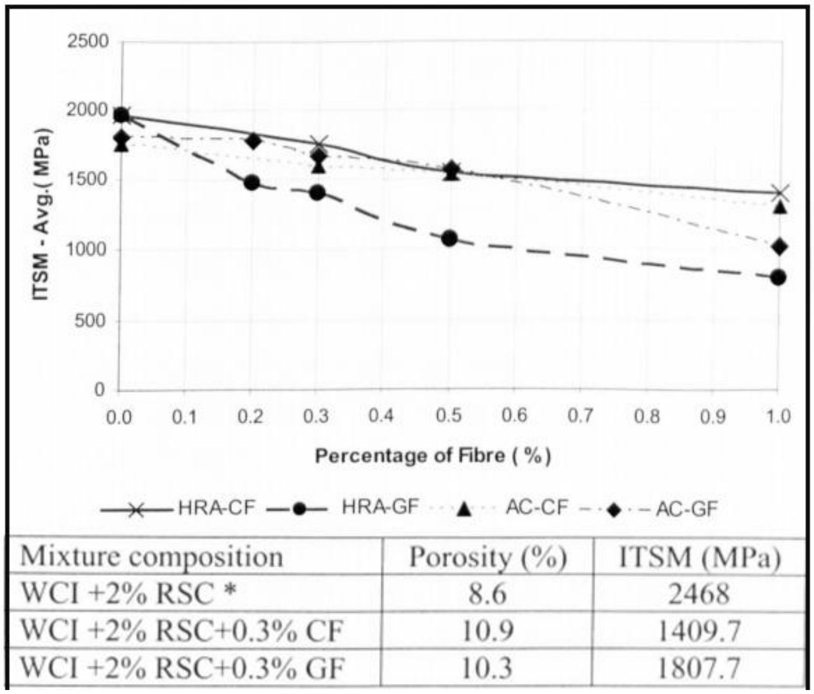
The idea of incorporating waste tire rubber is not new (in term of HMA). It was used since the late of 1960's as reported by Presti (2013). A field trial attempted to incorporate waste tire rubber in asphalt pavement since it is believed that some good properties could achieve due to such addition. In term of HMA, the treated mixtures with STR offers longer fatigue cracking, better resistance to skidding, and enhance pavement life as reported by Al-Abdul-Wahhab and Al-Amri (1991)

In term of CMA, Thanaya (2003) was the first researcher who attempted to incorporate crumb rubber as a partial replacement instead of virgin aggregate in CBEM. He reported that such compressible material with high elasticity was incompatible and unsuitable for using without treatment due to cracks occurrence in freshly CBEM.

2.5.4 Waste Fibers

Recycling of plastic waste in asphalt pavement have several economics and environmental benefits. Plastic fibers work as reinforcement in asphaltic mixtures. Thanaya (2003) studied the effect of addition waste plastic cells that made from PVC sheets as reinforcement for CMA since it was thought that it has the ability to reduce susceptibility to unrecoverable deformations. He found that plastic cells reflected a significant reduction in mixture vertical deformation under dynamic loading, a minor reduction in overall mixture stiffness (but still within recommended limits), a reduction in cracks propagation, and a promising results for enhancing CMA strength at early life. He further stated that existence of cement in addition to waste plastic strips improves overall system performance. Finally, he concluded that such materials could be vital in applications of road maintenance.

Thanaya (2003) evaluated the addition of fibers on CBEMs behavior. He tested two types of fibers, namely glass fibers (GF very fine threads) that manufactured from waste glass with a 10mm length, and cellulose fibers (CF) with diameter of 2 mm that made from recycling newspapers treated with silts. Both types incorporated with 0.3% by weight of total mix in addition to 2% rapid setting cement as mineral filler. He concluded that such addition increases mixture porosity, and resulted in ITSM reduction for both CF and GF respectively, as can be seen in Figure (2-16). Hence, incorporation of such materials reduce mixture workability, increase porosity, and reduce stiffness (Thanaya, 2003).



Mixture composition	Porosity (%)	ITSM (MPa)
WCI +2% RSC *	8.6	2468
WCI +2% RSC+0.3% CF	10.9	1409.7
WCI +2% RSC+0.3% GF	10.3	1807.7

Figure 2.16 Effect of addition different fibers amount and type on CBEM stiffness and porosity (Thanaya, 2003).

de S. Bueno et al. (2003) studied the engineering properties of both fibrillated fibers (FFs) and slit film fibers (SFFs) on dense graded cold asphalt emulsion mixture. The fiber had been included with percentages of 0.1%, 0.25%, and 0.5% by the total weight of the mix. Such addition caused a slight reduction in Marshall Stability, slight vibration in shear strength tri-axial parameters, reduction in mixture stiffness, causes no effect on the permanent strain.

2.5.5 Glass Waste

The glass is an inorganic non-metallic substance (Gautam et al., 2012). a large amount of glass waste is generated yearly worldwide. Such municipal waste represents a major problem whereas about 10 million tons in large cities is needed to dispose of worldwide. Thus, several methods are proposed to reduce the impact of glass waste (Modak et al., 2010). In civil engineering applications, crushed glass was used in road works for improving soil characteristics successfully (Disfani et al., 2011, Disfani et al., 2012) , also as an aggregate in asphalt mixtures (Wu et al., 2004b).

Glassphalt mixture is the terminology of asphalt mixture comprising glass waste (Chen et al., 2006). Since the late of the 1960s, about 33 locations field trial strips were constructed in the United States and Canada to evaluate glass effect in HMA .Also, about 17 streets were paved with Glassphalt mixture from the mid-1970 to the mid-1980 in Baltimore city for produce roads with sparkle effect (Wu et al., 2004a) . During the 1990 and through 1995, about 225000 metric ton of glassphalt hot mix was paved for resurfacing purposes in New York City. So, incorporation of glass waste in the hot Asphaltic mixture is not a new idea (Salem et al., 2017). The Effect of Crushed glass was evaluated by numerous researchers in different layers types such as base layer (Arnold et al., 2008), binder layer (Nichols and Lay, 2002),and the surface layer (Shafabakhsh and Sajed, 2014) .

Several researchers studied crushed glass effect on HMA performance, and conducted that environmental and cost-saving aspects could be achieved when using waste glass. Arabani (2011) reported in his study the effect of waste glass cullet on dynamic behavior of asphalt mixes for binder course gradation. He used crushed glass culled as fine aggregate with maximum size of 4.75 mm with different percentages of substitution in the mix. He conducted that 15% of glass aggregate satisfied the criteria of Marshall Stability and ITSM since it offers higher angularity of particles than version aggregate, as can be seen in Figure (2-17). Moreover, glass in asphalt mixtures reflects less temperature sensitivity compared to control mixes in case of dynamic behavior using ITSM test. He further stated that mixtures with glass aggregate in addition to 2% lime as mineral filler presented higher mix stiffness.

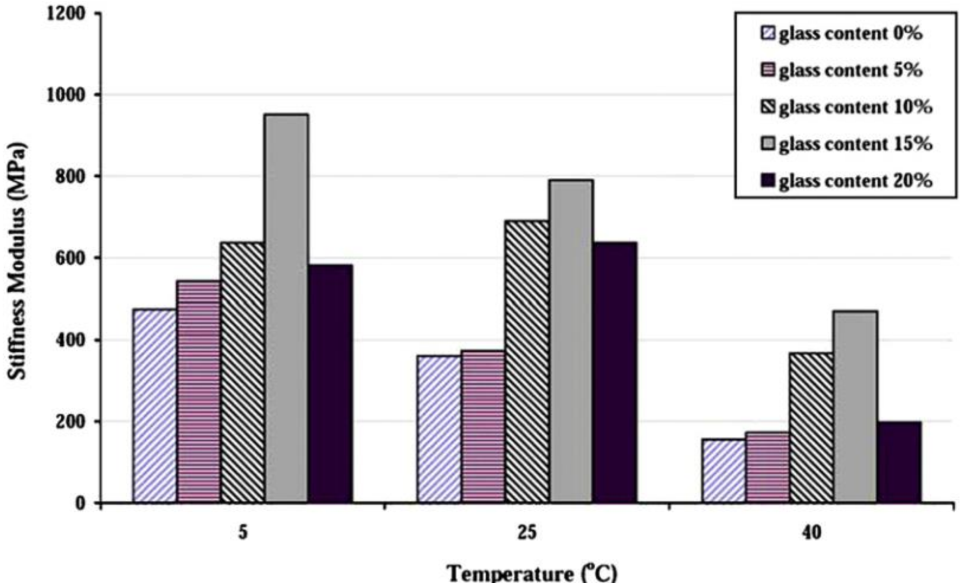
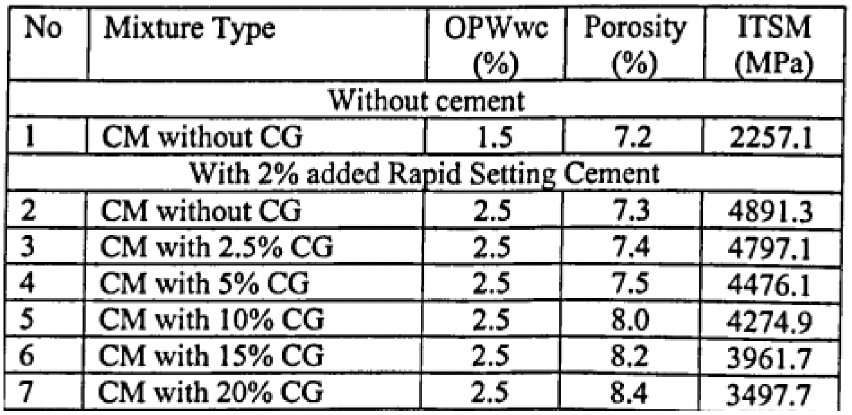


Figure 2.17 Effect of temperature and glass aggregates content on HMA stiffness modulus(Arabani, 2011).

Recently, a study conducted by Salem et al. (2017) were waste glass was used as aggregate with a maximal size of 2.36 mm. They concluded that 10% of waste glass could be used as optimal substitution percentage in HMA, and higher strength could be achieved if an anti-stripping agent used, such as lime or OPC. They further stated that utilizing waste glass in asphalt pavement reduces pollution and environmental problems.

In case of utilizing waste glass aggregate in CMA, the matter still confused and its behavior undiscussed. No studies have been found on such matter, except that one reported by the Thanaya in his PhD thesis in 2003. Thanaya (2003) investigated the effect of multiple wastes in CMA. He used waste glass as a fine aggregate with percentages 2.5%, 5%, 10%, 15%, and 20% in addition to using rapid setting cement as mineral filler in CMA. He found that such combination in incorporation reflects acceptable mechanical properties of CMA. He stated that increasing glass content led to increasing porosity (but still meet the specifications) and the ITSM showed acceptable results, as can be seen in Table (2.1). He further stated that the replacement of waste glass up to 30% resulted in a mix of 7.2% porosity and 4851.8 MPa stiffness.

Table 2-2 Effect of incorporation crushed glass in addition to 2% rapid setting cement on CBEM (Thanaya, 2003).



No	Mixture Type	OPWwc (%)	Porosity (%)	ITSM (MPa)
Without cement				
1	CM without CG	1.5	7.2	2257.1
With 2% added Rapid Setting Cement				
2	CM without CG	2.5	7.3	4891.3
3	CM with 2.5% CG	2.5	7.4	4797.1
4	CM with 5% CG	2.5	7.5	4476.1
5	CM with 10% CG	2.5	8.0	4274.9
6	CM with 15% CG	2.5	8.2	3961.7
7	CM with 20% CG	2.5	8.4	3497.7

The same researcher with others (Thanaya et al., 2009) investigated the performance of CBEMs with partial substitution of virgin aggregate and fly ash as a mineral filler. They used 68% limestone aggregate and 32% crushed waste glass as coarse aggregate, 70% quantize and 30% crushed glass as fine aggregate in composition with 4% fly ash filler. They concluded that such composition increases mixture stiffness compared to conventional CBEM, a slight reduction in mixture air void, higher workability, and lower compaction effort required when compared to HMA.

2.5.6 Limitations and Considerations of Using Waste Glass in Asphaltic Mixtures

Attention should be paid while using waste glass as secondary aggregate in asphaltic mixtures. Recommendations have restricted to use glass aggregate with maximum particle size up to 4.75mm for the surface layer. In other words, the glass should be used as fine aggregate in surface asphaltic mixtures (Anochie-Boateng and George, 2016).For base course, the specification has allowed using maximum glass aggregate particle size up to 15.3mm due to larger layer thickness of base course compared to surface layer. Also, for durability purposes, glass material is considered as brittle material and using it with particles larger than 4.75 mm are expected to fracture during handling. Using glass particle sizes as fine aggregate may help to avoid mixture potential raveling and stripping (Chesner et al., 1998).

A study revealed that when using glass in asphaltic mixture as fine aggregate, the new mix should behave like conventional one, where particles with sizes more than 4.75 mm may reduce mixture performance in term of stripping and raveling (Salem et al., 2017), and best performance can be achieved (Flynn, 1993).

Glass material has been known having low porosity, which may cause a critical problem when used since no binder absorption could be observed. Therefore, an anti-stripping agent is necessary to be dosed while manufacturing glassphalt mixtures since glass particles have hydrophilic nature. Studies reported that addition of lime or OPC could avoid stripping problems.(HCM, 1993, Salem et al., 2017, Wu et al., 2004a, Maupin Jr, 1998, Hughes, 1990)

When the glass is well crushed, it is expected to have high angular shape and high friction angle (approximately 50), which considers as a good feature and may help to increase lateral stability (Chesner et al., 1998).

In term of frictional properties, previous studies have shown that skid resistance of glassphalt hot mixtures are within the requirements of testing limits when mix glass particle size is equal or smaller than 4.75 mm. whereas larger particles sizes more than 19mm may cause smooth asphalt surface and can reduce skidding (Arnold et al., 2008).

In case of light reflection, recommendations have restricted max glass aggregate percentage to be no more than 15%. Otherwise, light reflection problems may be became a series problem due to the appearance of asphalt with noticeable glare (Chesner et al., 1998).

Most of the previous works data results recommended using glass with max 4.75mm in particle size. The percentage of optimum glass content in asphaltic mixtures falls between 5%-20% from mix total weight (Arabani, 2011, Airey et al., 2004, Salem et al., 2017). Others studies reported that incorporating 10-15% crushed glass may obtain satisfactory performance for wearing course layer (Chesner and Petrarca, 1987, Chesner et al., 1998, Nash et al., 1995, Anochie-Boateng and George, 2017).

2.6 Effect of Air Voids Content on CBEM Properties

As mentioned in Chapter One, one of the most critical properties that CMA suffers from is the higher generation of air voids in compacted specimen compared to HMA. The formation of voids backs to the high water content in the mix during compaction (water of coating plus water of asphalt emulsion), which leads to prevent the backing of the solid materials, then when this water evaporates later on, left the mix with high air voids. Air voids content has a direct effect on the overall mix properties, and as a result, researchers focused their studies on such matter to improve CMA properties.

Numerous studies investigated the effect of air voids content on asphalt pavement performance. Air voids content has a direct effect on mix stiffness modulus (Tayebali et al., 1994). Also, the value of air void is limited by road engineers to not less than 3% to avoid permanent deformation problems at pavements early life, as well as to prevent the entering of water and air which both reduce mixture durability. Another study conducted by Suparma (2001) stated that asphaltic mixtures with high air voids content are expected to have a higher risk of stripping. Thus, different research studies conducted to reduce such high level:

2.6.1 Increase Compaction Effort to Reduce Air Voids

A study investigated by Ibrahim (1998) to assess the effect of different compaction types on cold mixture performance. Three compaction methods types were investigated namely, Marshall Compactor, gyratory, and vibration compaction. He stated that the stiffness modulus significantly increased in term of vibrator compaction compared to other methods, and further compaction could reduce air voids content.

Thanaya (2007) had limited air voids content in CBEMs between 5%-10%, which could be achieved by Appling extra heavy compaction effort. He further stated that to achieve required volumetric properties, is necessary to consider the type of compaction method. In more detail, reducing air void could be reduced easily with increasing compaction effort.

Asphalt Institute (1997) reported that drying or aeration methods are recommended before compaction especially with mixture gradation contains a high amount of fine aggregates. Applying such method may results in cold mixtures with lower air voids content, higher density, and increase mixture strength compared to untreated mixes at same water content.

Oke (2011) stated that the mixing and compaction temperature is very important to produce lower air voids content in the cold mixture. In more detail, compaction of cold mixtures at temperature 32°C resulted in increasing mix strength and lowering air voids content compared to mixtures compacted at temperature of 20°C, as can be seen in Figure (2-18).

From other side, Khalid and Eta (1996) reported that the target air void is too hard to achieve even with increasing compaction effort due to excessive water content which tend to resist compaction forces by pore pressure. Also, Al-Busaltan (2012) remarked in this thesis, that although by increasing compaction effort the air void decrease, it still could not reach levels similar to HMA.

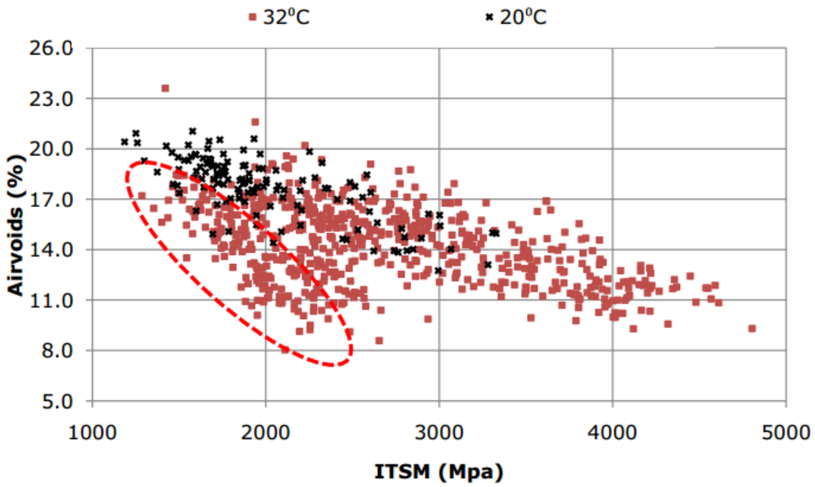


Figure 2.18 Effect of temperature of compaction and mixing on CBEM air voids and ITSM (Oke, 2011).

2.6.2 Utilization of Heating Energy in CMA Mixtures

Jenkins (2000) studied the possibility of producing bituminous mixtures as a temperature higher than the ambient and lower than 100°C, which termed the resulted mix as a half-warm mix. He reported that several advantages could be gained when heating mixture, such as increasing tensile strength, improve particle coating, and enhance durability.

Asphaltic mixes properties are directly affected by density and air voids content. Eggers (1990) reported in his study that preparing HWM at temperature 90°C can decrease air voids about 2% for each 42°C increment compaction temperature. Similarly, another study investigated by Jenkins (2000) who stated that a noticeable reduction in air voids content was observed when compacting at a temperature lower than 90°C, and the air voids may be reduced up to 30% when compacting at a temperature ranging between 45-90°C.

Lanre (2010) investigated the effect of compaction temperature on CBEMs specimens. He stated that compaction at 32°C resulted in higher stiffness and lower air voids compared to mixture compacted at temperature 20°C.

Also, compaction methods of CBEM specimens have a direct effect on enhancing density and reducing air voids. Jostein (2000) reported that that vibratory roller compactor resulted in higher density compared with static roller compactor, as can be seen in Figure (2-19)

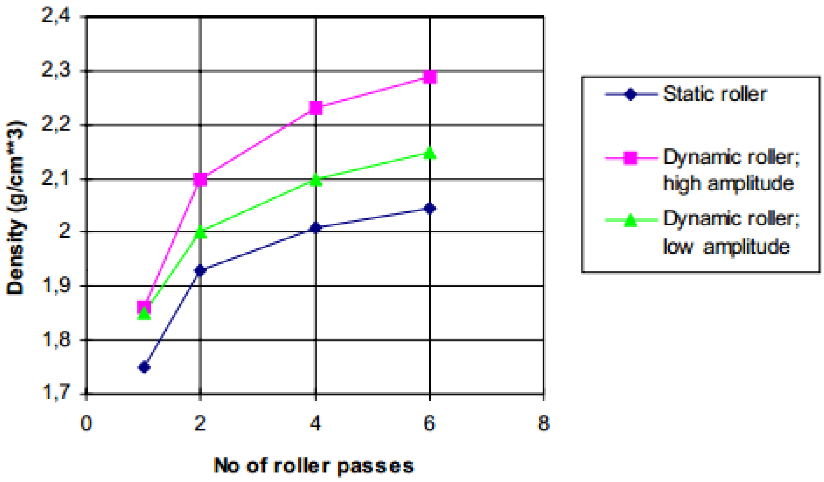


Figure 2.19 Effect of compaction method on CBEM density Jostein (2000).

2.6.3 Utilization of Microwave Heating Energy in CMA

Microwave technology has many advantages in road engineering applications. Besides it has been used in kitchens for more than 60 years ago. It has many advantages over conventional heating such as energy saving and accelerating heat as reported by Al-Busaltan (2012) and Thostenson and Chou (1999).

Such technology can penetrate substances and separate energy through overall material volume, which results in fast and uniform heating since energy is delivered directly to materials through interaction with electromagnetic filed (Thostenson and Chou, 1999).

In case of road engineering applications, Haque (1999) and Menéndez et al. (2010) reported that microwave technology can deal with carbon related materials such as bitumen and can process mineral materials. Also, pre-heating of bituminous mixtures using microwave can reduce the effect of bitumen oxidation during the heating process. Furthermore, Jeon et al. (2012) reported that microwave heating is very effective to destroy larger bitumen molecules and produce light liquid fractions.

Al-Busaltan (2012) investigated the possibility of enhancement cold bitumen emulsion, mixtures using microwave heating before compaction. He conducted that heating at temperature up to 100°C has significant effect on mixture engineering properties. Alternatively, applying microwave heating reduces mixtures porosity and enhance overall mix properties, i.e., superior properties could be obtained when CBEM heated in a microwave at full power levels with time 5 to 7.5 min, as cleared in Figure (2.20).

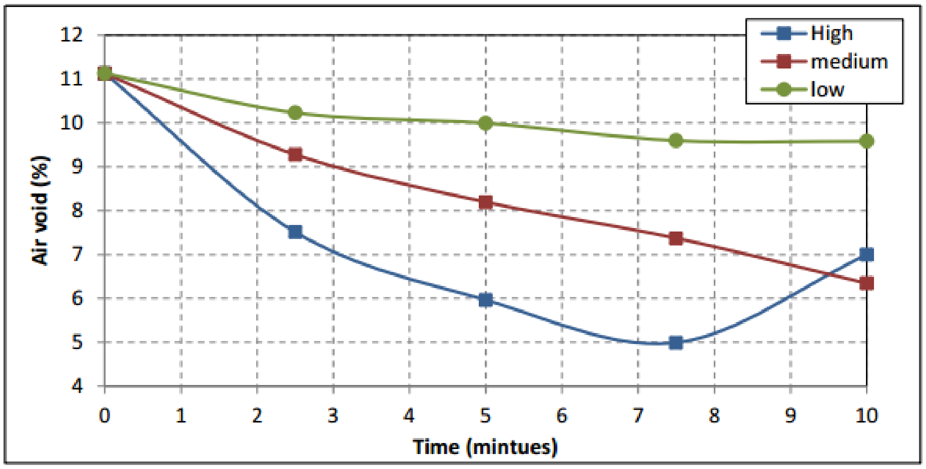


Figure 2.20 Microwave heating time vs. AV% content at different energy levels, (Al-Busaltan, 2012)

AL-Hdabi (2014) studied the effect of microwave heating on cold rolled mixtures. He found that such preheating at temperature 69°C after mixture post mixing process has a significant reduction in mixtures air voids content as can be seen in Figure (2.21). Also, it was found that such conditioning improves mix properties at an early life, and reduces mixture sensitivity to water damage compared to untreated mixes.

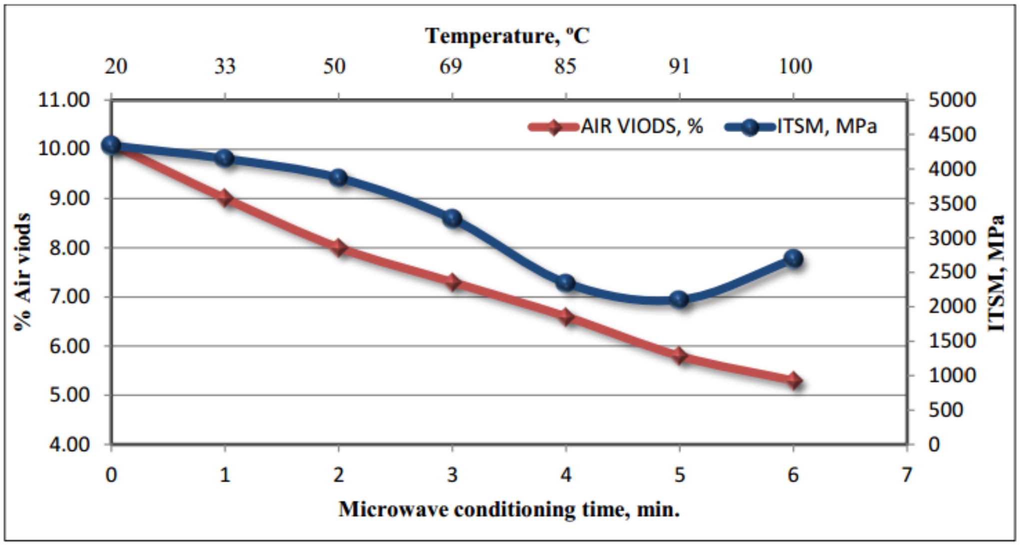


Figure 2.21 Effect of microwave heating time on CBEM air voids content, (AL-Hdabi, 2014)

2.7 Summary

From the extensive literature review that has been achieved, the following points can be highlighted

- Although HMA has a superior performance in terms of mechanical and durability properties, it still has a negative effect on the environment, safety, and can cause uneconomic issues.
- CBEM were introduced as promising alternative to HMA that may overcome such problems. However, it still has weak early properties if it is left without treatment or improvement. There are different ways to enhance CBEM, namely: by substituting virgin aggregates with other solid materials, or by using additives like polymer or fibers reinforcing, or by replacing conventional mineral filler with active one that produced naturally, or by-products.

Thus, it had been decided to sustain the current practice of CBEM technology with sustainable improvement approach in two stages proposed development. Firstly, evaluate the CBEM that have different percentages of municipal waste material (glass waste, as a case study). Secondly, further evaluation to the first stage one development by using low energy treatment; i.e. low energy heating in microwave. More details of such treatments will be revealed in the next chapters.

Chapter Three

MATERIALS, EXPERIMENTAL WORK, AND METHODOLOGY

3.1 Introduction

This chapter identifies all materials used, testing procedures for evaluation, and proposed CBEMs development methodology by comprising different municipal solid wastes and different preparation techniques.

3.2 Materials

In order to ensure the economic considerations and to sustain the local practice, all materials used in the research were obtained locally from Karbala, as much as it possible (except emulsion, as it does not produce locally). The materials selection was based on ensuring the compatibility with each other, and the wide availability.

3.2.1 Aggregates

Two types of aggregates were used in this study: virgin aggregates, and waste glass aggregates, as details in the next subsections.

3.2.1.1 Virgin Aggregates

Virgin aggregates were supplied from local quarries, which is located to the west of Karbala. They were crushed limestone aggregate with a degree of crushing exceed 90%. Virgin aggregate was sieved in the lab in order to meet the Iraqi general specification for roads and bridges GSRB (2003), in section R9, for dense-graded wearing course type IIIA. Table (3.1) and Figure (3.1) demonstrates the dense graded gradation used in the study.

3.2.1.2 Fine Glass Waste Aggregate (FGA)

The solid glass waste material was collected locally form municipal waste in Karbala city. Its resources are the disposed of useless of window glass, doors, and bottles. Many process were performed to reuse this waste as fine aggregate in the mixtures.

After collection of glass waste, separation process was made to eliminate colored glass, then, crashing process was performed to convert large glass pieces to small particles. Finally, sieving process was conducted to produce three gradation types, retained on sieve

No.8, 50, and 200 as recommended and specified in the specification. The gradation of glass waste was graded to meet fine aggregate particles size requirements. All particles are passing sieve No.4 and retained on sieve No.200. The fine glass waste aggregate (FGA) was used in CBEMs and HWBEM with different percentages of substitution to the virgin fine aggregate. Plate (3.1) illustrates the process of converting glass waste to FWGA.

Table 3-1 Aggregates gradation for surface layer based on GSRB requirements type IIIA. (GSRB, 2003)

Sieve size	**mm**	**%passing by weight**	**Used (Average)**
1	25	100	100
0.75	19	100	100
½	12.7	90-100	95
⅜	9.525	76-90	83
No. 4	4.75	44-74	59
No. 8	2.38	28-58	43
No. 50	0.3	5-21	13
No. 200	0.075	4-10	7

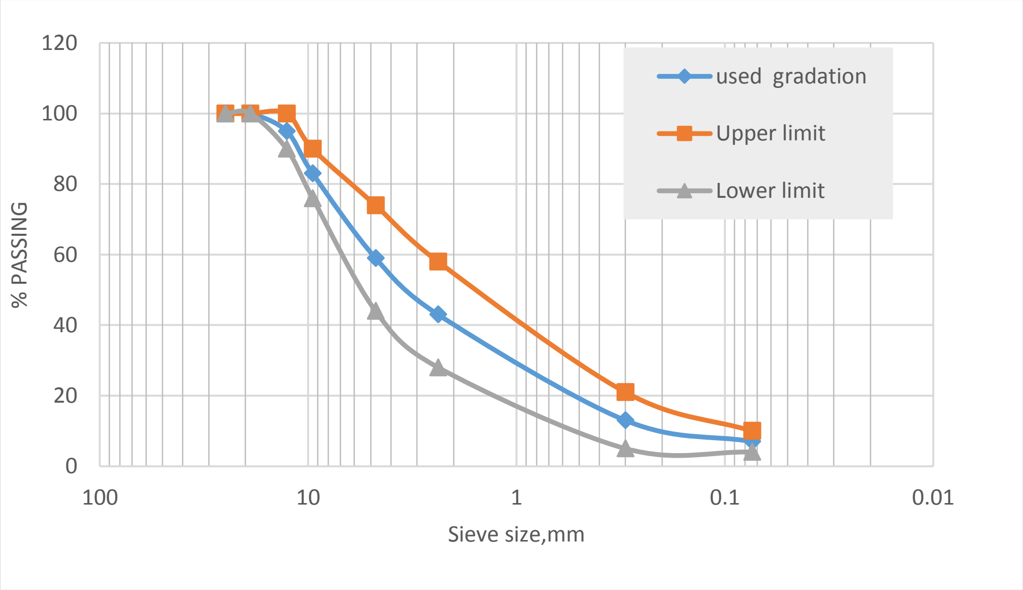


Figure 3.1 Particle size distribution of type IIIA dense graded wearing course used in the research work. (GSRB, 2003)

Plate 3.1 Process of converting waste glass to fine aggregate glass particles A-retained on sieve No.8, B-retained on sieve No.50, C-retained on sieve No.200.

3.2.1.3 Physical Properties of Virgin and Glass Aggregates

In this study, the crushed coarse and fine angular limestone aggregate, close to the whiteness were used for both coarse and fine aggregates. Table (3.2) illustrates the physical properties of coarse aggregate, which seems to be accepted according to the Iraqi general specifications for roads and bridges GSRB (2003) requirements.

Table 3-2 The physical properties of virgin coarse aggregates

Property	ASTM designation	Virgin Coarse Aggregate	GSRB Specification, (Surface coarse)
Bulk specific gravity, gm/cm^3	C127(ASTM, 2015c)	2.612	-
Apparent specific gravity, gm/cm^3	C127(ASTM, 2015c)	2.634	-
Bulk SSD specific gravity gm/cm^3	C127(ASTM, 2015c)	2.578	
Water absorption,%	C127(ASTM, 2015c)	1.370	-
Percent wear by los Angeles abrasion ,%	C131(ASTM, 2014b),T96	8.500	30% Max
Soundness loss by sodium sulfate,%	C88(ASTM, 2013c)	6.300	12% Max
Clay lumps,%	C142(ASTM, 2010b)	0.060	-
Flat and elongated particles,%	D4791(ASTM, 2010c),T89,T90	0.550	10% Max
Degree of crushing,%	---	94.0	90% min

The physical properties of the fine virgin aggregate and glass aggregate are listed in Table (3.3). The results of lab testing indicate that the properties of fine aggregate (i.e., virgin and glass waste) lies within acceptable ranges specified in GSRB of the Iraqi limitation.

Table 3-3 The physical properties of virgin and glass waste fine aggregates.

Property	ASTM & AASHTO Designation	Virgin Fine aggregate	Crushed Glass aggregates
Bulk specific gravity, gm/cm^3	C128(ASTM, 2015d)	2.630	2.486
Apparent specific gravity, gm/cm^3	C128(ASTM, 2015d)	2.650	2.517
Water absorption,%	C128(ASTM, 2015d)	1.890	0.481
Clay lumps , %	C142(ASTM, 2010b)	2.95	-

3.2.2 Filler Materials

The type and quantity of filler have an important role on the overall mixture performance and have a direct effect on mechanical properties for the dense-graded mix. Two types of fillers were used in this research; namely, Conventional Mineral Filler (CMF), and Ordinary Portland Cement (OPC) to recognize the role of filler in CBEM. Conventional mineral filler (CMF) can be obtained from the remaining powder that produced from the crushing process of the aggregates. The materials passing from sieve No.200 are used as CMF filler, which is very well known that such material filler types have no cementitious or it has inert properties; since no hydration processes will expect while using inert fillers. Table (3.4) illustrates the chemical and physical properties of CMF.

Table 3-4 The physical and chemical properties of OPC and CMF fillers

Physical		
Property	*Filler Type*	
	CMF	*OPC*
surface Area (m^2/kg)	223	345
Density (gm/cm^3)	2.650	2.981
Chemical		
SiO_2	81.89	25.410
Al_2O_3	3.78	2.324
Fe_2O_3	1.92	1.125
CaO	7.37	65.148
MgO	3.45	1.326
K2O	0.73	0.760
Na2O	0.19	1.714

The other type of fillers used in this research was OPC, which was supplied locally from Karbala Cement Plant. The OPC filler was well-known performance when added to asphaltic mixtures. It was used for both HMA and CBEMs. Table (3.4) identifies physical and chemical properties for used fillers.

Scanning Electron Microscopy (SEM) analysis for both fillers is illustrated in Plate (3.2). SEM was performed for different filler types to identify their morphology, which has the vital role in physical and chemical properties of the filler. It is worth to mention that the test results were taken from Ahmed (2017) thesis research work since the same materials were used in this study .

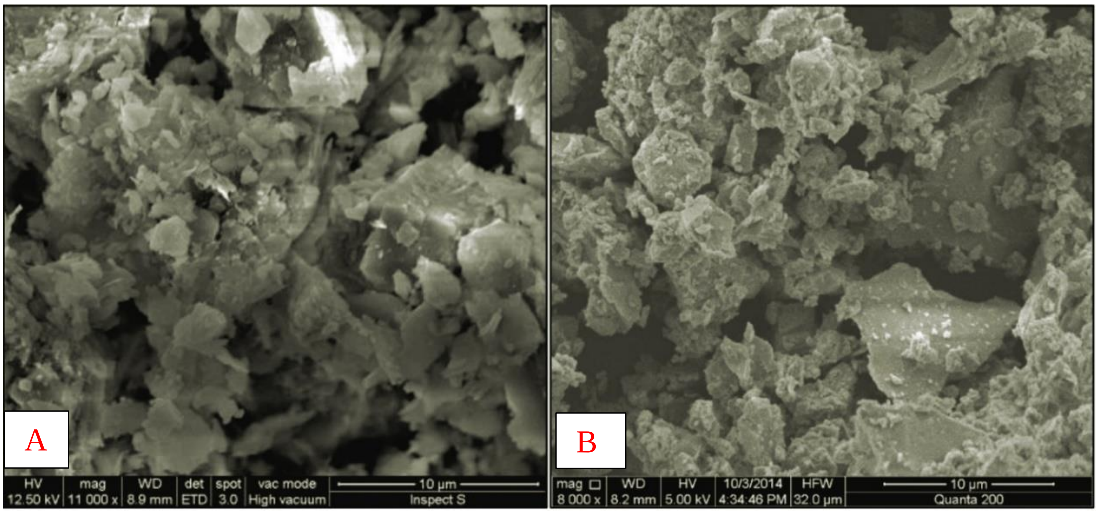


Plate 3.2 SEM analysis of the used fillers, A- OPC, B-CMF Ahmed (2017).

3.2.3 Bituminous Materials

For HMA, asphalt grade (40-50) was used that supplied from Al-Neasseria factory with properties described in Table (3.5). It is worth to comment that all tests were performed at University of Kerbala laboratories. The grade asphalt meets all the requirements of the Iraqi GSRB specifications.

Table 3-5 Properties of grade asphalt

Property	ASTM designation	Test results	GSRB requirements
Penetration,100 gm. ,25°C,5sec (1/10 mm)	D5 (ASTM, 2015b)	42	40-50
Specific Gravity, 25°C (gm/cm3)	D70 (ASTM, 2009a)	1.03	-
Ductility, 25°C , 5 cm/min (cm)	D113 (ASTM, 2007)	132	>100
Flash point, (°C)	D92 (ASTM, 2005)	310	>232
Softening point (°C)	D36 (ASTM, 2000)	47	-
Solubility in trichloroethylene, (%)	D2042 (ASTM, 2015e)	99.5	>99
After Thin Film Oven test			
Penetration of Residue (%)	D 1754 (ASTM, 2014a)	68.5	>55
Ductility of Residue, (cm)		65.3	>25

For bitumen emulsion material, it was supplied from a local market. It is a product of Henkel-Polybit Company under the commercial name “POLYCOAT”, as can be seen in Plate (3.3), with the properties illustrated in Table (3.6). Testing result of bitumen emulsion showed that it was a cationic bitumen emulsion type, which has a wide range of compatibility with aggregate, especially with the used one in this research. The used aggregate possess a negative charge on its surfaces and the used bitumen emulsion was positively charged. As a result, a strong compatibility will be established with a strong adhesion will be promoted. The bitumen emulsion was found to be very suitable for use in this research study.

Table 3-6 Properties of asphalt emulsion

Property	Specification, ASTM	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	55
Specific Gravity, gm/cm^3	D70(ASTM, 2009a)		1.02
Penetration, mm	D5(ASTM, 2015b)	100-250	215
Ductility, cm	D113(ASTM, 2007)	Min. 40	45
Viscosity, Rotational Paddle Viscometer 50 ℃ , mPa.s	D7226(ASTM, 2013b)	110-990	350
Freezing	D6929(ASTM, 2010a)	Homogenous, broken	Homogenous
Solubility in Trichloroethylene ,%	D2042(ASTM, 2015e)	Min. 97.5	97
Emulsified Asphalt/Job Aggregate Coating Practice	D244(ASTM, 2009b)	Good, fair, poor	good
Miscibility	D6999(ASTM, 2012a)		Non miscible
Aggregate Coating	D6998(ASTM, 2011)		Uniformly - thoroughly coated

3.3 Mix Design procedures

Different mix technologies need various mix design procedures. In this work, the most well-known design procedures were used. Of course, some modifications were achieved to be combatable with the local circumstances wherever it necessary is, as will be shown in the next subsections.

3.3.1 Design of HMA

The design method of Marshall was adopted to prepare the traditional HMA specimens, with five different asphalt content groups (3 replicates each trail). The materials that used were as mentioned previously, asphalt grade type (40-50) and aggregate gradation was based on Iraqi standard specification (GSRB) for surface layer (type IIIA), as described in Table (3.1). OPC filler type was only used to produce HMA specimens. Compaction effort was applied using Marshall Hammer with 75 blows each face. Specimens left to cool down before extraction from the mold, then they are ready for testing according to each testing procedures.

3.3.2 Design of CBEMs

The asphalt institute included two methods for CBEMs design, Hveem design method and Marshall design method. Hveem design method requires special equipment for testing which were not available at the local lab. On the other hand, Marshall method is a very well-known method. Therefore, The design procedure of Marshall method as stated in Asphalt Institute (1989) for CBEMs design was adopted. No local standard criteria for CBEMs design, the adopted Marshall design procedure was modified to meet Iraqi standards. As an example, the GSRB design criteria for surface course gradation was adopted to meet the requirement of Iraqi conditions.

3.3.2.1 Marshall Design Procedure of CBEM

The following procedure was performed for CBEM specimens design:

- Determination job mix of aggregate

The dense aggregate gradation of the Iraqi GSRB (2003) for surface layer (type IIIA) was adopted with maximum size 19 mm since such gradation provides sufficient mechanical interlock and high mastic performance. No change of the adopted aggregate gradation was made during the research, it was used for both HMA CBEMs design. It has to mention that the adopted gradation was designed using Fuller formula.

- Determination of Initial Residual Bitumen Content (IRBC)

The asphalt institute recommended to perform equivalent centrifuge kerosene test for determination of IRBC. If no equipment is available for such test, an empirical formula was suggested by MS-14 (Asphalt Institute, 1989) for dense graded mixes described below:

$$P = (0.05A + 0.1B + 0.5C) * 0.7 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 3-1}$$

Where:

P = amount of asphalt emulsion based on weight of graded mineral aggregate, %,

A = mineral aggregate retained on sieve (No.8), %,

B = mineral aggregate passing sieve (No.8) and retained on (No.200), %,

C = mineral aggregate passing (No.200), %.

Initial Emulsion Content (IEC) value was determined by dividing P by the percentage of the residual bitumen content in the emulsion, which was determined as 55%

$$IEC = \frac{P}{X} \quad \text{.......... Equation 3-2}$$

Where:

IEC = Initial Emulsion Content by mass of dry aggregate, %.

X = residual bitumen content of the emulsion.

Based on the adopted gradation, the P value was 6.95% based on equation (3.1), and the IEC was 12.63% based on Equation (3.2).

It is necessary to comment that the resulted value as mentioned was initial and does not represent the optimum residual bitumen emulsion (which will describe in the next step).

- Coating test

The next step after determination of IEC is to perform coating test or binder compatibility test to estimate the quantity of the required added water corresponding to best aggregate coating. Five mix trials were made with different water content, and with 0.5 % increment. Asphalt Institute recommended using 3% water content initially. The selected optimum water was 3.5% for OPC incorporated mixtures, 3% for mixtures with 50% OPC filler, and 2.5% for CMF incorporated mixtures.

All these percentages were selected based on visual estimation based on the fact that mixture with lowers moisture state should not be too stiff due to low water content or be too sloppy due to high added water, as can be seen in Plate (3.4).

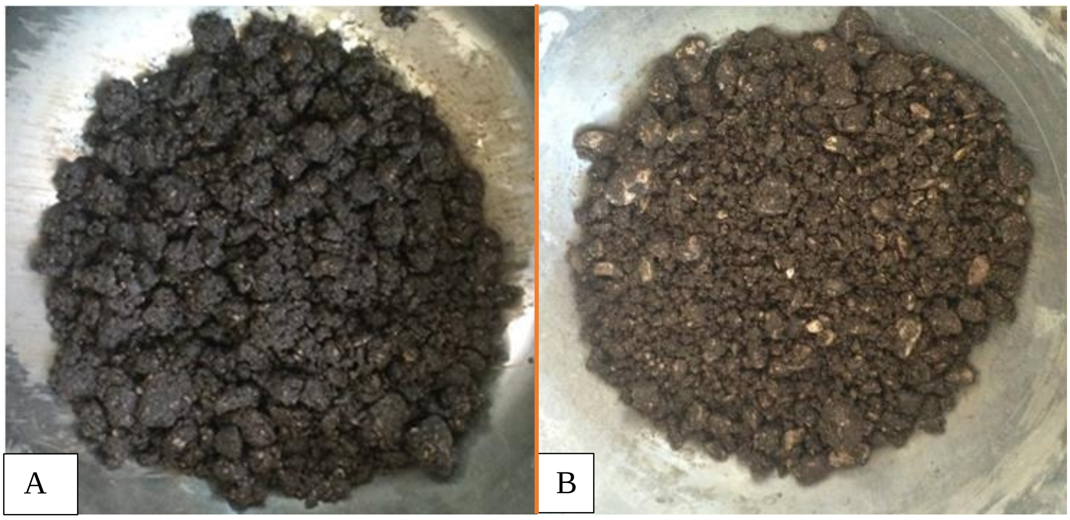


Plate 3.3 Effect of pre-wetting water content on aggregates coating, a: Sloppy mixture, b: stiff mixture

- Determination of Optimum Bitumen Emulsion Content (OBEC)

Based on what mentioned in the previous step, Marshall specimens were prepared using the value of IEC that previously determined in step1 (12.5%) as a middle value, with two percentage points on each side to determine OBEC. Five trials mix group were made with 0.5% increment in each step, and three specimens for each group. The selected OBEC was corresponding to best mixture mechanical properties. The resulted values of OBEC were varied with a variety of filler type within mixtures.

- Determination of total liquid content at compaction (TLC)

TLC is the summation of optimum added water for coating and optimum emulsion content resulted from the total liquid content. It is necessary to mention that the resulted value seems to be higher than the value of optimum total liquid content at compaction. Therefore, mixture should be exposed for drying by either leaving mixture for short time period or applying air van to ensure getting better mechanical properties.

3.3.2.2 Mixing Procedure for CBEM Components

Aggregate coating has a significant effect on CMA mixture performance. Consequently, considering best coating value is necessary during mixture design. Several trial mixes were made for estimating best pre-wetted water. First, all aggregates types with filler added to gather in mixing container, followed by water addition with the specific amount (3% as an initial amount suggested by Asphalt Institute (MS-14), after that, the initial quantity of emulsion was added and mixing is done manually using a spatula for maximum time of 2-3 min as recommended. In case of using the automatic electric mixer, it has been observed that mixture was suffered from segregation as fine materials are still uncoated at the bottom of the container. Therefore , a mixing procedure as recommended by Thanaya (2003) was adopted, which stated to mix course and fine aggregate with filler in dry condition; then the same composition is remixed after addition of water. Finally, asphalt emulsion is added and then mixed again using an automatic electric mixer. The previous procedure for coating test gave aggregate coating value more than 50% for different types of aggregate used.

3.3.2.3 Compaction

In this research, the compaction method adopted in this research used Marshall Hammer by applying 75 blows each face to simulate heavy traffic load. Thanaya (2003) stated that applying heavy compaction effort resulted in 10%-15% target porosity of specimens. Also, dense graded bitumen emulsion mixture still suffers high porosity even with increasing compaction effort.

It has to mention that during compaction process, it has been noticed an amount of liquid squeezed out from Marshall mold and varied based on the amount of total liquid content. This value was estimated approximately about 5-10% of total liquid content.

3.3.2.4 Curing Protocols for CBEM

In general, CBEM requires a long time to reach required design strength, since it has well known that the mechanical characteristics of CBEMs is time dependent Al-Busaltan (2012). In order to accelerate mixture strength, researchers have adopted several protocols for CBEM curing. There are two common protocols used by most of the researchers as illustrated as follows:

1- To simulate mixture strength after 7-14 days in place curing (normal curing), CBEM specimens were left in the mold for 24hr at lab temperature, followed by 24hr in the oven at 40°C, as recommended by Jenkins (2000). Such protocols was adopted for Marshall Test, IDT test, and creep compliance test. Plate (3.5) illustrates specimens under curing protocol. Such curing protocols has adopted by several researchers namely,(Thanaya, 2003, Al-Busaltan, 2012, AL-Hdabi, 2014, Dulaimi, 2017). Adopting a normal curing temperature in this research will simulate the production, compaction and placing of such mixtures in field conditions and will also avoid any premature ageing of the binder (Ojum, 2015b)

2- To simulate full strength of mixture (full curing), specimens were left for 24hr in the mold at lab temperature, then conditioned in the oven for 14 days at 40°C. As recommended by Thanaya (2003). Such protocols were adopted by Al-Hdabi et al. (2014a) and Dulaimi et al. (2017b) for wheel track test specimens as can be seen in Plate (3.12).

3- Further, Serfass et al. (2004) developed a curing protocol for CBEM. The method included exposing specimens for 14 days at 35°C and 20 humidity to simulate site conditions after 1-3 years.

Plate 3.4 Preparation and curing of Marshall CBEM specimens

3.3.2.5 CBEM Volumetric Properties

(Asphalt Institute, 1989) in MS-14 recommended to apply the following equation procedure in case of mixture volumetric analysis (air voids, voids in mineral aggregate, voids in total mix, and void filled with bitumen):

$$G = \frac{D}{F-E} \quad \ldots\ldots \quad \textit{Equation 3-3}$$

$$G_d = G \times \frac{(100+A)}{(100+A+K)} \quad \ldots\ldots \quad \textit{Equation 3-4}$$

$$K\,\% = \frac{\textit{mass of water,gm}}{\textit{mass of dry mixture,gm}} * (100+A) \quad \ldots\ldots \quad \textit{Equation 3-5}$$

$$V.M.A\,\% = \left[\left(\frac{100+A+K}{G} - \frac{100}{C}\right) \div \left(\frac{100+A+K}{G}\right)\right] \times 100 \quad \ldots\ldots \quad \textit{Equation 3-6}$$

$$V.T.M\,\% = \left[\left(\frac{100+A+K}{G} - \frac{100}{C} - \frac{A}{B}\right) \div \left(\frac{100+A+K}{G}\right)\right] \times 100 \quad \ldots\ldots \quad \textit{Equation 3-7}$$

$$\textit{Air Voids}\,\% = V - \left[\left(\frac{K \times 100}{L}\right) \div \left(\frac{100+A+K}{G}\right)\right] \quad \ldots\ldots \quad \textit{Equation 3-8}$$

$$V.F.B\ \% = \frac{V.M.A\ \% - V.T.M\ \%}{V.M.A\ \%}$$ ……………………………………………………..Equation 3-9

Where:

G_d = dry bulk specific gravity

G = bulk specific gravity

K = water content at testing

D = mass of specimen in air, gm

E = mass of specimen in water, gm

F = mass of specimen in saturated surface-dry (SSD) condition, gm

A = bitumen residue as percentage of dry aggregate mass

B = specific gravity of bitumen

C = apparent specific gravity of aggregate

L = specific gravity of water.

3.3.3 Design of HWBEM

The design of HWBEM includes the same steps mentioned in the design of CBEM, but with one modification, where loose mixture after mixing was subjected to microwave heating at a certain time after determination optimum time that reflects best properties before compaction, Plate (3.6) illustrates such heating process. Compaction, mixing, and curing are the same as what mentioned in CBEM.

Plate 3.5 CBEM loose mixture subjected to microwave heating energy

3.4.1 Marshall Testing Criteria

Marshall Test is a common well-known empirical destructive test, which measures mixture resistance to plastic deformation and flow. In this research, Marshall test was performed for both HMA and CMA, according to ASTM D6927 (ASTM, 2015a).

There is no large difference between HMA and CBEM Marshall test, only in specimens curing before running the test as cleared in table (3.7).

Table 3-7 Marshall Test condition based on ASTM D6927

Item		Range	Used for HMA	Used for CBEM and HWBEM
Asphalt temperature ℃		150−165	150	Lab temperature
Aggregate heated ºC		170	170	No heating, but pre-wetting with specified amount of water
Loose Mix temperature, C		130-180	140	25°C for CBEM 91°C for HWCBEM
Number of required specimens		3	3	3
Rate of load application mm/min		50 ± 5	51.3	51.3
Measuring device accuracy		Min. 50 N	0.001	0.001
Test temperature ºC		60 ± 1	60	60
Specimen diameters mm		101.6-101.7	101.6	101.6
Specimen thickness mm		63.5 ± 2.5	vary	vary
Compaction		Marshall 75x 2	75x2	75x2
Curing		24hr in mold at Lab	24 hr. at lab temperature+ 24hr in oven at 40 °C	24 hr. at lab temperature+ 24hr in oven at 40 °C
Specimen conditioning, min	water bath	30-40	30 min.	30 min.
	in oven	120−130	Not used	Not used

For HMA, prepared specimens were followed the traditional procedure for the determination of optimum bitumen content for wearing course by inducing five criteria, which are: stability, flow, air voids content, voids in mineral aggregate, and voids filled with bitumen. In brief explanation way, five group sets with each consist of 3 specimens were prepared with different asphalt content for each group and with 0.5% increment step ranging from 3.5% to 5.5% from total mixture weight. Then, specimens subjected to curing protocol by leaving the specimen to cool down after compaction by Marshall Hammer (75 blows each face to simulate heavy traffic load). After that the specimens were de-molded using manual extractor jack. Finally, specimens were subjected to 30-40 min in water path at 60 ºC to be ready for testing.

It is interesting to say that a load-deformation computer recorder device in conjunction with a load cell and linear variable differential transducer (LVDT) and of accuracy reaching to 10^6 for LVDT flow measurement was used for Marshall testing.

The optimum bitumen content was found to be 4.65%, and the selection based on the Iraqi GSRB (2003) specifications, which described in Appendix (A). Table (3.8) refers to Marshall testing requirement according to Iraq specifications (GSRB, 2003).

Table 3-8 GSRB limitation for surface layer, section R9 (GSRB, 2003)

property	GSRB Requirements
stability, Kg	>800
Flow, 1/10mm	2-4
Air Void, %	3-5
Retained strength, %	>70
VMA, %	>14

3.4.2 Indirect Tensile Strength Test (IDT)

Numerous researchers used Indirect Tensile Strength test (IDT) as a basic test procedure to measure the ability of asphaltic mixtures to resist tensile cracks failure. In a simple way, Marshall specimen is subjected to compression loading by two strips across the specimen's diameter until reaching failure according to ASTM D6931(ASTM, 2012b), as can be seen in the setup cleared in Figure (3.2).

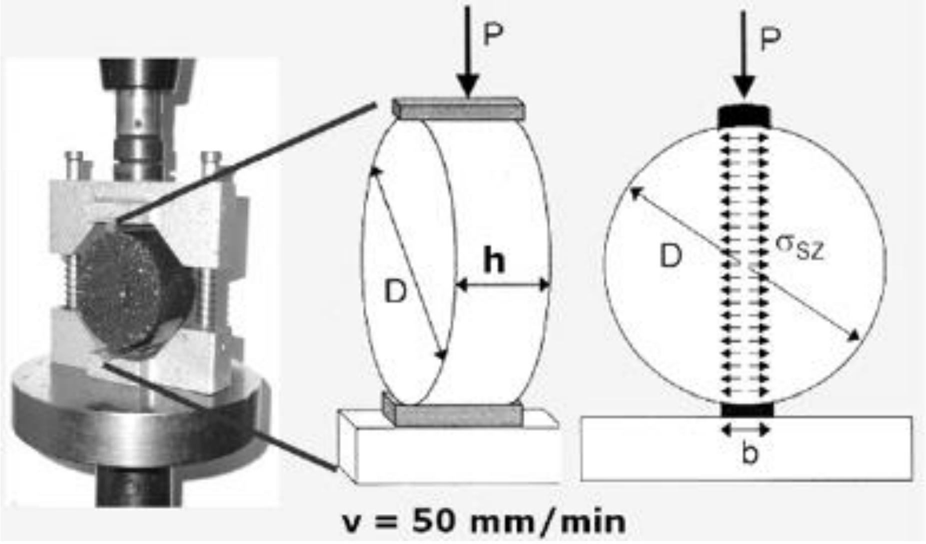


Figure 3.2- Indirect tensile test stresses mode under diametrical applied load

It is believed that in such loading condition, bi-axil stresses shall be distributed along specimen’s diameter resulting in tension stresses and compression stresses. Test configuration can be seen in Plate (3.7), and Table (3.9) demonstrates the test protocol for HMA, CBEM, and HWBEM.IDT can be calculated using Equation 3-10 (ASTM, 2012b):

$$ITS = \frac{2P}{\pi.D.t} \quad \text{……………………………………………………} \textit{Equation 3-10}$$

Where:

ITS = indirect tensile strength, KPa
P = maximum load, N
t = specimen height immediately before test, mm
D = $specimen\ diameter$, mm

Table 3-9 IDT test conditions

Item		ASTM D6931	Used for HMA	Used for CBEM and HWBEM
No. of specimens		3	3	3
Rate of loading, mm/min		50 ± 5	51.3	51.3
device accuracy		Min. 50 N	0.001 N	0.001 N
Test temperature, °C		25 ± 2	25 ± 2	25 ± 2
Specimen diameters, mm		101.6, 150	101.6	101.6
Specimen height for selected diameter, mm		50.8-65.5	unspecified	unspecified
Compaction(Marshall Hammer)		75 blow each face	75 blow each face	75 blow each face
Specimen conditioning before test	Water Bath	30-40 min.	Not used	Not used
	Oven dry	120-130 min.	120 min.	120 min.
Curing		…….	24hr in mold at lab temperature	24hr at Lab temperature+24hr. in oven dry at 40 C

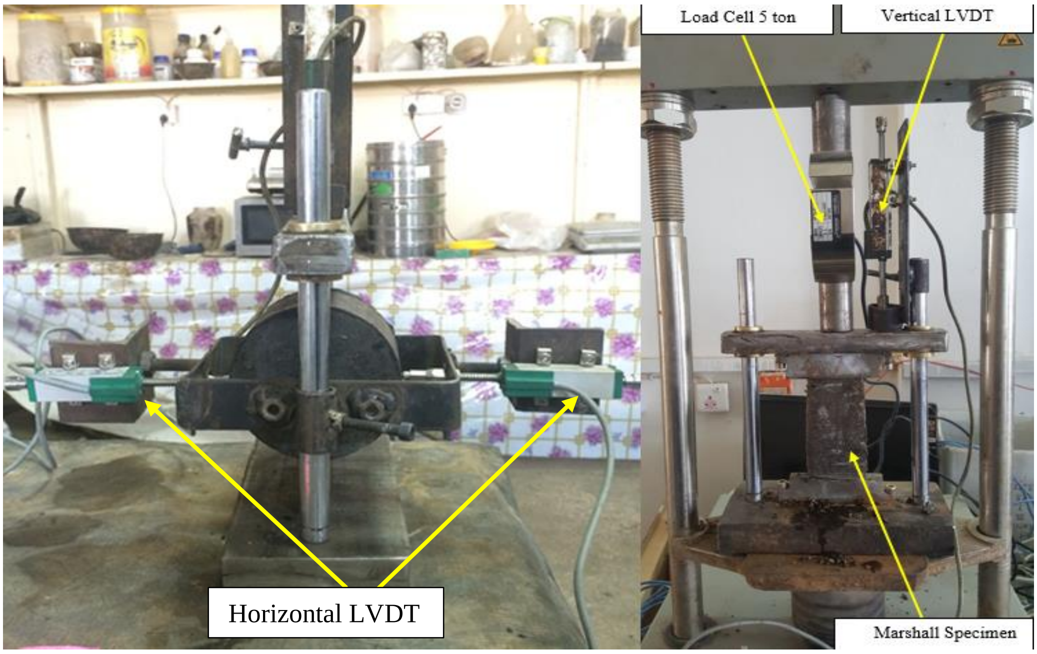


Plate 3.6 Indirect tensile strength equipment

3.4.3 Creep Compliance Test (CC)

Creep compliance test is used to examine how crack develops in the asphaltic pavement and propagate with time. It is time-dependent strain per unit stress. It considers as a primary input parameter for thermal cracking analysis or low temperature cracking in term of empirical mechanistic pavement design method. However, it is also used to indicate the ability of mixture to resist crack propagation. Table (3.10) illustrates the test conditions under specification. Equation (3.11) describes the determination of creep compliance according to (AASHTO, 2007) T322 specifications:

$$D(t) = \frac{\Delta X \times D_{avg} \times b_{avg}}{GL \times P_{avg}} \times C_{Cmpl} \text{ ....} \textit{Equation 3-11}$$

Where:

ΔX = trimmed mean of the horizontal deformations,

Davg = average specimen diameter,

Bavg = average specimen thickness,

Pavg = average force during the test,

GL = gage length

C_{cmpl}= creep compliance parameter at any given time, computed as:

$$C_{Cmpl} = 0.6345 \times \left(\frac{X}{Y}\right)^{-1} - 0.332 \text{ ....} \textit{Equation 3-12}$$

Where:

X/Y is the ratio of horizontal to vertical deformation, taken at mid testing time.

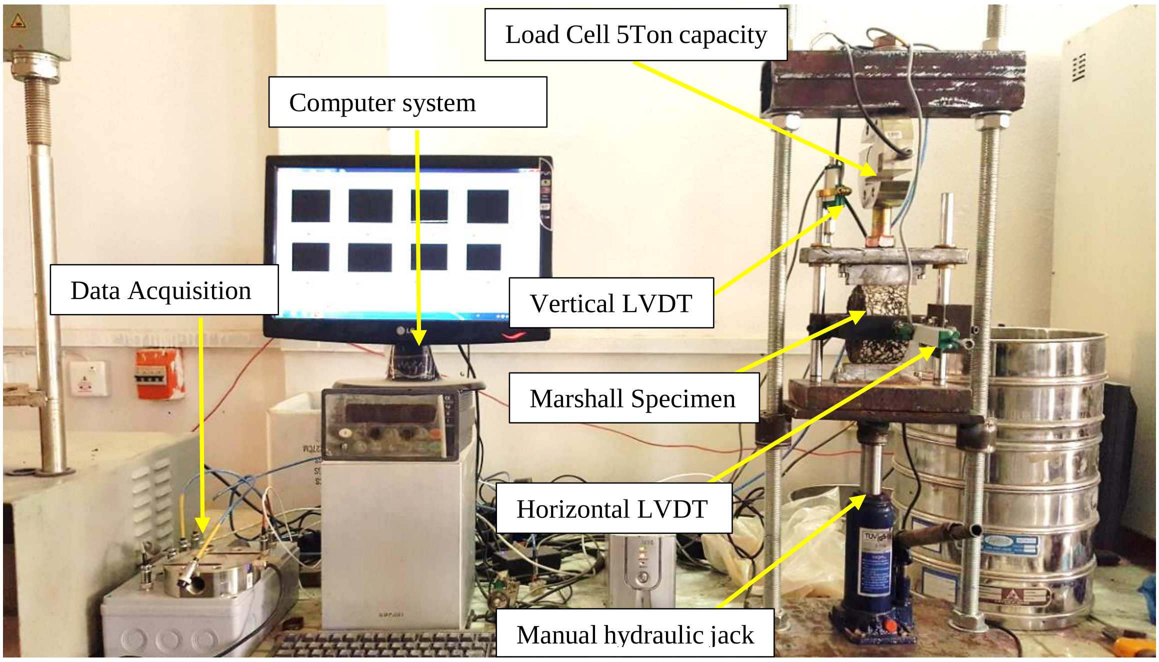
The C_{cmpl} factor should be limited between ranges as listened the following Equations:

$$\left[0.704 - 0.213\left(\frac{b_{avg}}{D_{avg}}\right)\right] \leq C_{Cmpl} \leq \left[1.566 - 0.195\left(\frac{b_{avg}}{D_{avg}}\right)\right] \ldots\ldots\ldots\ldots \text{Equation 3-13}$$

Table 3-10 Test conditions of creep compliance

Item	Typical value based on AASTHO T322	Used conditions
No. of specimens	3	2
Ram movement (vertical) mm/min	12.5	10
device accuracy	Min. 5 N	0.001N
Frequency rate , Hz	1 -10	High rate reach to 1000
Applied load in term of horizontal deformation, mm	0.00125-0.0190	Variable within range
Testing time, sec	100 ± 2 or 1000±20.5	100 ± 2
Test temperature, ºC	0 ,-10 ,-20 °C	0
Specimen diameter, mm	150±9	101.6
Specimen height, mm	38-50	50±10
Compaction (Marshall Hammer)	unspecified	75 blow each face
Specimens conditioning (oven dry)	120- 130 min	120 min

Although creep compliance test recommended using specimen 150 mm in diameter, Marshall specimens with diameter 101.6 mm were prepared since no equipment available to compact such diameter size. Another modification on the test was the gauge length, which horizontal deformation was taken around the diametrical plane (101.6 mm) instead of 38 mm. Also, it has to mention that load was applied using a manual hydraulic jack and controlled perfectly by hand to produce a constant stress with accuracy ±2% from the total applied load. The applied load was sufficient to produce horizontal deformation within range of 0.00125 mm to 0.019 mm as recommended to keep specimens strain within linear viscoelastic limits. The system was connected to data acquisition which converts LVDT sensors and load cell signals to a computer with high-frequency rate reach to 100,000 reading per second. Data were logged to an excel file after test finish and then ready for processing. Plate (3.8) clarifies CC test configurations. The test was performed at 0°C temperature, where specimens were stored in a freezer for 2 hr. prior to test, as can be seen in Plate (3.11). On the other hand, it has noticed that cold mix asphalt has lower temperature susceptibility effect compared to HMA.



Load Cell 5Ton capacity

Computer system

Data Acquisition

Vertical LVDT

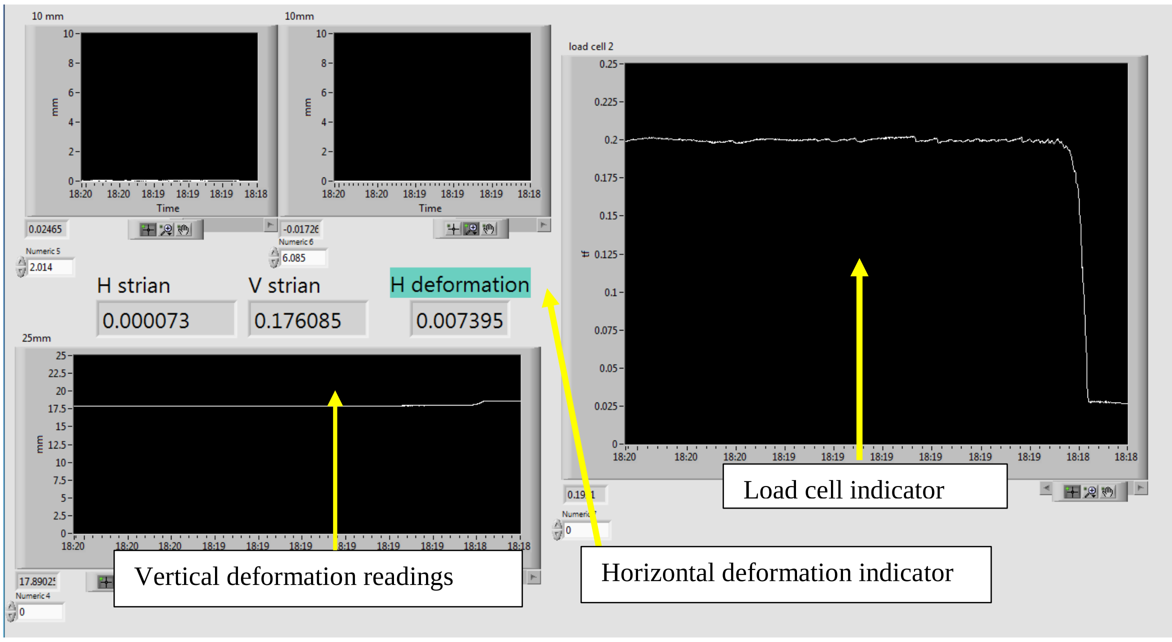
Marshall Specimen

Horizontal LVDT

Manual hydraulic jack

Plate 3.7 Creep compliance testing device

Creep compliance test package was programmed with Lab view as shown in Plate (3.9). The screen clears loading indicator box in ton, vertical deformation curve, and the two horizontal LVDT data at the top left of the screen. Load control was easy after several trails were made for practicing before test to ensure load error within limitation (±2% from applied load) as can be seen in Figure (3.3).



0.02465

Numeric 5 2.014

-0.01726

Numeric 6 6.085

H strian 0.000073

V strian 0.176085

H deformation 0.007395

17.89025

Numeric 4 0

0.19.1

Numeric 7 0

Load cell indicator

Vertical deformation readings

Horizontal deformation indicator

Plate 3.8 Screen capture of used creep compliance with Lab view program package

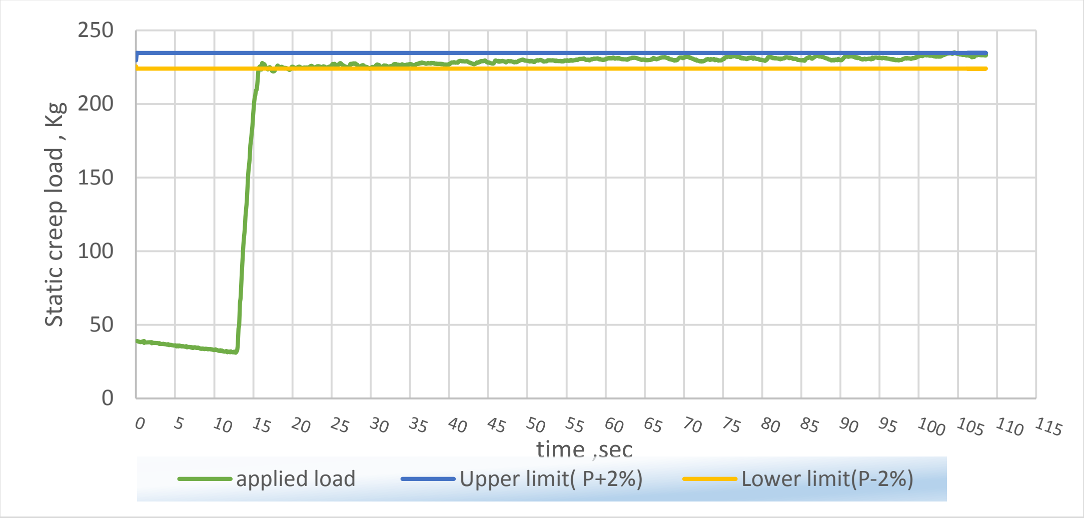
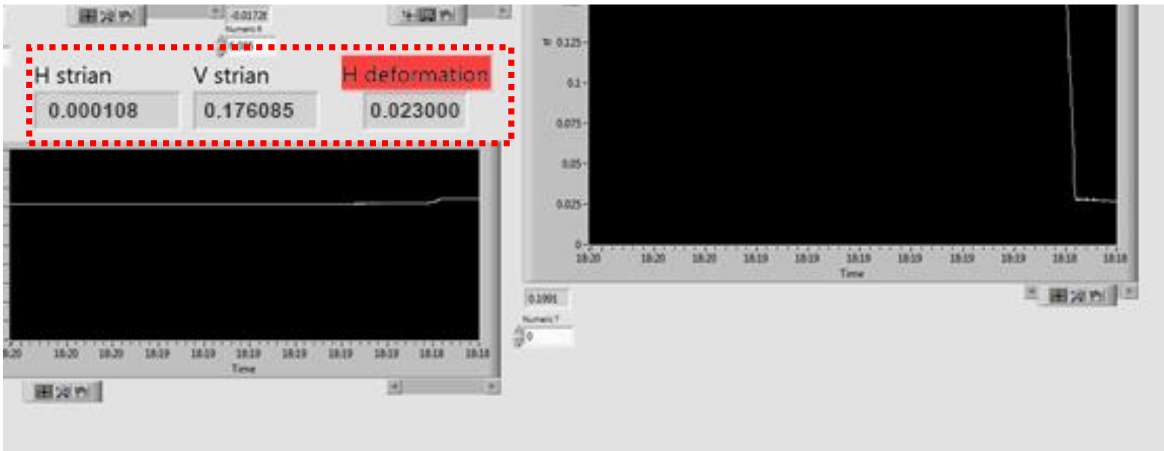


Figure 3.3 Manual static applied load for creep compliance test for HMA

Also, a problem related to equipment electrical noise has been observed, which was another reason for repeating the test several times to get acceptable results. As cleared in the same Plate (3.8), a horizontal deformation indicator was another challenge to put its value within limits. So, when the value is below the minimum limit (0.00125 mm), the color of horizontal deformation box will convert to black. When the value is within 0.00125 to 0.019 mm, the box has colored with green one. And when the reading above 0.019 mm, red color will saturate the box reading and the test should be repeated again after leaving specimen to release for 5 min, as can be shown in Fig (3.10).



H strian 0.000108

V strian 0.176085

H deformation 0.023000

Plate 3.9 Creep compliance packages indicator when the horizontal strain lay above the specified limits (>0.019)

The preparation of different mixture specimens is briefed in Table (3.11). Since creep compliance test are none destructive test, so, any specimen prepared for such test, can perform indirect tensile strength test on it, except some cases were specimens distracted during the test should be manufactured again.

Table 3-11 Preperation of different asphaltic mixture for creep compliance cest

Item		**HMA**	**CBEM**	**HWBEM**
Selected gradation		Type IIIA dense graded as cleared in table (3.1)	Type IIIA dense graded as cleared in table (3.1)	Type IIIA dense graded as cleared in table (3.1)
Aggregates type	Course	Virgin	virgin	virgin
	Fine	Virgin	Virgin and Crushed glass	Virgin and Crashed Glass
Filler type		OPC	OPC and CMF	OPC
Bitumen type		40-50 grade Asphalt	Cationic medium setting bitumen Emulsion	Cationic medium setting bitumen Emulsion
Aggregates Pre wetting water content, %		No pre-wetting , but drying at temperature 170 C	2.5 % For CBEM incorporated CMF	3.5%
			3.5% for CBEM incorporated OPC	
Bitumen content,%		4.65	12.5% For CBEM incorporated OPC	12.5%
			12% For CBEM incorporated CMF	
Compaction temperature, C		140	Lab temperature (25-30 C)	91
Specimens Diameter, mm		101.63	101.63	101.63
Compaction(Marshall Hammer)		75x2	75x2	75x2
Curing protocol		24 hr. in mold at Lab temperature	24hr @ 20°C in mold + 24hr in oven at 40°C	24hr @ 20°C in mold + 24hr in oven at 40°C

Plate 3.10 Condition of Marshall specimens at 0°C temperature in the freezer for CC test

Sensors Calibration

All measuring sensors are necessary to calibrate periodically prior preforming any test program. Since the new devices that connected for measuring are new, it is necessary to calibrate them to ensure data accuracy. After programming lab view package to perform a specific mission, the new load cell was calibrated as following:

- The new load cell is put orthogonally on a calibrated load cell, which its indicator can be observed in plate (3.12). The new load cell output values is shown in the lab view screen
- Then, the two load cell are applied to constant pressure, with different intensities, to see if the calibration is linear or nonlinear at higher levels.
- It has noticed a large difference between load cells result, estimated about 50% higher than the correct load cell as can be noticed in plate (3.13).
- The new load cell reading is multiplied by a factor of 0.5, and the new results as can be seen in plate (3.14)
- Finally, the device is ready for testing

While in case of LVDT sensors, it has observed that no correction is required to do so, hence no calibration is made.

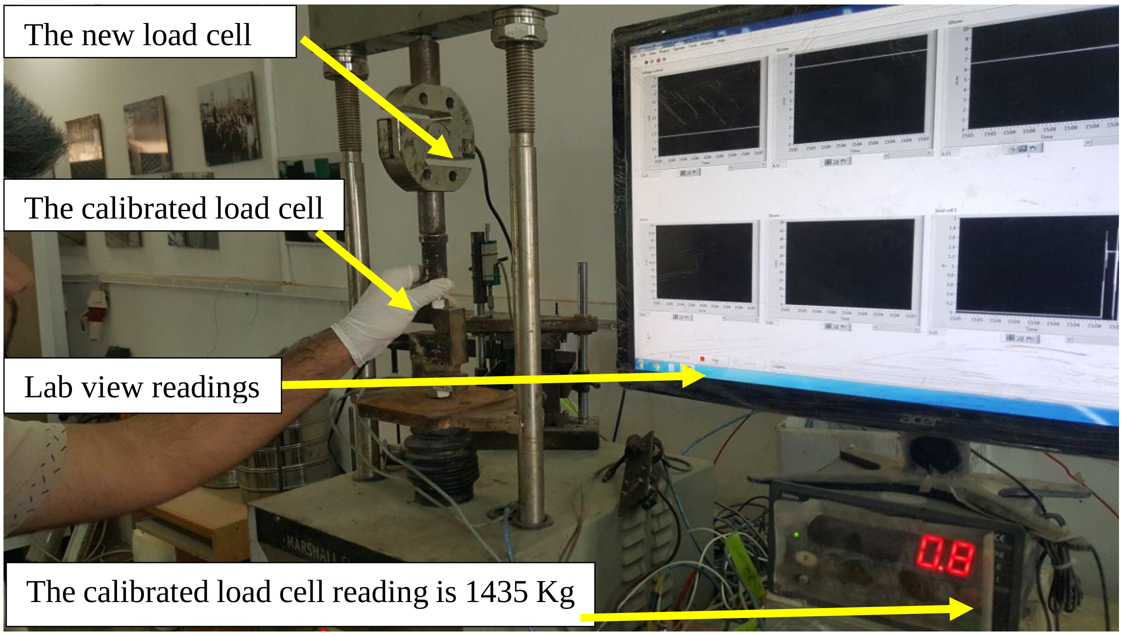


Plate 3.11 method of calibration a new Load cell

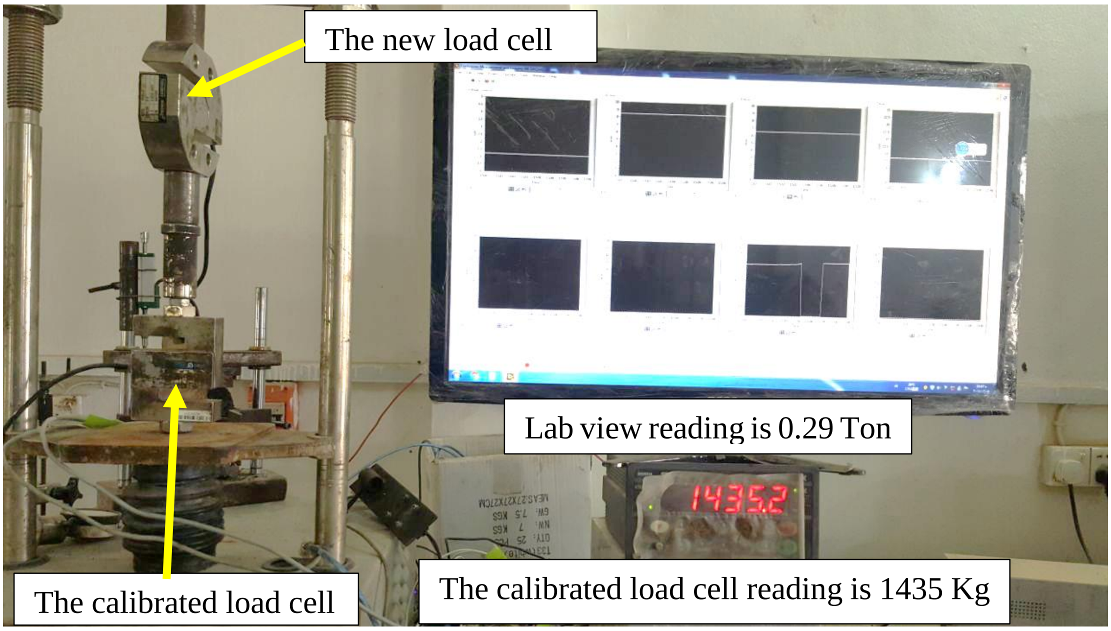
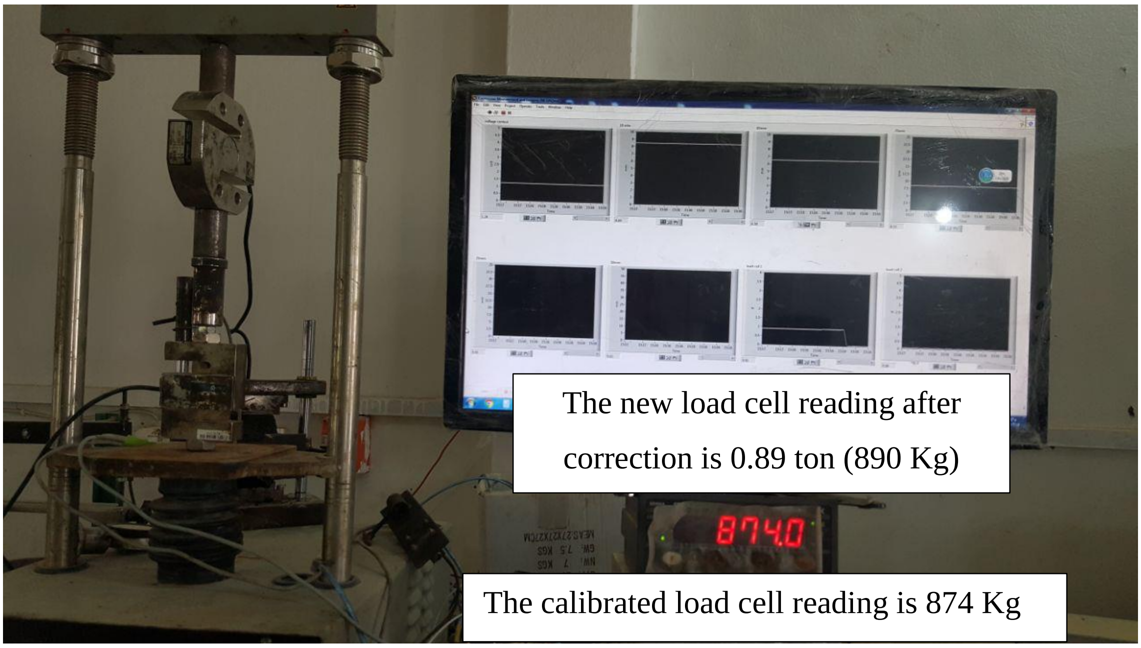


Plate 3.12 The difference between a calibrated load cell and a new load cell



The new load cell reading after correction is 0.89 ton (890 Kg)

The calibrated load cell reading is 874 Kg

Plate 3.13 Load cells readings after multiplying by a correction factor of 0.5

3.4.4 Wheel Track Test (WTT) and Dynamic Stability Test (DS)

Wheel track test (WTT) is a common well known simulative test, which describes mixture resistance to rutting or permanent deformation. The WTT gives an indication for mixture stiffness and rate of permanent deformation. It can be performed for both CMA and HMA mixtures with a difference only in the curing protocol. The test has performed according to BS EN 12697-22: 2003 (EN, 2003) specifications.

The preparation of HMA specimens includes preparation of rectangular slab specimen with dimension 5x16x30 cm. The mixture was prepared with optimum asphalt content that determined from Marshall test. Trial mixes with different compaction effort was applied to determine specified target air void specified in BS standard (BSI: EN, 2003), as can be seen in Plate (3.15). Four trail mixes were made to determine optimum compaction effort time corresponding to the target air void. A target air void content of 7%was selected based on as constructed pavement condition, as can be seen in Figure (3.4) (Read and Whiteoak, 2015).

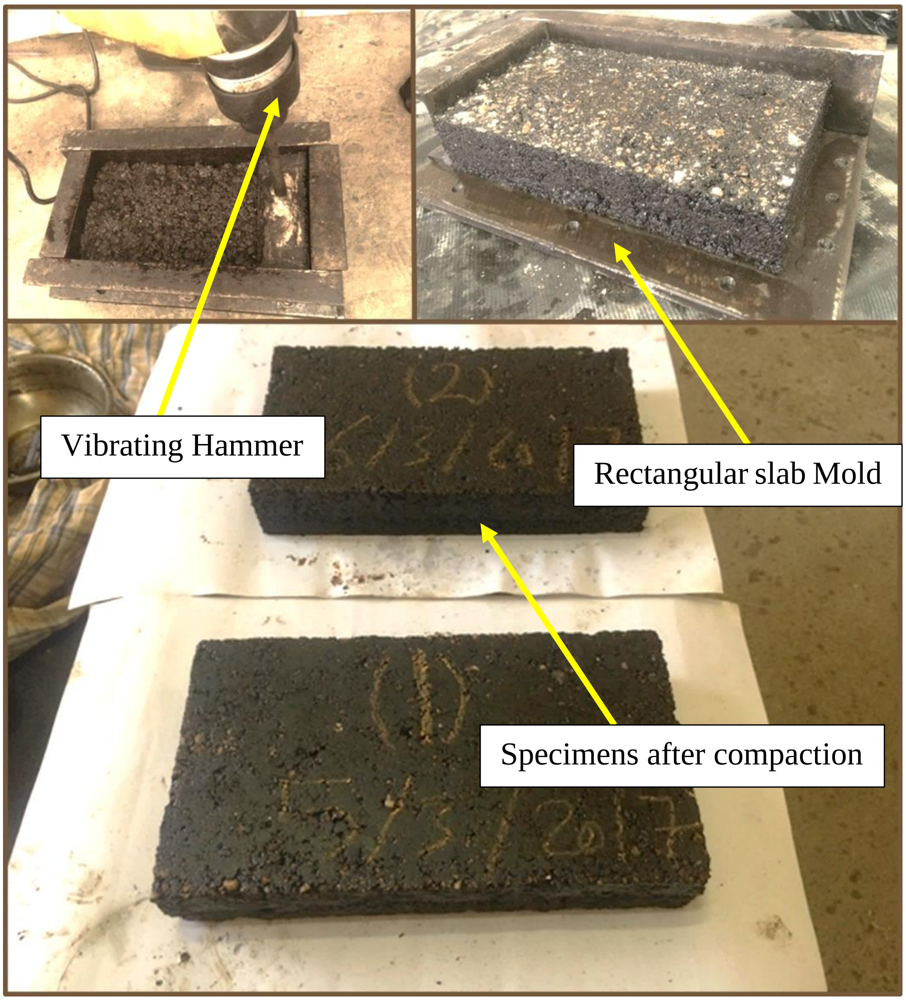


Plate 3.14 Compaction method of slab specimens of WTT

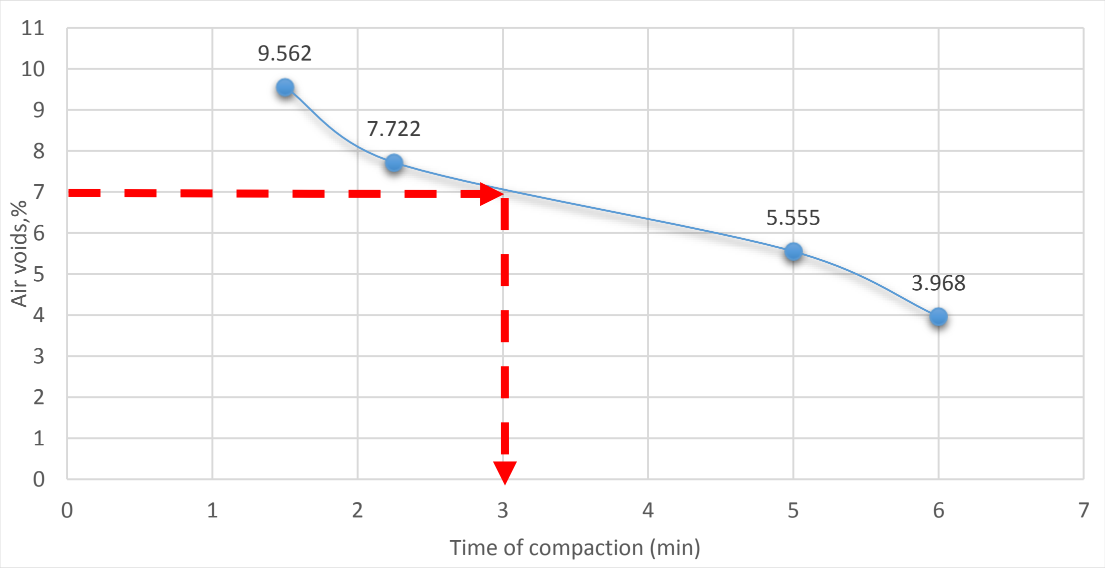


Figure 3.4 AV% content vs. time of compaction for HMA slab specimens

The curing protocol of HMA specimens consisted of leaving specimens in a mold to cool down for 24h and then extracted from the mold. After that specimens were conditioned in WTT chamber at temperature 60°C for 2hr. to ensure the distribution of the heat all over the specimen before the test. It is interesting to say that the WTT device was built locally with same specifications of small wheel track device that recommended by the BS specification as cleared in Plates (3.13 and 3.14).

In case of CBEM, the matter is different. HMA offers less air voids content with increasing the time of compaction effort. While in case of CBEM specimens, it has well-known that CBEM offers relatively higher air void due to the trapped water in mixtures. So, it is not easy to obtain comparable air void to HMA. A field study concluded that most of CBEM offer higher air void than HMA, and gradually decreasing after road opening to reach stable air void content ranging between 10%-15% in midterm condition (Thanaya, 2003). In this research, a trial mixes were made to obtain design air void content. Specimens were prepared for CBEM with the optimum bitumen content and then compacted in a 5x16x30 rectangular mold by using different compaction effort time. The results showed that specimens were suffering high air voids content and no significant changing in air voids content was obtained even with increasing the time of compaction as noticed in HMA mixes. The resulted air void content was ranging between 11%-12% for CBEM specimens, as illustrated in Figure (3.5). Therefore, the same compaction effort time of traditional HMA specimens was adopted (3mintues).

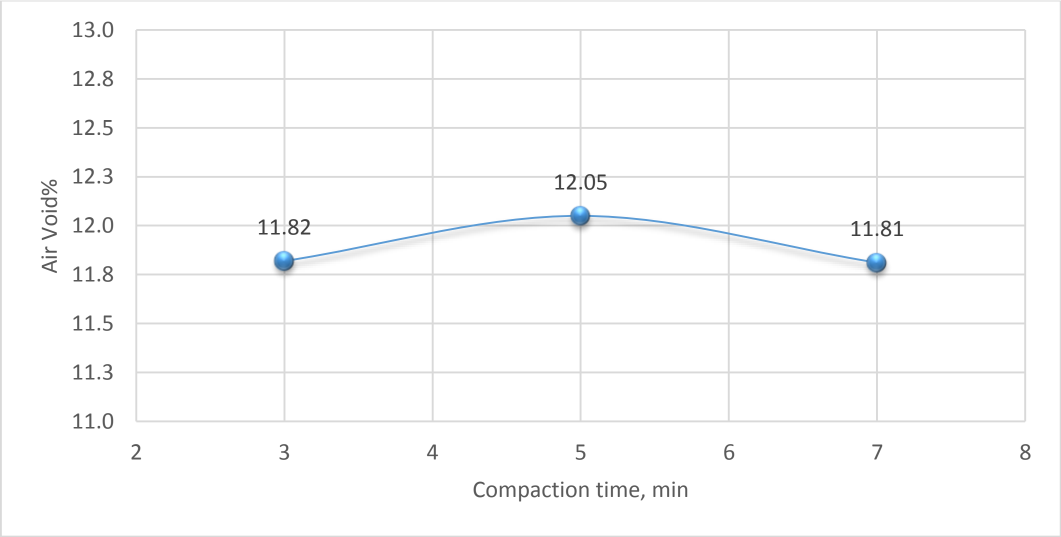


Figure 3.5 compaction time vs. air void content after 14 day curing @40 °C

In case of HWBEM, the preparation of specimens included determination of optimum compaction effort time corresponding to the target air voids by making trials mixes. Each specimen is prepared by placing loose mixture in a microwave for 6 min (determined from Marshall Test as optimum post-heating time corresponding to best mechanical and volumetric properties), then compaction effort applied with 4.35 min distributed on two layers as cleared in Figure (3.6).

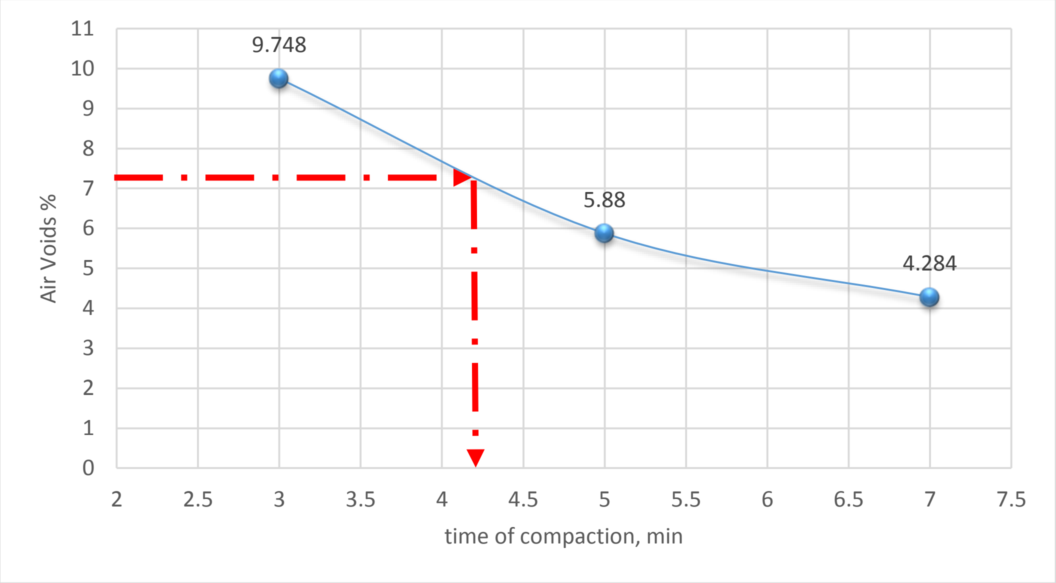


Figure 3.6 Time of compaction vs. AV% content for HWBEM

The performance of prepared CBEM specimens cannot be evaluated without curing since high moisture content is still trapped within it. There are several protocols for curing CMA specimens. The most well-known curing protocol stated that placing CMA specimens for 24hr in an oven at 40°C simulate road opening after 7-14 days form being constructed. While conditioning CMA specimens for 14 days in oven at 40°C reflects mixture full strength simulation (Thanaya, 2003). The full curing protocol was adopted in this study for preparing CBEM wheel track specimens as can be seen in Plate (3.12).

For HWBEMs, although mixtures placed in a microwave for 6 min, it still contains water, especially when mixes incorporated FGA. Relation between percentages of water loss with time while curing in oven at temperature 40°C was examined for some HWBEMs specimens, as cleared in Figure (3.7). The Figure states that water evaporation with time. Therefore, the full curing protocol was applied (1 day in mold + 14 days in the oven at 40°C) as cleared in Plate (3.16). It has to mention that such curing has recommended by Al-Busaltan (2012), AL-Hdabi (2014), and (Dulaimi, 2017)

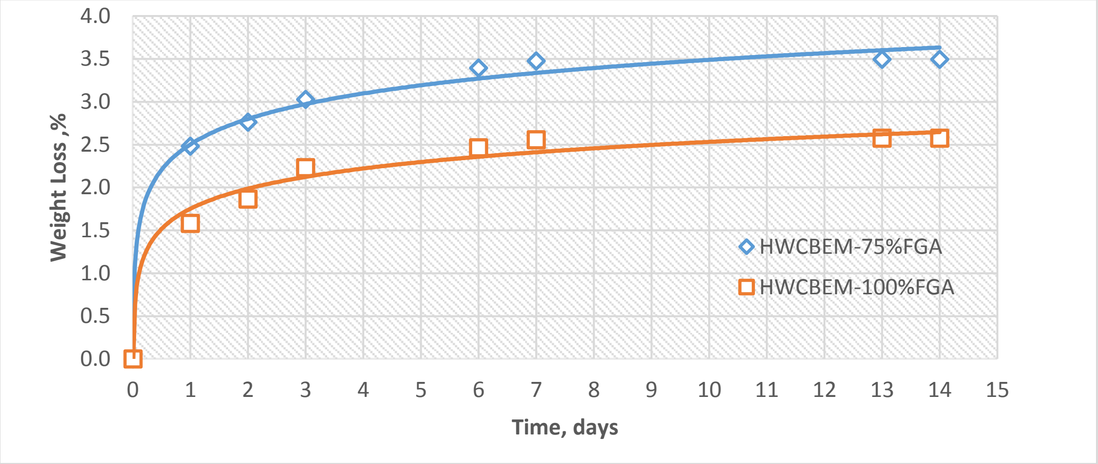


Figure 3.7 Moisture loss with time for HWBEM comprised FGA (in oven dry @40C)

Plate 3.15 Conditioning WTT specimens in oven at 40°C for 14days for CBEM and HWBEM mixes.

- **WTT device conditions**

The following specifications were adopted for WTT based on (EN 12697-22: 2003) (EN, 2003) small device wheel tracker described in Table (3.12). it is worth to say that the device was manufactured locally and supplied with high resolution sensors, as can be seen in plates (3.17 and 3.18)

Table 3-12 WTT device conditions

Item	Typical value based on (EN 12697-22: 2008)	Applied conditions
No. of specimens	2	1
Wheel Diameter, cm	20±0.5	20
Wheel load, N	700±5	708
Wheel speed, min m/sec	26.5	28
Specimens dimensions, cm	5x26 x 41	5x12x30
Specimen preloading , cycles	5	5
Compaction effort reflects 7% Air voids, min	HMA	3
	CBEM	3
	HWBEM	4.35
Specimen height, cm	4-10	5-6
Compaction method	Static press, roller compactor, vibrator compactor	Vibratory compactor
Conditioning temperature, °C	60 ± 2	60 ± 2
Specimen conditioning before test in term of oven dry, min.	120-130	120

Dynamic Stability (DS) is another useful indication for asphaltic mixture resistance to rutting deformation. DS refers to a number of wheels passes required to cause a unit rut depth in asphaltic mixtures (Read and Whiteoak, 2015). The test was performed According to the "Chinese Highway Engineering Asphalt and Asphalt Mixture Test Code"(JTG-E20, 2011). Dynamic stability (DS) gives an indication for a high-temperature stability of asphalt mixture. It is mainly carry out at 60℃ temperature rut test to obtain the high-temperature stability index. To obtain DS value, the following formula can be applied (JTG-E20, 2011):

$$DS = \frac{N_{15}}{D_{60}-D_{45}} \quad \text{................Equation 3-14}$$

Where:

DS is Dynamic stability (passes/mm)

N_{15} is number of 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).

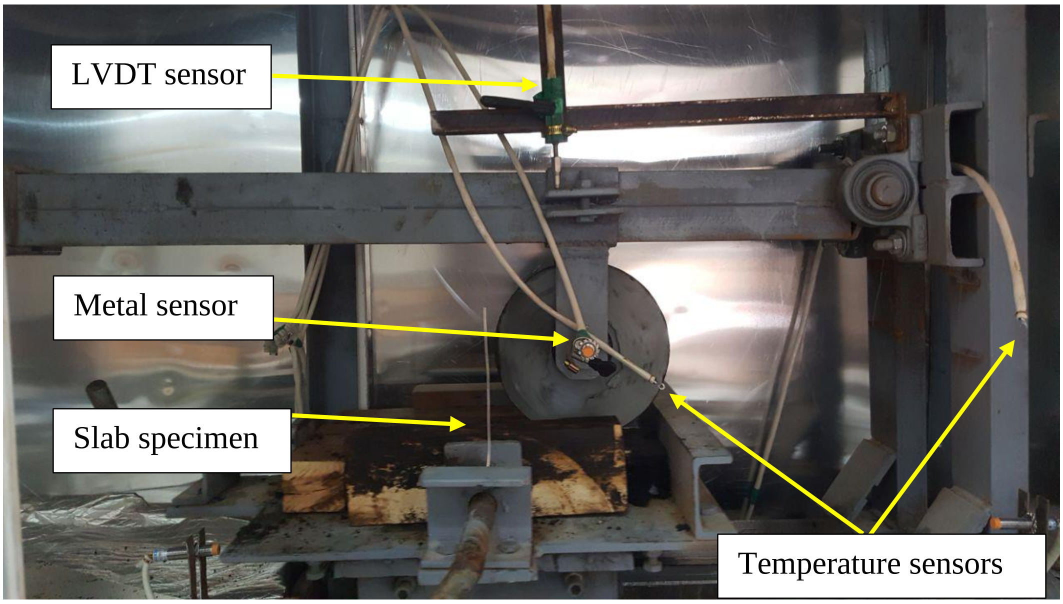


Plate 3.16 Wheel track device components

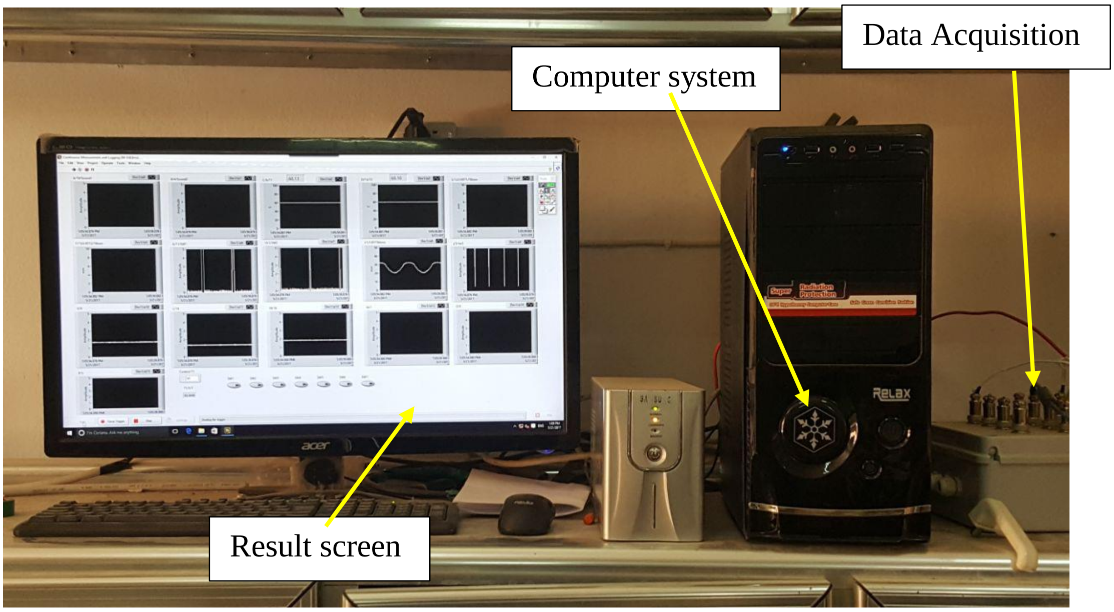


Plate 3.17 Screen results of the wheel track device (data capture)

3.4 Durability Test

Water sensitivity of asphaltic mixtures is one of the most common test to examine mix performance under effect of weathering. When asphalt pavement exposed to continuous water action, its performance will be deteriorated resulting weak mechanical properties. There are many tests that describe asphalt pavement behavior under action of water such as; indirect tensile strength ratio (TSR) (ASSHTO T283), retained Marshall Stability test (ASTM D1559), wheel track test (AASHTO T 324).

In this study, the effect of water action on asphalt mixtures was evaluated in term Marshall Retained Stability test as shall be described later.

3.5.1 Retained Marshall Stability Test (RMS)

The RMS is used to evaluate Marshall Stability loss when specimens are subjected to water action according to MS-14 (Asphalt Institute, 1989) requirements. The water sensitivity in terms of loss of Marshall Stability is determined by dividing the average of socked specimens group by the average standard Marshall Specimens group. However, the Asphalt Institute (1989) MS-14 specified the ratio of conditioned to unconditioned specimens should not be less than 50%.For CMA specimens, the standard (unconditioned) Marshall specimens are conditioned for 30-40 min in water bath at 60°C. While in case of socked (conditioned) specimens, they are placed for 24hr at 60°C in water bath before test running. The same protocol was used for CBEM and HWBEM specimens, except the curing after compaction for both mixes, as can be illustrated in Table (3.13).

Table 3-13 Conditioning protocols for water sensitivity tests

unconditioned specimens	**conditioned specimens**
24hr in mold @ lab temperature	24hr in mold @ lab temperature
24hr in oven @ 40 °C	24hr in oven @ 40 °C
………………..	24hr in water bath @ 60 °C

After curing, specimens conditioned in an oven at 60°C for 2hr, and finally preforming the test. The RMS value can be obtained using the following formula:

$$RMS\% = \frac{average\ of\ conditoned\ specimens}{average\ of\ unconditoned\ specimens} \times 100\% \quad \text{.................. Equation 3-15}$$

3.5 Research Methodology

As mentioned previously, the main aim of this study is to upgrade the current local practice of CBEM in a sustainable way. Thus, two stage techniques are suggested (i.e., use a municipal waste material, and low energy heating) to achieve such aim. However, the following methodological phases are designed to process the requested development operation. More details are illustrated in Figure (3.8):

- Phase 1: Design of traditional HMA control mix (virgin coarse and fine aggregates, with OPC as a mineral filler)

- Phase 2: Design of conventional cold mix asphalt mixture (CBEM-CMF) (virgin coarse and fine aggregates, with CMF as a mineral filler)
- Phase 3: Incorporation of OPC as mineral filler instead of CMF in three percentages (0%, 50%, and 100%),
- Phase 4: Incorporation of waste glass aggregate with different percentages (25%, 50%, 75%, and 100%) as fine aggregate instead of virgin fine aggregate in addition to 100% OPC from filler weight.
- Phase 5: Optimize cold mixtures by utilizing microwave energy (virgin coarse and fine aggregates, and OPC as mineral filler).
- Phase 6: Repeat Phase 4 with applying microwave post heating energy after determination optimum time for microwave post heating.

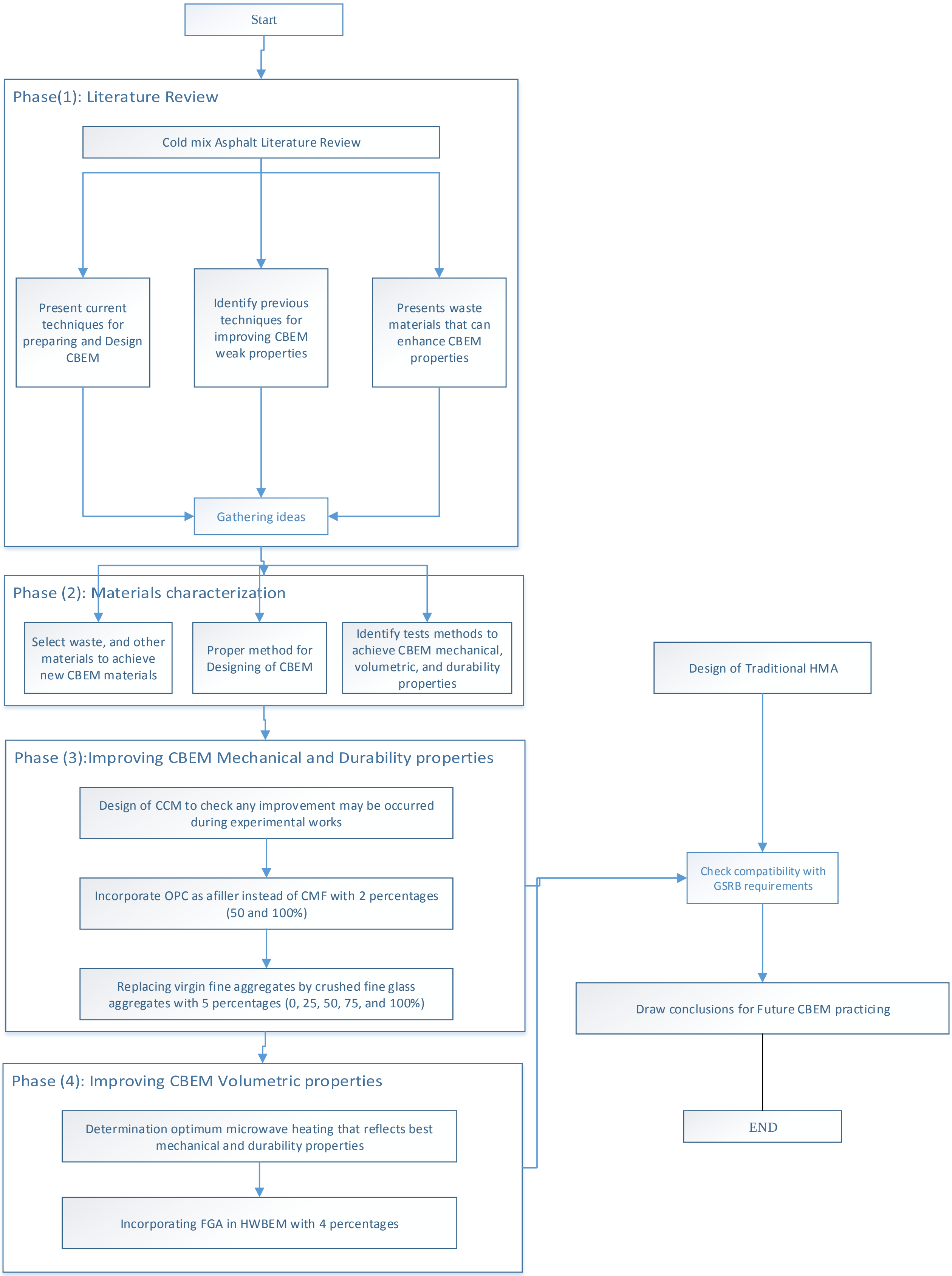


Figure 3.8 Research methodology flowchart

3.6 Summary

Suggesting sustainable technology for paving material is in high demand. Such operation is not easy, but a catchable job. The promising characteristics of CBEM shin a spot light in a long tunnel to satisfy a newly developed technology. However, methodological process rises the need to start in developing local materials, which successfully control in this study. On the other hand, up to nowadays, no unified accepted design procedure for CBEM universally. However, in this research, a trial has been made to check how far (Asphalt Institute, 1989) design procedure (MS-14) can be compatible with the Iraqi GSRB specifications, and suitability of such combination to produce CBEM for local applications.

From the above, a feasible opportunity could be achieved to produce CMA with comparable properties to HMA using local materials dosed with local municipal solid waste under traditional testing methods for asphaltic mixtures.

Chapter Four

TESTS RESULTS AND ANALYSIS – PHASE 1: ENHANCING CBEMS MECHANICAL PROPERTIES

4.1 Introduction

This chapter presents the results obtained from testing of compacted specimens with comprehensive analysis of the variables affected mix parameters. HMA was used as a control mix for comparing the variation in the development of CBEM properties. In addition, conventional CBEM characteristics results are presented for compassion with other newly developed cold mix specimens.

4.2 Traditional Hot Mix Asphalt (HMA)

The preparation of control HMA was established for comparison with control and modified cold mix. HMA mixture materials were asphalt grade 40-50 type. Virgin coarse and fine aggregates, with OPC filler type. The preparation of aggregate gradation was based on GSRB, section R9 (GSRB, 2003) as cleared previously in Figure (3.1). So, to determinate the optimum asphalt content, five trials were carried out with five different asphalt contents ranging between 3.5%-5.5% with an incremental step of 0.5%, through three sample for each percent. The bitumen content was found to be 4.65% according to Marshall test results, which corresponding to best mechanical and volumetric properties that satisfy limitations of GSRB criteria.

Moreover, HMA specimens were tested in term of Marshall test, wheel track test (WTT), creep compliance test (CC), indirect tensile strength test (IDT), and water sensitivity tests in term of RMS%, which will be presented for comparison with CBEM mixes hereafter. Marshall design mechanical and volumetric characteristics are demonstrated in Appendix (A). The characteristics of HMA that has the optimum asphalt content can be seen in appendix (A.1)

4.3 Conventional Cold Bituminous Emulsion mixture (CBEM-CMF)

Conventional cold mix used as a reference mixture for other mixes to examine the level of development of CBEM. CMF is used as a mineral filler; it considers as inert filler since no reactivity is recognized when mixing with water. This section illustrates the trend of mechanical and volumetric properties of CBEM-CMF, which clears how other cold mixes were improved using different suggested techniques.

4.3.1 CBEM-CMF Preparation

CBEM-CMFs were prepared under the followings:

- Bitumen emulsion type cationic medium setting was used, which recommended by Asphalt Institute (MS-14), with properties illustrated in Table (3.6).
- CMF used as mineral filler.
- Determination of IEC

After applying the formula of the initial residual emulsion content, it was found to be 6.96%. Moreover, initial emulsion bitumen content was 12.67% since 55% of the emulsion was bitumen residual according to Equation (3.1).

- OPWwc: although Asphalt Institute (MS-14) recommended using 3% as initial OPWwc, it was found that such value resulted in sloppy mixture. Thus, OPWwc was obtained after 5 trials made with different water content ranging between 2%-4% with 0.5% step increment as recommended by asphalt institute Ms-14. It was found by visual inspection that 2.5% of water content was sufficient to get the best coating of aggregate without producing stiff or sloppy mixture.
- Determination of optimum emulsion content

Five different percentage of emulsion content were performed after fixing OPWwc value to 2.5%. An initial value of 12.5% was selected as mid value with 0.5% step. The optimum value was found to be 12% based on Marshall mechanical and volumetric tests results.

- The total liquid content was basically12.5+2.5 (or 15%), but this value was reduced since loose mixture was exposed to van air to evaporate unnecessary moisture, hence TLC was found to be 14.5%.

4.3.2 CBEM-CMF Volumetric Properties

Volumetric properties were obtained for CBEM-CMF with various emulsion contents. The results reveal the following:

- Density of CBEM-CMF specimens, as shown in Figure (4.1), is increased with higher amount of bitumen emulsion until reach maximum value. Then decreased gradually since extra water will present with higher emulsion content then when evaporate it leave more voids in a compacted specimen.

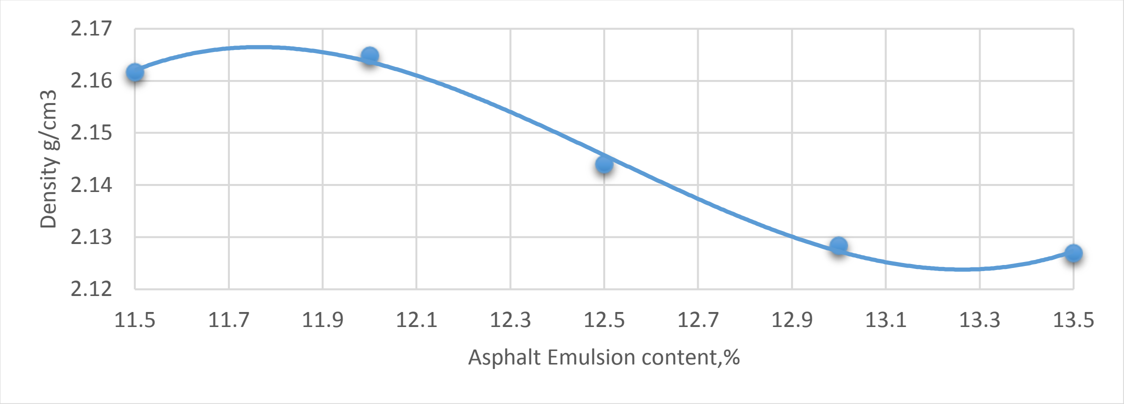


Figure 4.1 Density vs. AEC% for CBEM-CMF

- Figure (4.2) shows air voids in compacted CBEM-CMF, which is decreased with increasing amount of bitumen emulsion until a specified limit due to lubrication action of the presence of emulsion and water that help the backing of mix constitutes. Then it decreases slightly since higher emulsion means higher water content, which leads to higher air voids after evaporation. It is worth to mention that the air voids values for different emulsion content are out of GSRB limits.

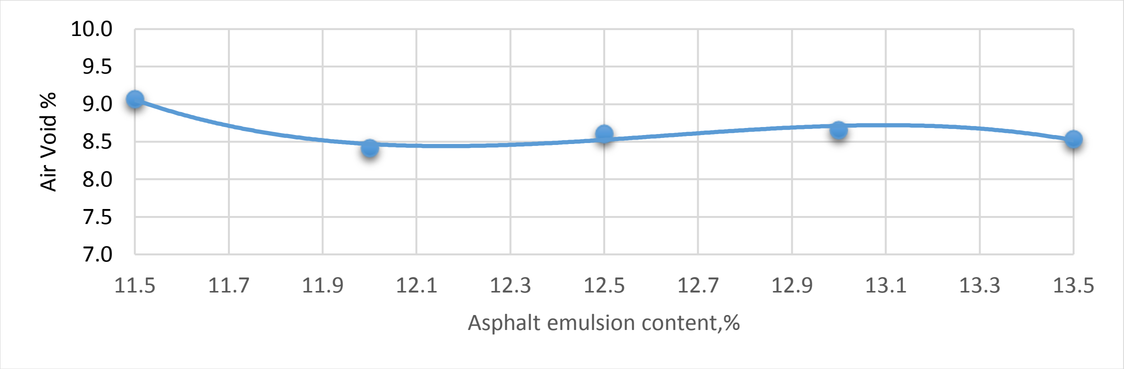


Figure 4.2AV% vs. AEC% for CBEM-CMF

- The result of voids filled with bitumen (VFB) as shown in Figure (4.3), which clears how percentage of VMA that filled with bitumen binder, increased normally with higher amount of bitumen emulsion since higher percentage of voids are filled bitumen with higher amount of bitumen emulsion.

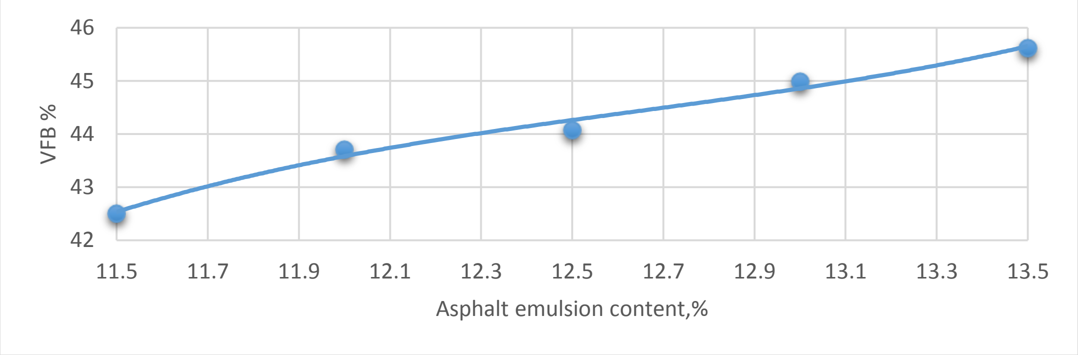


Figure 4.3 VFB% vs. AEC% for CBEM-CMF Mixtures

- In Figure (4.4), the VMA looks to be increased with increasing amount of bitumen emulsion, which represents volume of air voids plus net binder volume. So, the initial increasing resulted from increasing value of bitumen emulsion, which leads to reduce air voids percentage and VMA%. Then a slight raising appeared due to the fact of increasing bitumen emulsion quantity which makes the specimen suffering higher air void content.

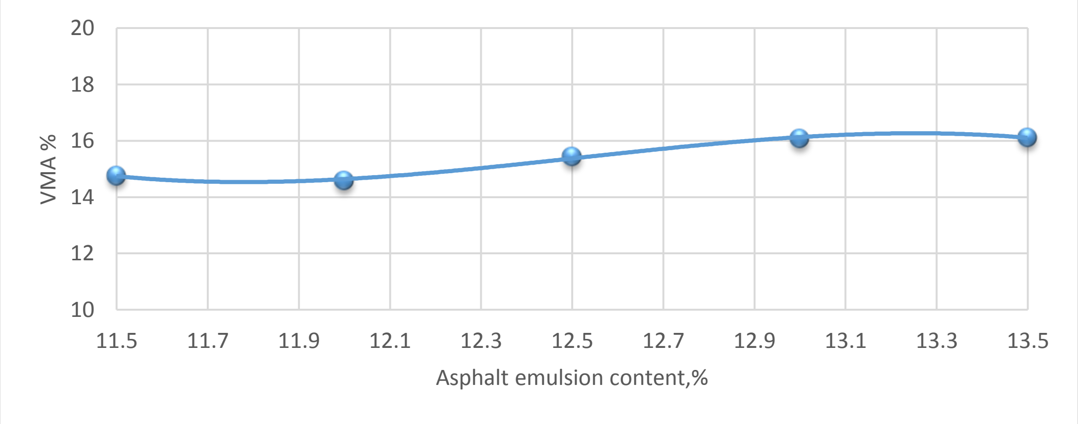


Figure 4.4 VMA% vs. AEC% for CBEM-CMF Mixtures

4.3.3 CBEM-CMF Mechanical Properties

4.3.3.1 Marshall Test Result

From Figure (4.5), the maximum stability value is equal to (523 Kg) at 12% Optimum Emulsion Content (OEC), which relatively lower than HMA maximum stability (1300 Kg), i.e., it is about 2.5 times the value of CBEM-CMF. Several reasons could affect Marshall Stability; first, the binder viscosity has the significant effect on Marshall Stability value, with proportional relationship. Low mixture stability backs to emulsion consistency, which has a lower viscosity than grade asphalt, as can be seen from Table (3.1). Secondly, the binding provided by the bitumen emulsion not as strong as provided by grade asphalt.

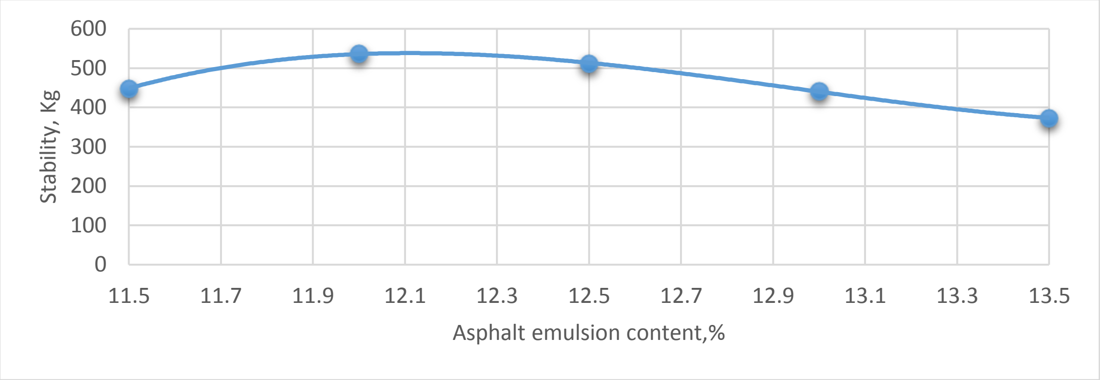


Figure 4.5 Stability vs. AEC% for CBEM-CMF Mixtures

From Figure (4.6), Marshall Flow of CBEM-CMF looks to be higher about 2.13 times the HMA flow. Such increment backs to the emulsion binder softness, which considers softer than grade asphalt, further to poor early life strength due to the existence of trapped water, with high air voids and low density.

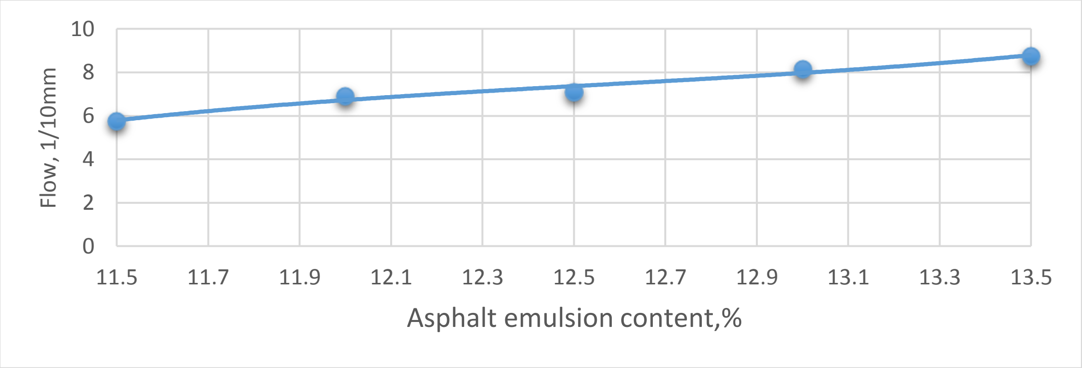


Figure 4.6 Flow vs. AEC% for CBEM-CMF Mixtures

The stability-Flow curves in Figure (4.7) demonstrates a far range of mixture behavior under the same loading condition of Marshall test.

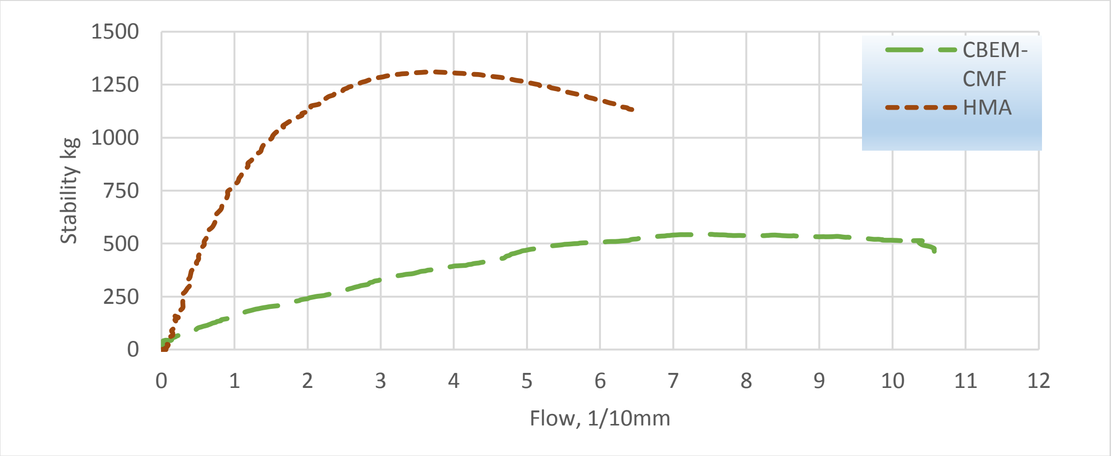


Figure 4.7 Stability- Flow curves for CBEM-CMF compared with HMA Mixtures

4.3.3.2 WTT Results of CBEM-CMF Mixture

Firstly, trial mixes were prepared with different compaction efforts to determine the target required air voids content of slab specimens, as cleared previously in Figure (3.6). Using vibration compaction, different time of compaction efforts have applied, but CBEM-CMF specimens still suffering from higher air void contents. Therefore, required air voids of 7% could not be established, and compaction time of 3 minutes was taken as reference time compaction for other CBEM mixes, as this compaction time associate higher density and less air voids.

The same conditions used in testing HMA specimens were applied for CBEM-CMF testing. Figure (4.8) represents how rut depth increased with increase the number of wheel passes. It can clearly notice that the rate of deformation is increased dramatically, then gradually be stable with time since densification processes had occurred which resulted in lower air void content. CBEM-CMF specimens show higher rut depth compared to HMA specimen, as a result of low strength, further to higher air voids content in CBEM-CMF (i.e., it is 11.81% in contrast to (7% for HMA). Another reason that affected significantly on rutting which is the low binder viscosity of CBEM-CMF at 60°C; i.e. cold emulsion bitumen grade type is 100-250, while hot bitumen grade is 40-50.

It can be seen from Figure (4.8) that the CBEM-CMF specimens deformed about one-half times more than traditional HMA. Moreover, it can be observed that trend line of conventional cold mix approaches a uniform curve, and the permanent strain distributed along wheel passing equally. Unlike HMA, that its rate of permanent deformation was initially high, followed by gradual reduction through the time of testing. Dynamic stability for both CBEM-CMF and HMA mixtures are presented in Figure (4.9). The figure clears that about 43.6% reduction in DS for CBEM-CMF compared to HMA.

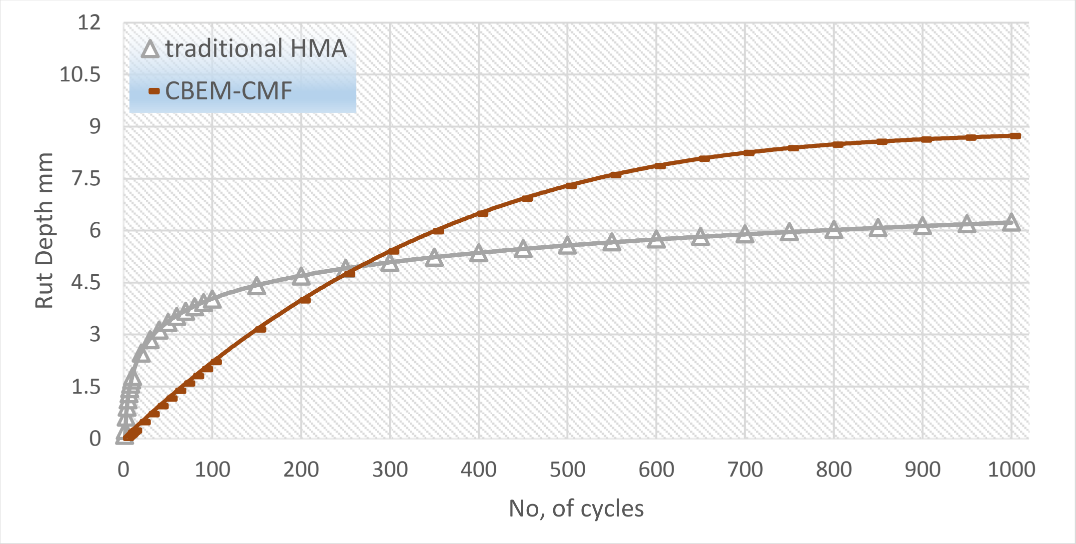


Figure 4.8 Rutting vs. number of cycles for CBEM-CMF compared with HMA

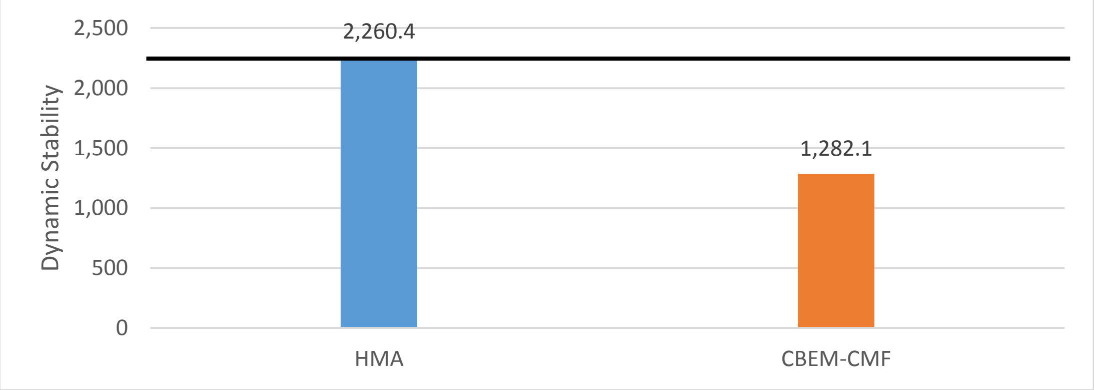


Figure 4.9 Dynamic stability for CBEM-CMF compared with HMA

4.3.3.3 IDT Test Results

From Figure (4.10), it clears that CBEM-CMF resistance to tensile cracking is rather poor compared to HMA. Also, it can be observed that IDT for HMA is higher than CBEM-CMF by about 5 times, which could be because of high moisture content within mix at an early life, and poor adhesion between aggregates and bitumen binder due to trapped water existence in CBEM-CMF that create a separation layer in the interface.

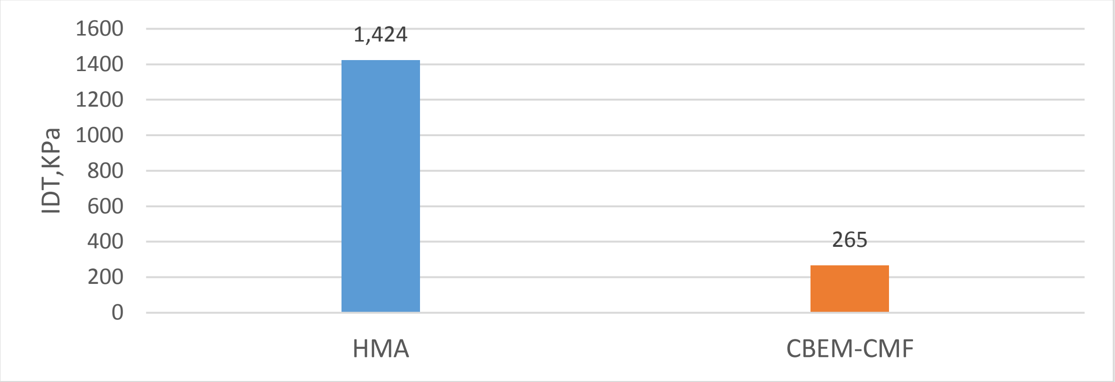


Figure 4.10 IDT for CBEM-CMF compared with HMA

4.3.3.4 Creep Compliance Test Results

Creep compliance test result shows that the CBEM-CMF specimen's resistance to crack prorogation is weak compared to HMA specimens after 100 sec of performing test as presented in Figure (4.11). Also, the same figure clears that the CBEM-CMF trend curve of creep with time is higher than HMA. It should be noticed that crack initiation of CBEM-CMF is relatively high at the beginning of testing time, followed by a gradual reduction in curve slope with time. Unlike HMA behavior, which shows that curve trend behaves like a straight line because of binder viscosity which has very important role in resistance of creep cracking.

Creep stiffness results in figure (4.12), clears that HMA stiffer than CBEM-CMF by 6 times in term of tensile creep cracking resistance, as a result of the same reasons

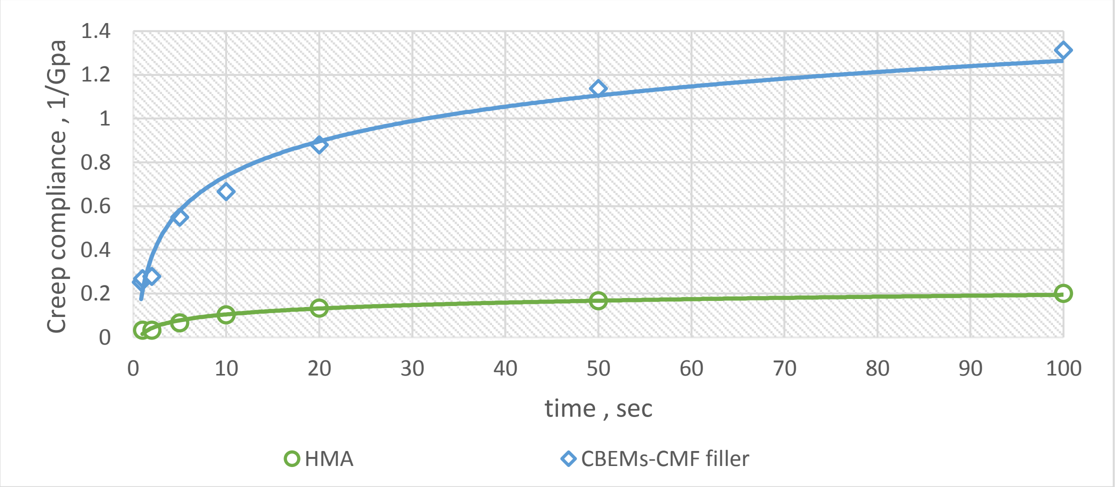


Figure 4.11Creep compliance vs. time for CBEM-CMF Mixtures compared with HMA

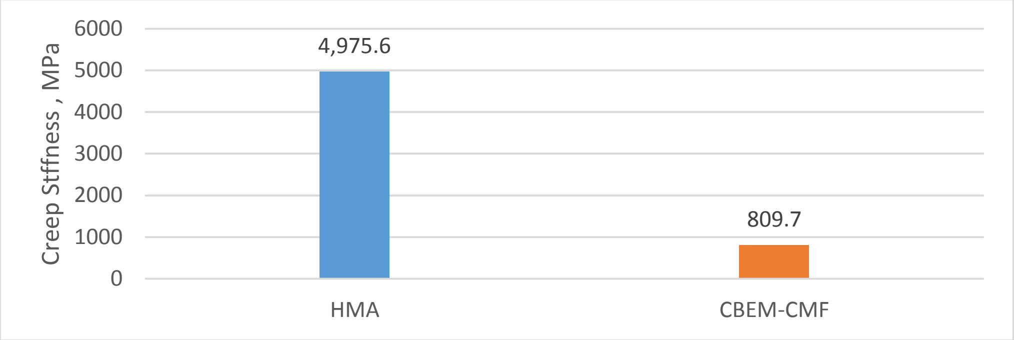


Figure 4.12 Creep stiffness for CBEM-CMF compared with HMA

4.3.3.5 Water Sensitivity Results

Effect of water on asphaltic mixtures was evaluated in term of retained Marshall Stability (RMS %) for CBEM-CMF and compared with traditional HMA, as can be seen in Figure (4.13). Results show that CBEM-CMF Marshall Stability was decreased by about 65% and 15% for CBEM-CMF and HMA mixes, respectively due to the effect of water action. Such low value for CBEM-CMF backs to higher air voids content, which water can pervade through and reduce overall mix strength. Moreover, the inferiority bonding strength of the CBEM-CMF constituents could not resist the stripping action in the presence of water. It is worth to mention that CBEM-CMF-RMS value is far away from specification limits.

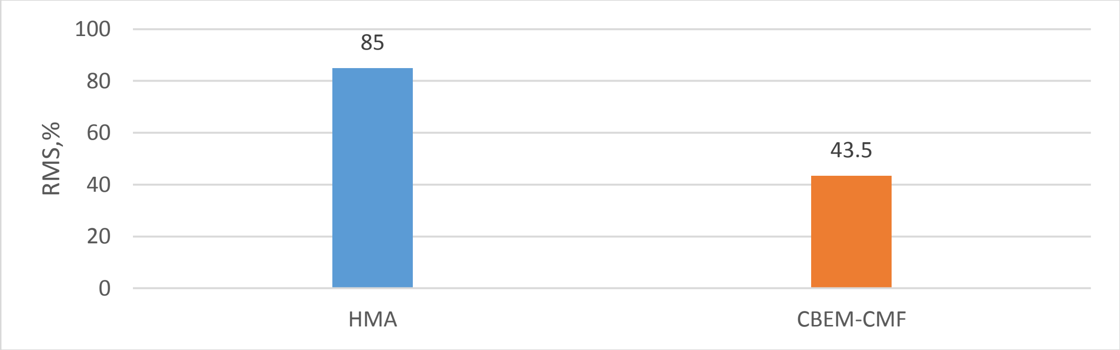


Figure 4.13 RMS% for CBEM-CMF compared with HMA

4.4 Improving CBEM by OPC

From the result presented in section 4.3, it has been noticed that the CBEM-CMF showed so inferior volumetric and mechanical characteristics. Thus, developing such mixture is in high demand for its eco-environmental beneficial characteristics. As mentioned in chapter two, OPC showed a vital remedy to such inferiority. However, the current section will present and discuss the characteristics of CBEM comprising OPC.

4.4.1 Mix Preparation

The same procedure in design of CBEM-CMF was followed to prepare modified CBEM incorporated OPC filler, with main difference points which are described below:

- As a result of coating test, the pre-wetting water contents were 3% and 3.5% for CBEMs with 50% and 100% OPC filler by weight of the total mix. They were higher than the value in CBEM-CMF. The higher amount of water required for aggregate coating backs to the cement particle's nature, which has higher surface area than CMF filler as observed by SEM analysis, which enables to absorb the higher amount of water rapidly before aggregate components take enough water for coating in addition to further to hydration process that absorbs some water.
- The optimum emulsion content value was determined using the same procedure mentioned in CBEM-CMF section. The initial emulsion content was the same (i.e. 12.7%). The optimum bitumen residue content was found to be 12% for CBEM-50% OPC, and 12.5% for CBEM-100% OPC mixes after trial mixes made with different emulsion percentages as mentioned in preparing CBEM-CMF section.
- Overall moisture contents were equal to 15% for CBEM-100% OPC mixes, and 14.5% for CBEM-50% OPC mixes.

4.4.2 Volumetric Properties of CBEM-OPC

The same procedure used in section CBEM-CMF for determination mixtures volumetric properties was adopted in this section. Results of the modified CMA are listened as follows:

- From Figure (4.14), density results clear that continuous reduction can be obtained with higher emulsion amount in case of CBEM-50%OPC specimens, while CBEM-100%OPC type showed a similar behavior to CBEM-CMF type. In general, no significant enhancement was observed when OPC filler was used instead of CMF type in comparison to HMA specimens densities.

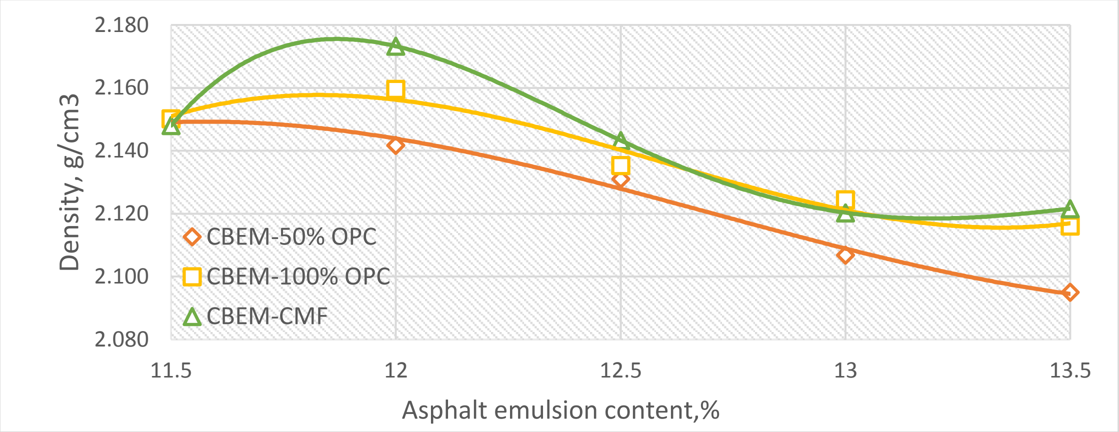


Figure 4.14 Density vs. AEC% for CBEM comprised different OPC content

- Air voids results in Figure (4.15) clear that CBEM-50%OPC mix type has a gradual rise in air voids content with the increasing in amount of asphalt emulsion. While in case of CBEM-100%OPC, the same behavior of CBEM-CMF was noticed. Air voids contents were ranged from 8-10% for all mix types. It has been noticed that no clear behavior between OPC fill amount and voids content up to 12.5% emulsion content. After 12.5%, CBEM-CMF has shown slightly lower air voids content compared to other modified mixes. This is might be as a result of absorbing the water that facilitates the lubrication for better compaction. However, the resulted values still out of limitations of GSRB.

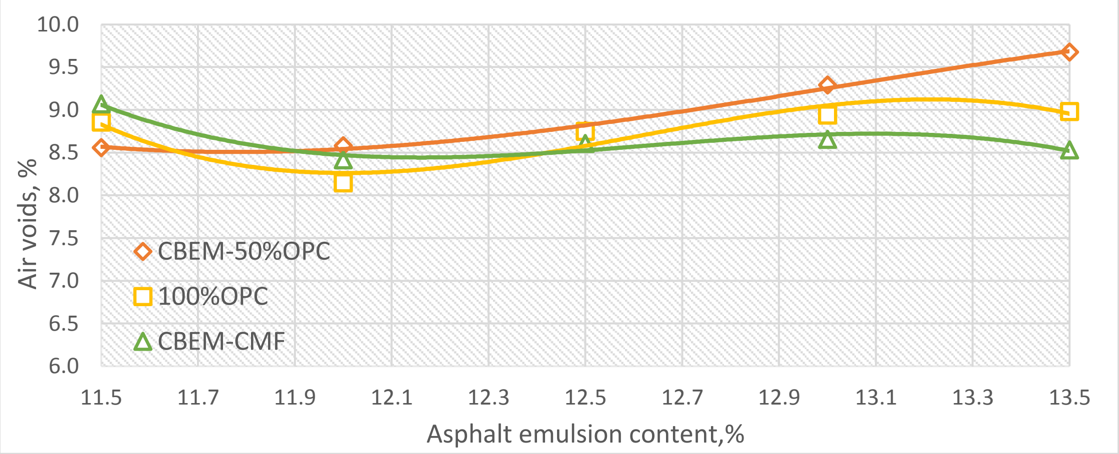


Figure 4.15AV% vs. AEC% for CBEM comprised different OPC content

- Voids filled with bitumen are illustrated in Figure (4.16). The value of VFB% increased with the higher emulsion content, due to the fact of filling voids with bitumen that increased with higher quantity of emulsion. A bit change had observed between a quantity of OPC filler in CMA and VFB%. Both modified mixes have shown similar trend to each other up to 13% of asphalt emulsion content, after that value CBEM-50% OPC has slightly higher VFB compared to other mixes. Again, the results are out of GSRB criteria.

- The VMA% results are presented in Figure (4.17). The VMA values are satisfied the GSRB criteria, as it is mainly a result of the aggregate gradation. However, a bit increase in VMA can be recognized with increase emulsion content, with some variation among the different mix, due to filler type and absorption of the water that facilitate the backing of the constitutes.

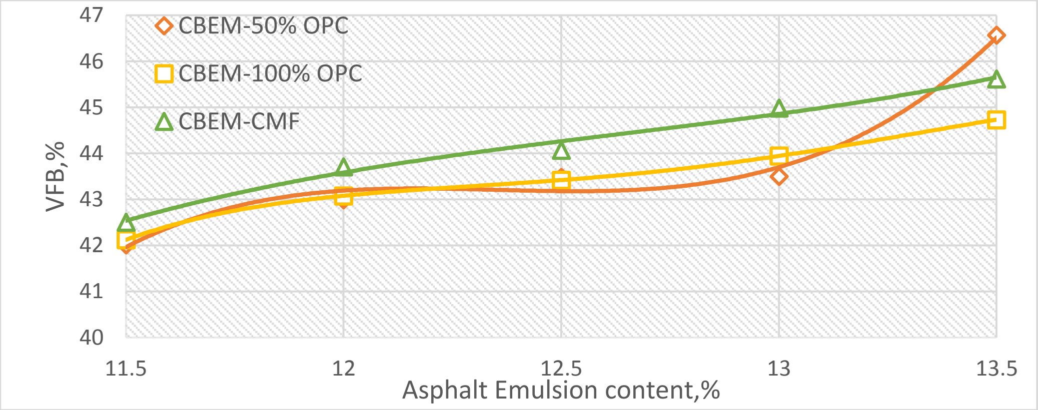


Figure 4.16 VFB% vs. AEC% for CBEM comprised different OPC content

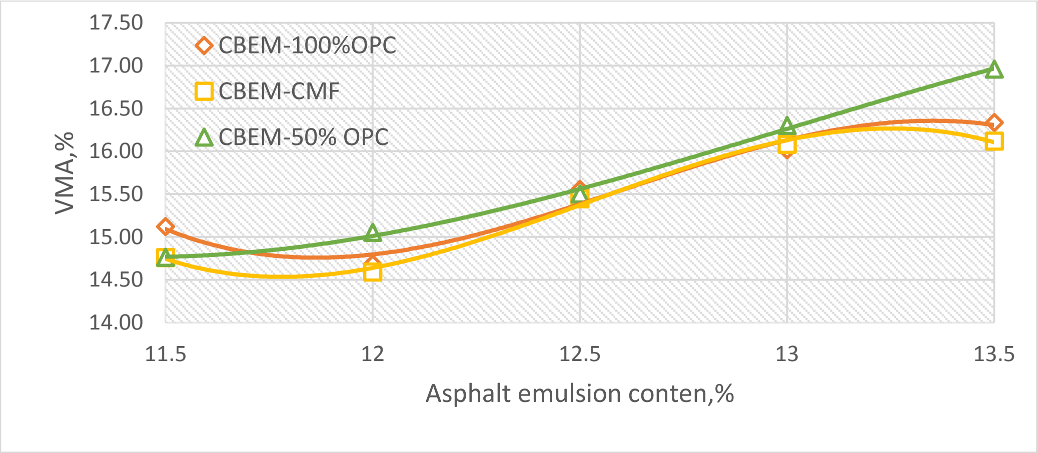


Figure 4.17 VMA% vs. AEC% for CBEM comprised different OPC content

4.4.3 Mechanical Properties for CBEM-OPC

4.4.3.1 Marshall Test Results

Marshall Stability: the behavior of improved mixtures is illustrated in Figure (4.18). The results showed a similar to what mentioned in CBEM-CMF section. The initial increase had been noticed to reach maximum value at a specific point, then gradual decrease occurred with higher amount of emulsion content for the same reasons. It is worth to mention that the existence of OPC as filler in CBEM has significantly improved Marshall Stability by about 155% and 215% for mixtures comprised 50% and 100% OPC, respectively, compared to CBEM-CMF. OPC filler has accelerated mix curing due to the effect of hydration process, which tends to absorb mix moisture at early life. Also, OPC worked as a second binder in addition to the bituminous binder in the mix.

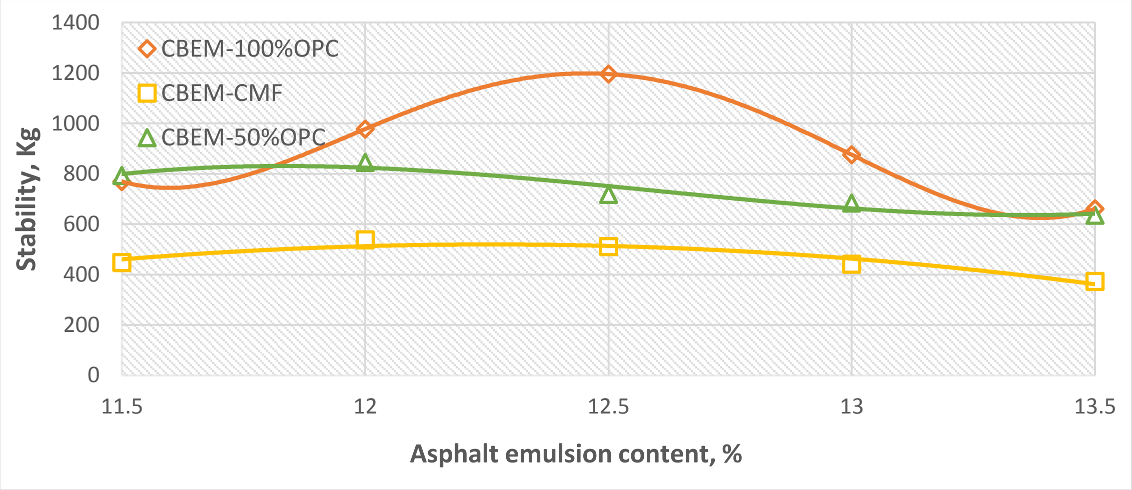


Figure 4.18 Stability vs. AEC% for CBEM comprised different OPC content

Marshall Flow results are shown in Figure (4.19). The plotted trends have cleared that the flow values increase with the proportional increase in bitumen emulsion content and is similar to CBEM-CMF behavior. Mixtures with OPC filler demonstrated an increase in mix brittleness and shifted flow curves down. A noticeable enhancement in flow values was occurred. Flow decreased by about 28.5% and 46.6% for CBEM-50% and 100% OPC, respectively. Hence, it can be said that the flow of CBEM-100% OPC satisfied the GSRB requirements.

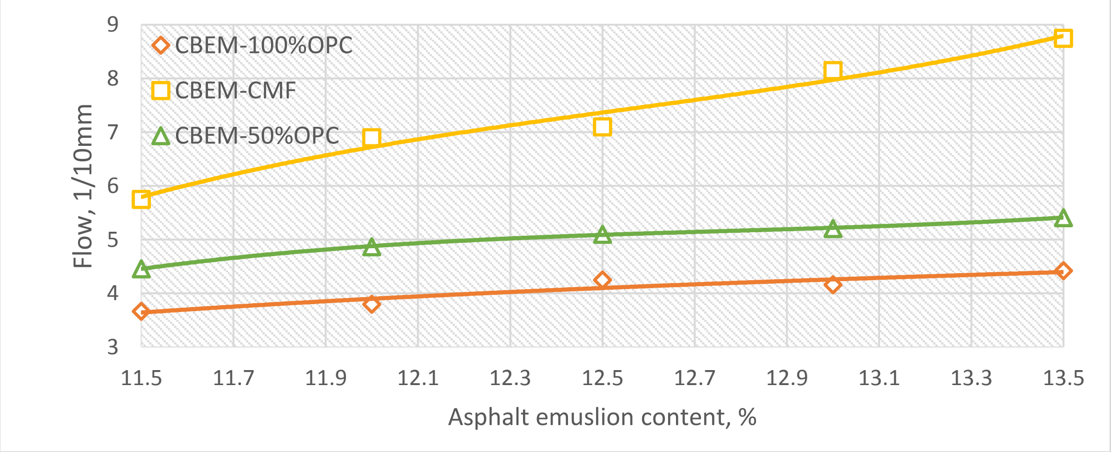


Figure 4.19 Flow vs. AEC% for CBEM comprised different OPC content

Stability- flow curves are plotted in Figure (4.20). CBEM-CMF is appeared no clear failure point, while improvement in CBEMs is appeared with different behavior compared to CBEM-CMF. Slopes of modified mixes were higher, and noticeable load failure points can be observed. It can also be observed from the figure that mix brittleness increased with higher slope line, i.e. 100% OPC modified CMA has the highest brittleness value compared to other mixes.

Until now, the newly developed CMA with 100% OPC filler has shown comparable properties to the HMA mix, and within limitations of GSRB in term of Marshall Stability, flow, and VMA%. Other important properties such as air void property have still high out of GSRB limitations.

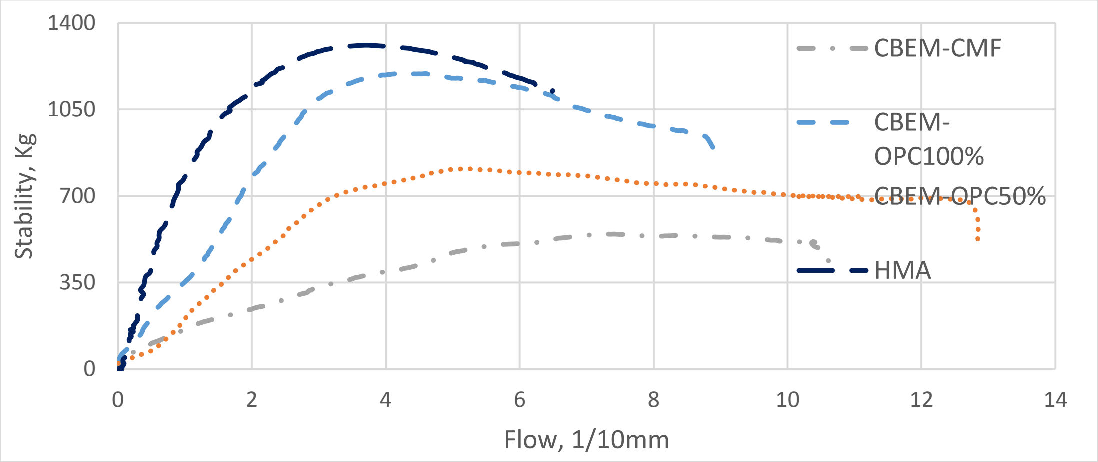


Figure 4.20 Stability-flow curves for CBEM comprised different OPC content compared with HMA

4.4.3.2 Wheel Track Test

Result data of wheel track test are organized in Figure (4.21). Although CBEM-100%OPC slab specimen contained 11.85% air voids, rutting was found to be 0.94 mm after 1000 cycle, on the contrary to HMA which has 7% air voids content, with a rut depth of 6.25 mm. Thus, it can be concluded that, CBEM with OPC filler has refuted the fact of decreasing air void content leading to decrease mixture rut depth when compared to HMA. The modified CBEM with OPC have changed mixture behavior and became more resistant to permanent deformation. The elastic phase of the developed CBEM has significantly outweighed the viscous one. Also, CBEM comprising OPC filler improved mixture resistance to rutting by 6.63 and 9.28 times compared with HMA and conventional CBEM-CMF, respectively.

Dynamic stability of CBEM-100%OPC mix compared to other mixes is presented in Figure (4.22). CBEM-100%OPC mix is higher than other mixes by 13.13 and 7.45 times compared to CBEM-CMF and HMA, respectively. OPC filler has improved efficiently the dynamic stability of CBEM mixture, and made it stiff enough to resist applied repeated loads, as a result of double binding process and absorption of the trapped water.

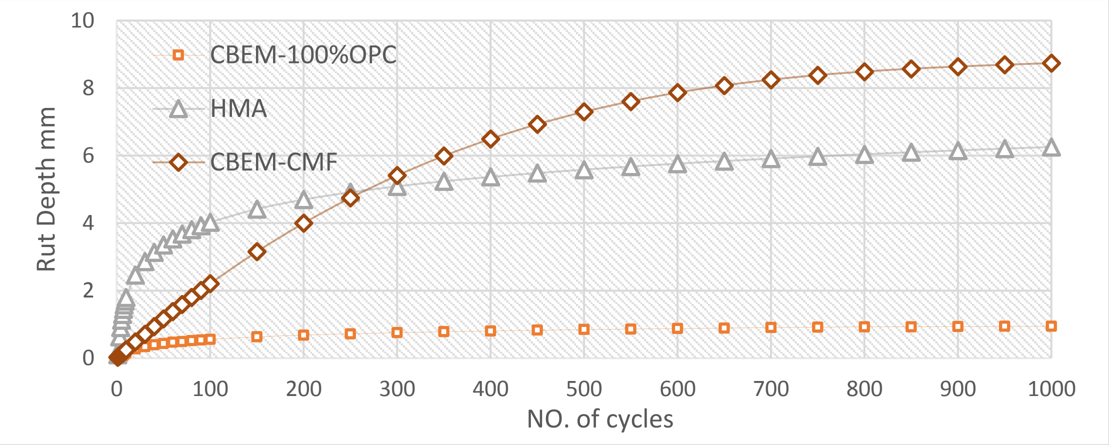


Figure 4.21 Rutting vs. number of cycle curves for CBEM comprised different OPC content compared with HMA.

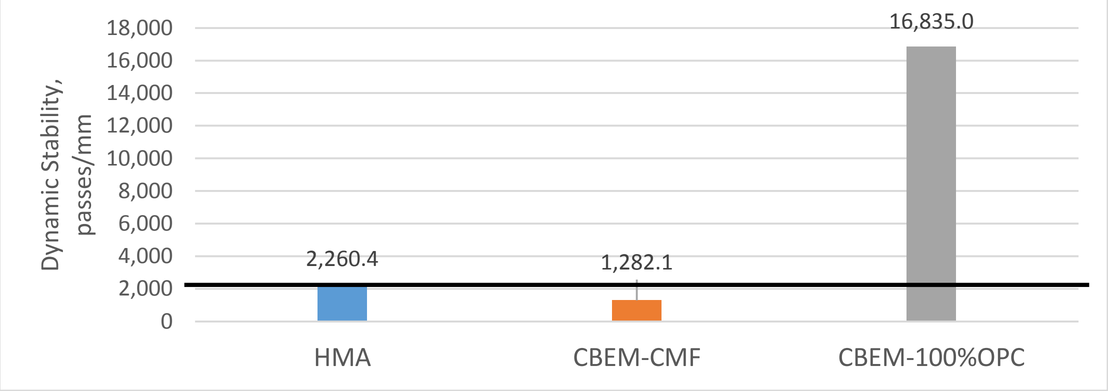


Figure 4.22 Dynamic stability for CBEM comprised different OPC content compared with HMA

4.4.3.3 Creep compliance test

The creep compliance test was performed for 100%OPC treated CBEM as plotted in Figure (4.23). The Same behavior observed in CBEM-CMF mixtures has noticed in CBEM-100% OPC, but with different creep levels. Creep rate at the first 20 seconds of testing time was relatively high, followed by gradual creep rate at 40 sec to the end of a test. The creep compliance of the CBEM-100%OPC has improved by about 55% compared to CBEM-CMF in spite of the applied constant load was increased to double. The developed mixture is still suffering high horizontal strain levels compared to

HMA. Tensile cracks growth was initially high at the early life of test, followed by transitional phase which material behavior in term of cracks prorogation has decreased to reach constant strain approximately at 50 sec to the end of the test.

Creep stiffness for tensile cracks results after 100 seconds are illustrated in Figure (4.24), which clears that OPC improved CBEM mix in term of crack propagation by 1.74 times compared to untreated mix. However, HMA mix still has the highest stiffness among other mixes.

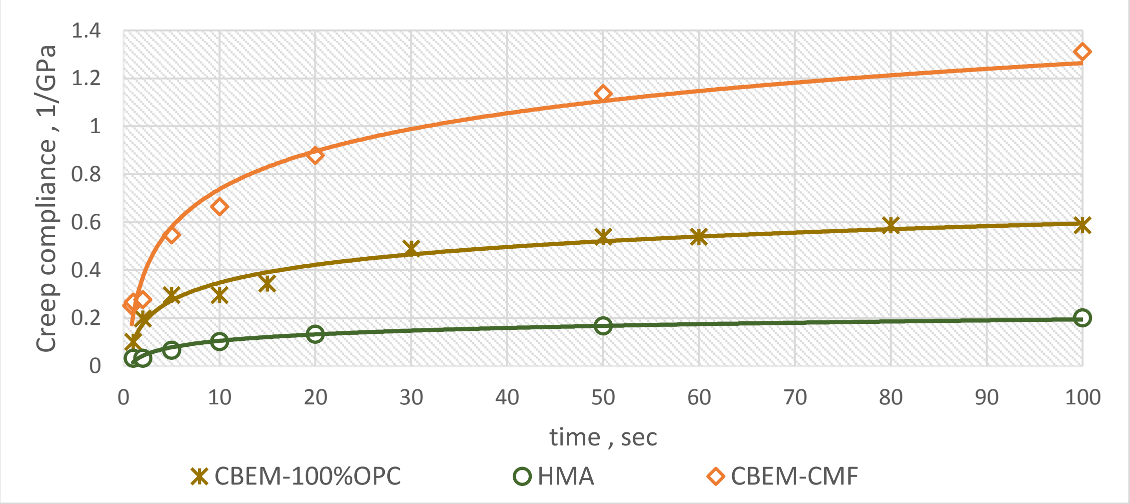


Figure 4.23 Creep compliance vs. time for CBEM comprised different OPC content compared with HMA

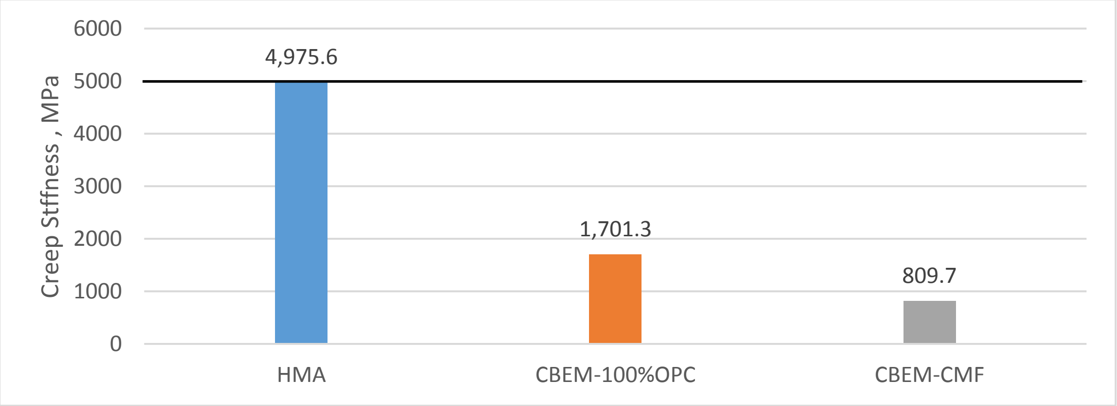


Figure 4.24 Creep stiffness for CBEM comprised different OPC content compared with HMA.

4.4.3.4 IDT Test Result

Test results of IDT for treated mixes with OPC filler are cleared in Figure (4.25), which shows significant improvement in resistance to tensile cracking compared to other mixes.

Addition of 100% OPC to CBEM has enhanced IDT about 4.88 times compared to CBEM-CMF. The treated mix has comparable strength to HMA.

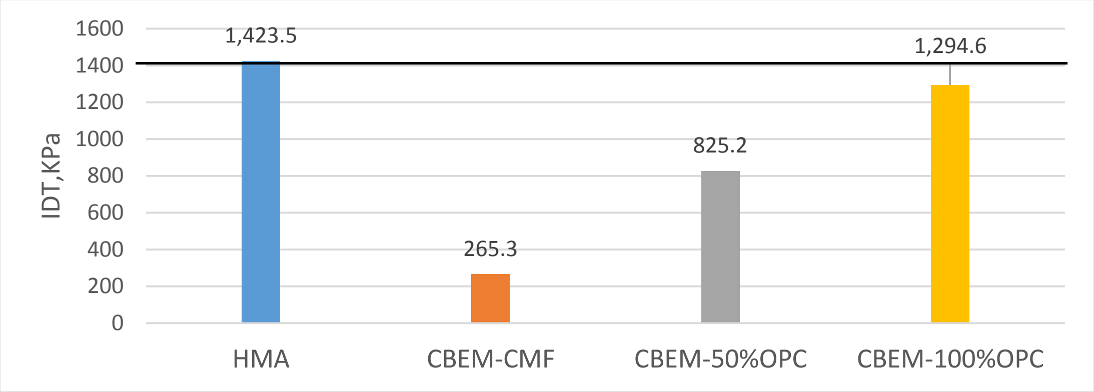


Figure 4.25 IDT% for CBEM comprised different OPC content compared with HMA

4.4.3.5 Water Sensitivity Tests

Water sensitivity in term of RMS is shown in Figure (4.26). At optimum Asphalt emulsion content, mixtures comprised CMF filler have poor and the lowest resistance to water action, On the contrary of the modified CBEM-OPC, which have the highest resistance to such conditions compared to CBEM-CMF and HMA. CBEM-100% OPC has RMS value above 100% since conditioned specimens have higher stability value than unconditioned one. It believed that some OPC particles have enhanced with required water to complete hydration process during specimens conditioning, which resulted in higher bonding property and higher stability.

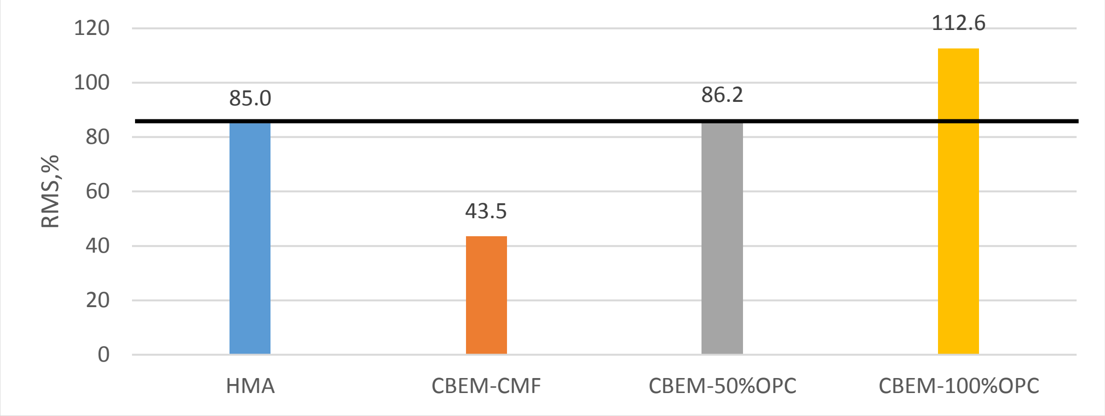


Figure 4.26 RMS% for CBEM comprised different OPC content compared with HMA.

Water damage in term of Retained Marshall Stability was performed at different emulsion content for CMA with and without OPC filler as presented in Figure (4.27). Test results clear that CBEM with CMF filler has maximum resistance to water action at 11.5% emulsion content. While in case of mixture comprised 50% OPC filler, a mixture highest resistance to such conditioning was 89% at 12.25% asphalt emulsion content, and 140% for mixtures incorporated 100% OPC filler at 13.5% asphalt emulsion content. It can observe that increasing amount of emulsion resulted in higher resistance to stripping because of a higher aggregate coating.

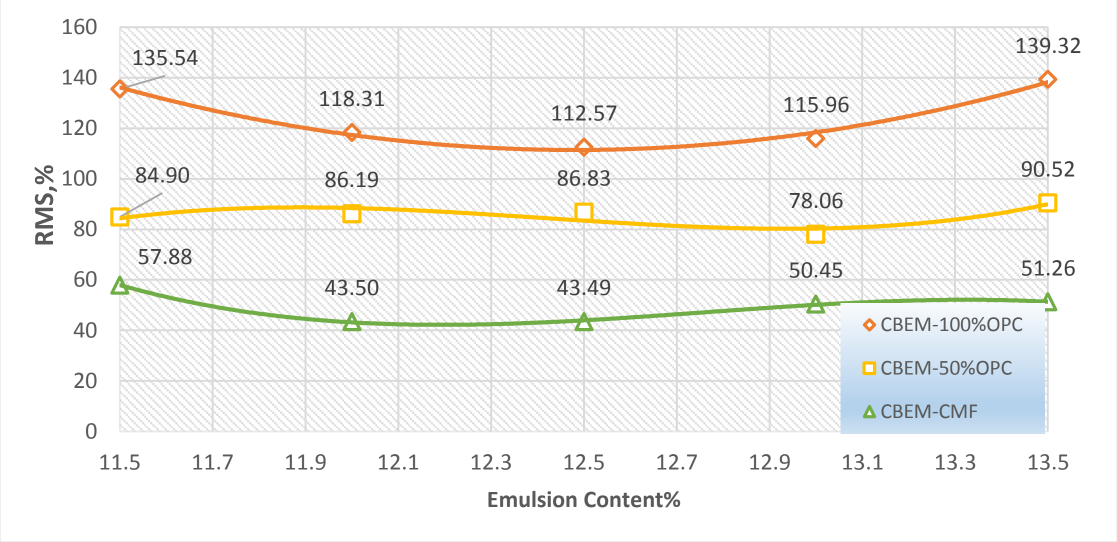


Figure 4.27 RMS% vs. AEC% IDT% for CBEM comprised different OPC content

From the same graph, it can be observed that OPC filler has improved CBEM resistance to water damage significantly, and in case of CBEM-100% OPC mixtures stability was higher than unconditioned specimens since a significant amount of cementitious materials have complete their reaction with water during conditioning. Thus, based on results discussed previously, it has taken full incorporation of 100% OPC as mineral filler instead of CMF for other development processes. It is worth to mention that CBEM treated with OPC has improved mechanical and durability properties significantly, but air voids content still high, and unsuitable according to GSRB requirements.

4.5 CBEMs Comprising Waste Crushed Glass as Fine Aggregates (CBEM-FGA)

An attempt to enhance or at less get acceptable mechanical and volumetric properties of CBEM according to GSRB specifications for surface layer by substitution virgin fine aggregate with waste glass with different percentages. Such approach will facilitate minimizing the huge impact of municipal waste on landfills, whereas the fine virgin aggregate percentage was replaced by fine glass aggregate (FGA) with four substitution percentages, namely, 25%, 50%, 75%, and 100%.

4.5.1 Mix Preparation

The new CBEMs were prepared under the followings:

- Aggregate: virgin course aggregate, with virgin and/or crushed waste glass fine aggregates (FGA).
- Gradation: same gradation used in Table (3.1).
- Filler material: OPC type for all glass aggregate substitution percentages.
- Emulsion type: cationic medium setting as described previously.
- Emulsion content was 12.5%.
- Pre-wetting water content: slightly less than what used in 100% incorporated OPC mixes, since glass absorbs water lower than virgin aggregate. The percent of water for coating purposes was reduced based on percent of glass content in mix, and ranged from 3.5% for 0% glass to 2.5% for 100% fine glass aggregate content.
- Aeration time: CBEM incorporated glass aggregate is suffering from a sloppy condition, even with reducing the amount of water for aggregate coating. Therefore, and to avoid losing time in waiting for reaching loose mixture better moisture condition, emulsion content was slightly reduced by about 10% for each 25% glass substitution.
- Compaction: same as described previously.
- Curing: same as described previously.

4.5.2 Volumetric Properties of CBEM-FGA

Density trend curves of CBEM-FGA are graphed in Figure (4.28). Noticeable reduction in mixture density is observed with higher amount of FGA. The reason for such reduction may be back to the physical properties of FGA. The density of GFA is lower than density of virgin fine aggregates, as can be seen in Table (3.3), however, with a higher amount of FGA in the mixture resulted in overall specimen’s density reduction. Moreover, FGA absorbs little water than virgin fine aggregates, which results in higher voids compared to untreated mix.

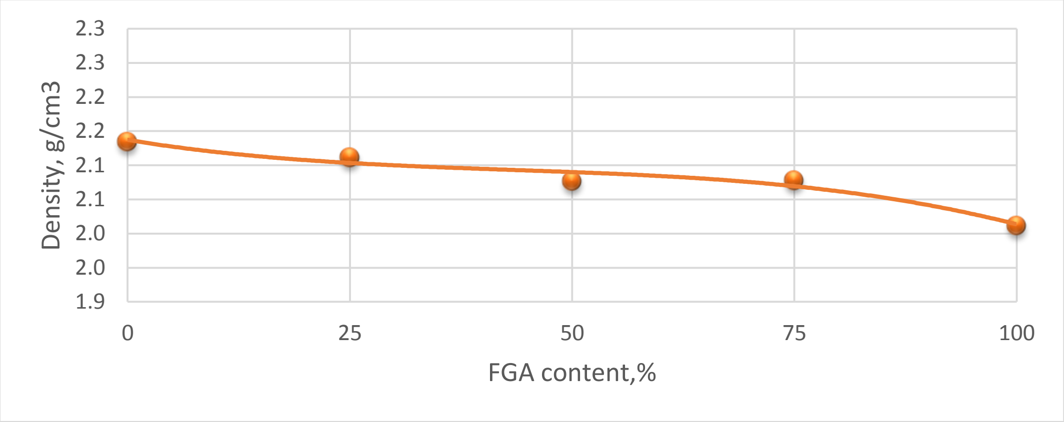


Figure 4.28 Density vs. FGA% content for CBEM

Air voids content results are illustrated in Figure (4.29). Significant incensement in air void content has been noticed with the higher doses of FGA in a mixture. FGA absorption compared to virgin FA is less by about 14.19%, which means large amount of trapped water will be free, resulting in a significant volume of voids will be left in the compacted specimen after evaporation. It has to mention that CBEM-FGA air voids ranged between 9% - 14.3%, which are unacceptable limits compared to GSRB or when compared to HMA. Also, a wide gap has observed when this range compared to CBEM-100% OPC, which contains 8.9% air voids.

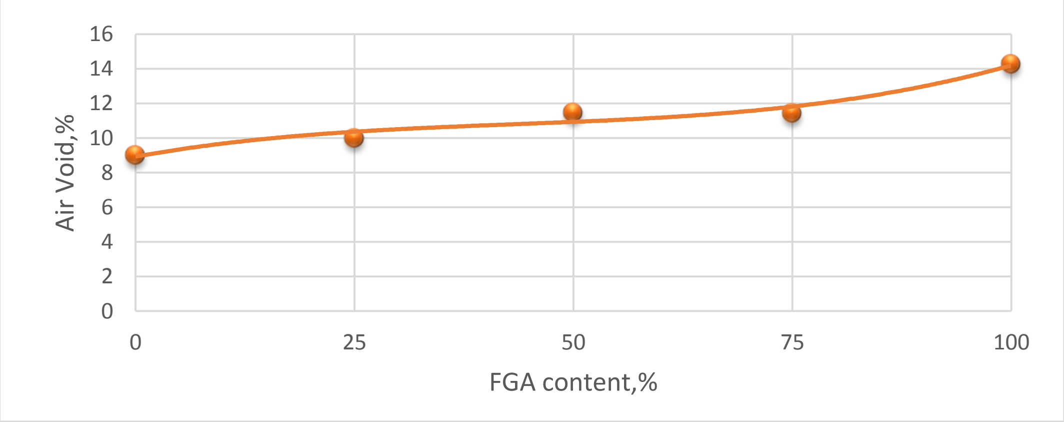


Figure 4.29 AV% vs. FGA% content for CBEM

The results of VFB% are cleared in Figure (4.30). The figure shows a reduction in VFB% values with the higher incorporation of FGA within the mix. The values are ranged from 32-43%, which are unfavorable range compared to GSRB. FGA has a lower amount of porosity compared to virgin FA, which resulted in such increase in the voids filed with water instead of binder.

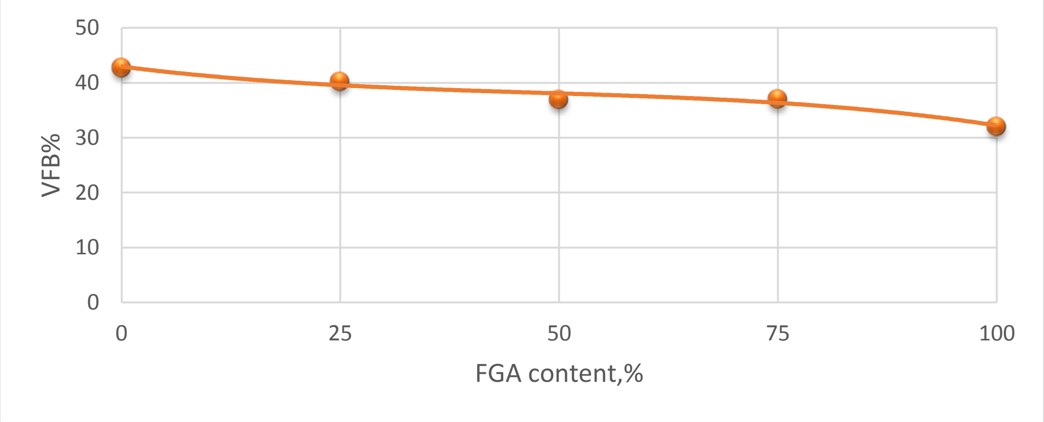


Figure 4.30 VFB% vs. FGA% content for CBEM

VMA% results are illustrated in Figure (4.31). VMA% values ranged between 15.75-21%. The resulted data are within GSRB limitations. The higher amount of VMA resulted from higher air voids due to higher existence to trapped water.

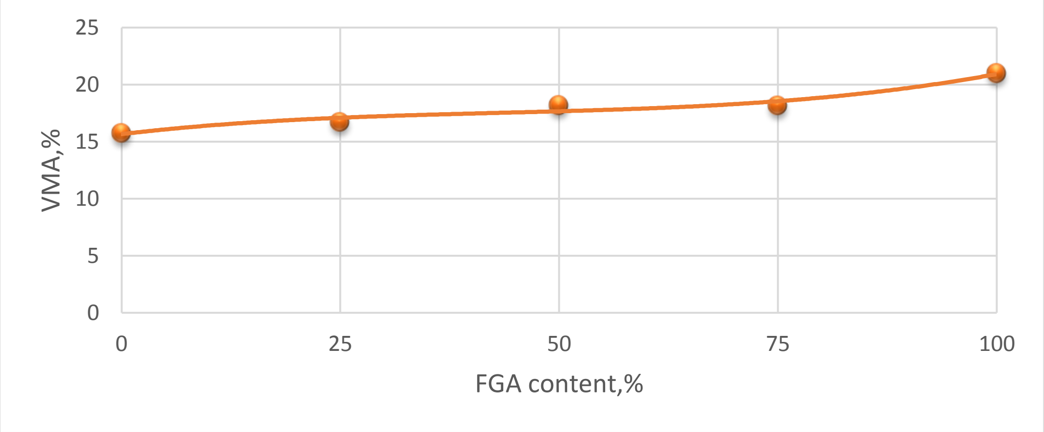


Figure 4.31 VMA% vs. FGA% content for CBEM

4.5.3 Mechanical Properties of CBEM-FGA

4.5.3.1 Marshall Mechanical Properties

Marshall Stability results are plotted in Figure (4.32). The curve clears a noticeable reduction in stability values with the higher amount of FGA up to 50%, followed by gradual rising up to 100% of FGA. Glass affinity with bitumen was lower than virgin aggregates relatively, which resulted in lowering adhesion property of bituminous mortar with new aggregates composite. On the other hand, FGA particles can interlock better than virgin aggregate since FGA particles have irregular edges and the degree of crushing is higher than VFA%. It is interesting to say that all FGA incorporation percentages are within the requirement of GSRB in term of stability (i.e., >800 Kg).

Marshall Flow results are shown in Figure (4.33). The graph clears that flow values are increasing proportionally with FGA up to 40% with 7.1 mm flow, follows by gradual reduction to reach 4.1 mm at 100% FGA substitution. Incorporation of 100% FGA resulted in a slight rising of Marshall Flow, and seem to be unacceptable with GSRB requirements since all values are above higher limits of criteria (4 mm). CBEM comprising100%FGA shows 4.1 mm flow value, which above the higher limit about 0.1 mm.

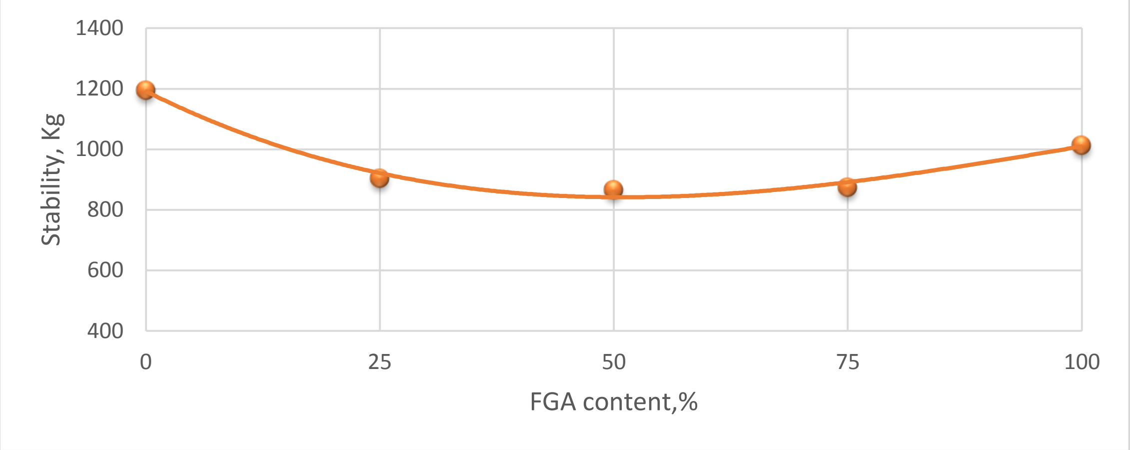


Figure 4.32 Stability vs. FGA% content for CBEM

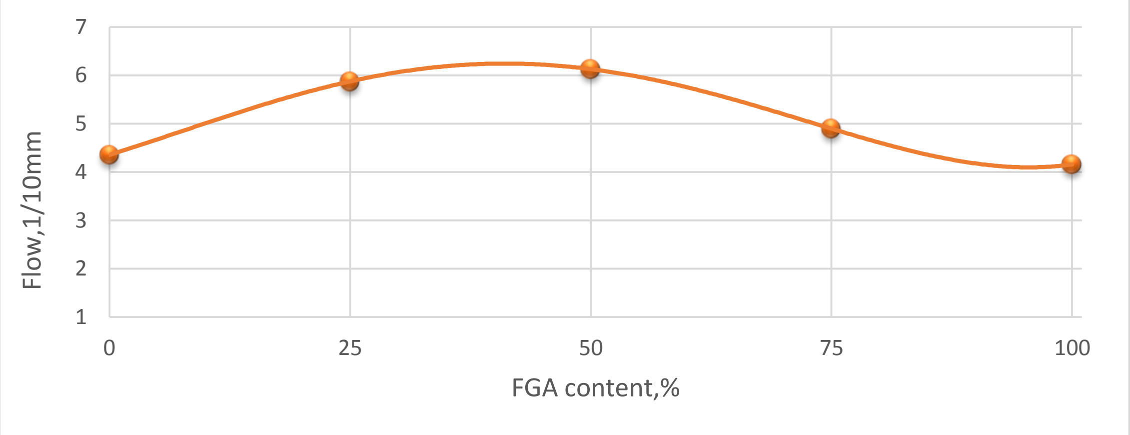


Figure 4.33 Flow vs. FGA% content for CBEM

The stability – flow curves has also constructed for each incorporation percentage, and compared with untreated mix as illustrated in Figure (4.34). The Figure shows that HMA curve has the highest among than other mixes curves, but curves associate more similarity and close to HMA behavior with an increase in FGA content.

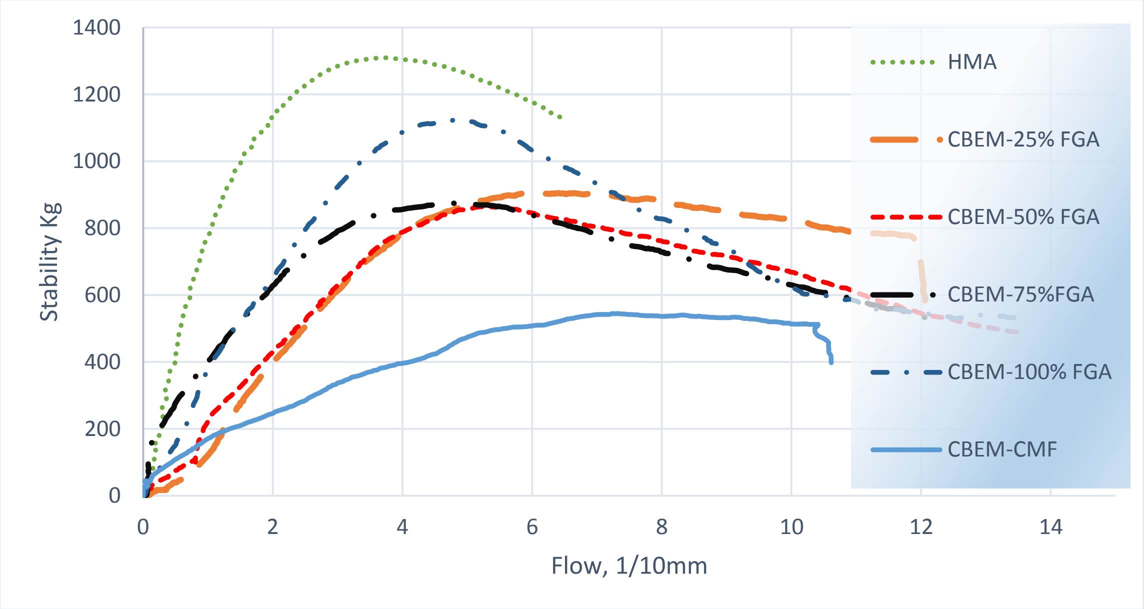


Figure 4.34 Stability-Flow curves for CBEM comprised different FGA% content compared with CBEM-CMF and HMA

4.5.3.2 Wheel Track Test

The new mix was also evaluated in term of resistance to permanent deformation using WTT, which performed for all percentages of FGA as cleared in Figure (4.35). After 1000 cycles in the device, the result of data showed the following points:

- Mix incorporated 25% FGA behaved as untreated mix (CBEM-100%OPC), in which no change occurred during the test.
- In case of specimens incorporated with 50% FGA, rut depth value was 1.4 mm, which more than untreated mix about 32.1%.
- For 75% FGA substituted mixture, the value of rutting was less than rutting of 25% FGA specimens by about 12% , and higher than untreated mix by about 38%.
- 100% FGA treated mix showed 2.5 mm rut depth.
- Rutting values for various FGA percentages were less than conventional cold mix and HMA, and were acceptable according to specifications.
- Dynamic stability results are plotted in Figure (2.36), which clears that all values of CBEM comprising FGA were higher than HMA and CBEM-CMF, but lower than CBEM-100%OPC

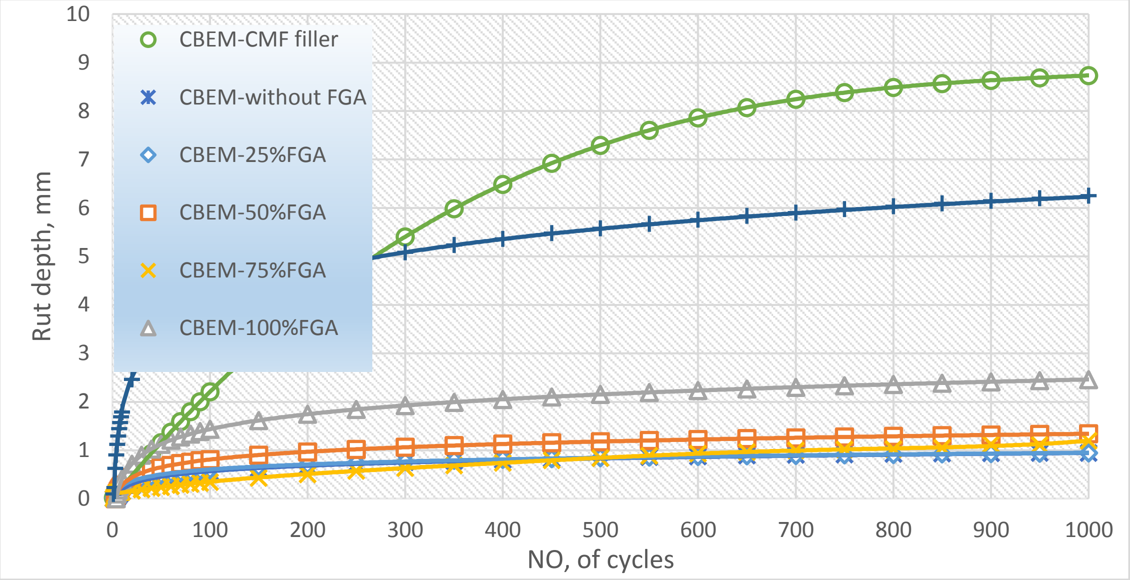


Figure 4.35 Rut depth vs. number of cycle curves for CBEM comprised different FGA% content compared with CBEM-CMF and HMA

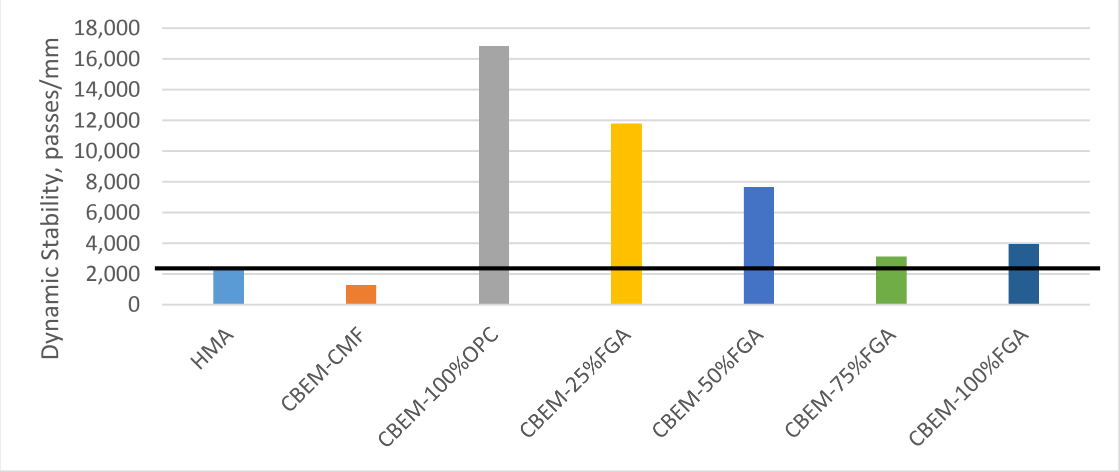


Figure 4.36 Dynamic stability for CBEM comprised different FGA% content compared with CBEM-CMF and HMA

4.5.3.3 Creep Complicate Test

Creep compliance test was performed to evaluate mixtures behavior in term of crack progression resistance with time for all FGA percentages. Based on results in Figure (4.37), the following points can be observed:

- Mixture with 75 and 100% FGA, have lower compliance than other CBEM incorporated FGA, which means higher stiffness in term of tensile cracking resistance.
- It can be observed that CBEM with 75 and 100% have a comparable compliance to HMA, and showed better compliance compared to untreated CBEM.

- Such improvement could be a result of enhancement in particle interlock due to angularity of FGA, in addition to minimizing the pre wetting water content of the CBEM with FGA.

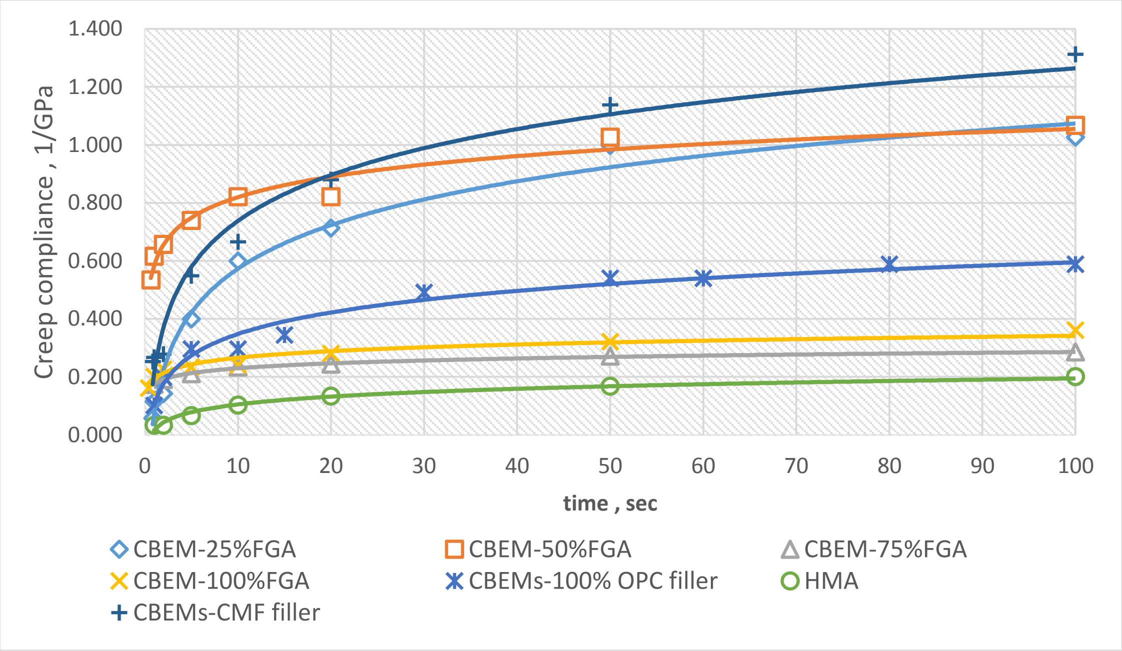


Figure 4.37 Creep compliance vs. time curves for CBEM comprised different FGA% content compared with CBEM-CMF and HMA

Creep stiffness results are plotted in Figure (4.38), which clears that CBEM incorporated FGA has CS higher than CBEM-CMF, but still incomparable to HMA, except CBEM-75%FGA, which seem to be comparable to HMA in such strength resistance.

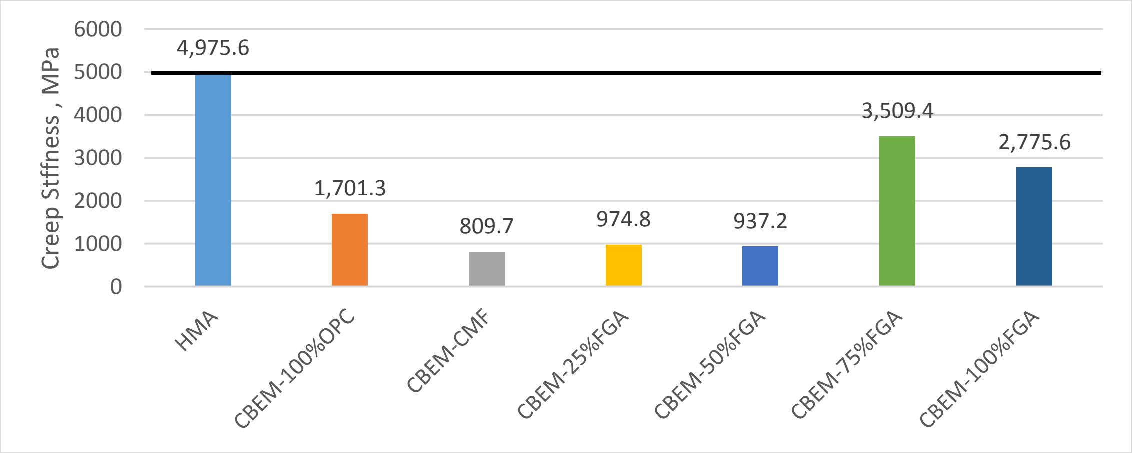


Figure 4.38 Creep stiffness of mixture crack resistance for CBEM comprised different FGA% content compared with CBEM-CMF and HMA.

4.5.3.4 IDT Test Results

Test results as presented in Figure (4.39) have cleared that FGA% in CBEM has a comparable effect to virgin aggregates. IDT results for all CBEM incorporated various FGA percentages have comparable properties to HMA. Till now, it has to mention that HMA, in term of IDT, is still the superior one. The glass particles angularity has significant effect on mixture strength in term of crack resistance, in addition to the reduction in pre-wetting water content of the CBEM with FGA.

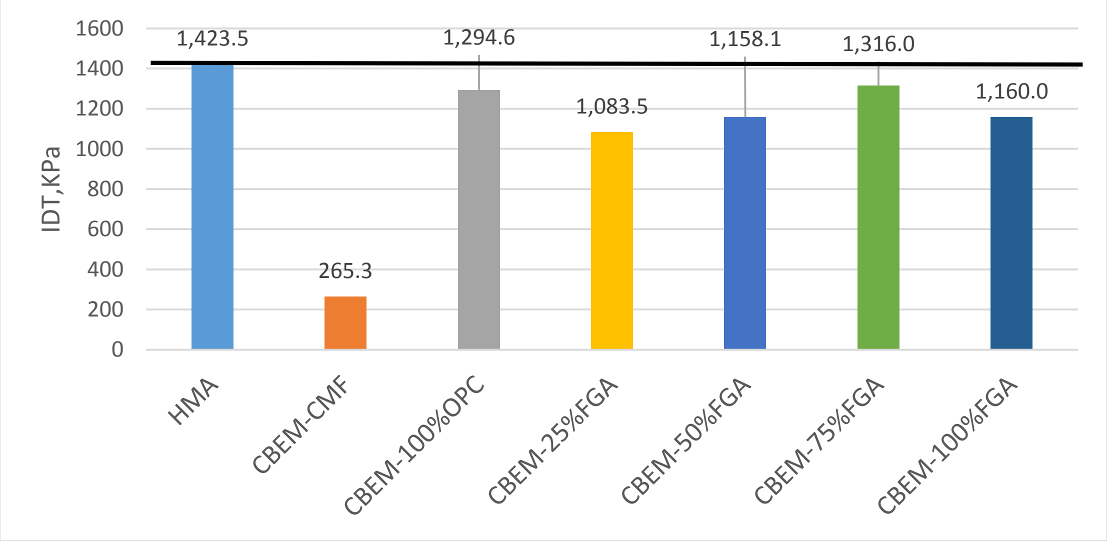


Figure 4.39 IDT% for CBEM comprised different FGA% content compared with CBEM-CMF and HMA.

4.5.3.5 Water Sensitivity Tests

Water damage effect on CBEM incorporated FGA was evaluated in term of RMS as plotted in Figure (4.40). The figure clears a superior or at least comparable results of the new mixtures compared to HMA and CBEM-CMF. Where all FGA dosing values result within limitations of GSRB. There was a noticeable reduction in RMS values in contrast to CBEM-OPC, but this reduction still keep the value over the specification limits, and comparative to HMA value. Such reduction could be a result of minimizing in the bounding of binder (both cement and emulsion) with fine aggregates; in other words, as FGA increase less bonding associated.

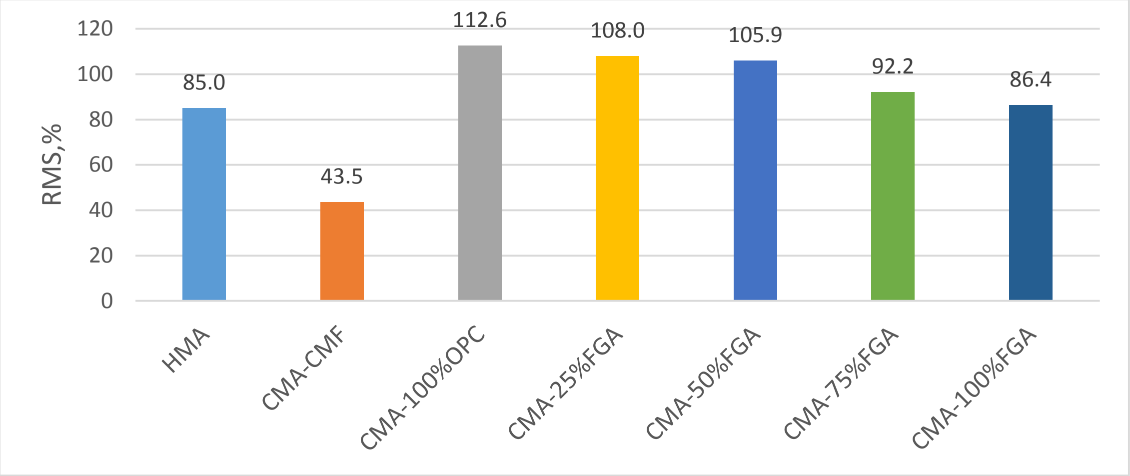


Figure 4.40 RMS% for CBEM comprised different FGA% content compared with CBEM-CMF and HMA

4.6 Summary

The results of the conducted testing program for improving CBEM using different materials, can be summarized in the following points:

1- Testing program confirms previous researches findings of the inferiority of CBEM in contrast to HMA in terms of volumetric, mechanical and durability properties

2- Testing program confirms previous researches findings of the ability of OPC to improve CBEM to comparative level of HMA in terms of mechanical and durability properties. But, volumetric properties still with unacceptable level by the specification.

3- Testing program and for the first time proves the ability totally or partially to replace virgin materials by municipal waste material (FGA), where the developed CBEM-FGA still have almost the same advantages of mechanical and durability of CBEM-OPC characteristics. Nevertheless, again the volumetric properties still with unacceptable level by the specification.

Chapter Five

TEST RESULTS AND ANALYSIS - PHASE 2: FURTHER ENHANCING TO CBEMS UTILIZING LOW ENERGY HEATING

5.1 Introduction

This Chapter reveals the results of the experimental study that has been conducted to overcoming the inferiority of volumetric properties of developed CBEM with the aid of low energy heating; i.e., by utilizing microwave energy. The experimental process included the determination of the optimum time required for heating of CBEM that reflects best mix volumetric properties within the specified limitation of Iraqi GSRB.

It is interesting to say that till now, CBEM incorporated 100% waste glass has acceptable mechanical properties, but still suffering from high air voids content which is not allowed by GSRB specifications for the surface layer. Thus, the success of such attempt facilitates new CBEM with satisfactory mechanical, volumetric and durability properties, further to the sustainable solution, i.e., replacing virgin materials by waste material, and using low energy technique.

5.2 Determination of Optimum Heating Time

The trapped water within CBEM makes it suffers from high air voids and undesirable properties compared to HMA. Therefore, the purpose of heating of CBEM is to increase the rate of water evaporation, indeed, higher mix temperature facilitates lower viscosity of the bitumen ensure better coating and get higher properties at early life. To determine the optimum microwave heating time, the following points were followed for mix preparation:

- Virgin Aggregates used with gradation as cleared in Table (3.1).
- OPC is used as filler material.
- Cationic medium setting bitumen emulsion type.
- 3.5% pre-wetting water content was used.
- 12.5% bitumen emulsion content was added.

- After mixing, the mentioned components, loose mixture was exposed to microwave home-type heating with low level application output power at different time ranging from 1.5 to 7.5 min, with 1.5 min time incremental step.
- Then mixture is molded quickly and applied to the specific required compaction according to the test method, using the same effort as that mentioned previously in Chapter three.
- Curing: same curing protocols were applied as mentioned in the testing methods.

However, the temperatures of the treated mixes were recorded after the heating process. Figure (5.1) presents the relation between microwave heating times and associated mixture temperatures for CBEM. It is worth to mention that almost treatment temperature is under 100 °C. Thus, the new developed mix can be called Half Warm Bitumen Emulsion Mixture (HWBEM).

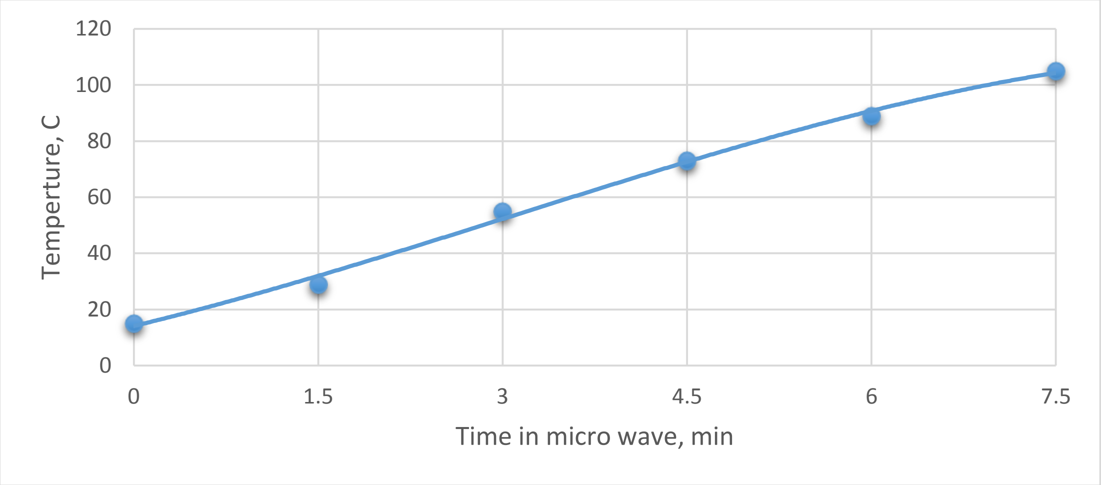


Figure 5.1 Temperature vs. heating time in microwave

5.2.1 Effect of Microwave Post Heating on HWBEM Volumetric Properties

Figure (5.2) demonstrates the increases in densities of the mixes with the increase in heating time, up to 6 min. This could be a result of, firstly, decrease in binder viscosity due to increase in mix temperature which in turns increases the workability of the mix, and secondly, the losing of water by evaporation. Both are led to decreasing voids in the compacted specimen at constant volume. After 6 min heating time, a noticeable reduction in density value observed, which could be due to significant loss of water. It is believed that in HWBEM both water and moderate mix temperature are after the workability of the mix. A balance should be achieved between the required quantity of water and temperature to facilitate the optimum workability, and ensure the best backing of material during compaction.

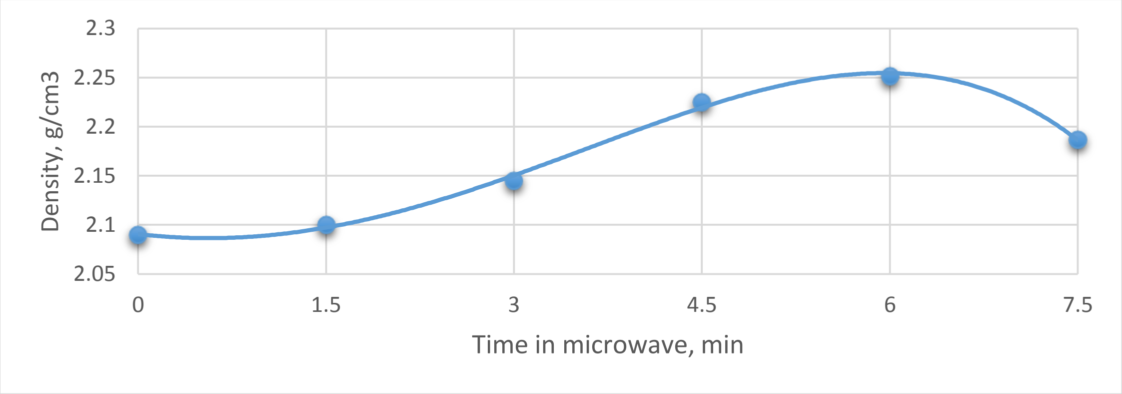


Figure 5.2 Density vs. heating time in microwave

Air voids content results are demonstrated in Figure (5.3). A Significant reduction in air voids content with higher post-heating time as recognized, which is due to loss of trapped water up to 6 min, followed by noticeable increasing in air voids content since the high amount of moisture has been evaporated which affect the workability as explained before. Up to 6 min heating, which associates a mix temperature of 91°C, the air voids reach to a level of 4%.

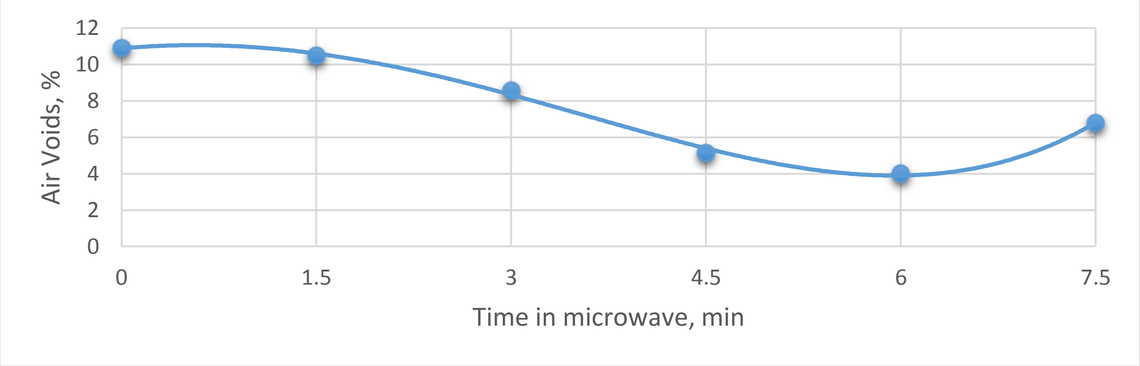


Figure 5.3 AV% vs. heating time in microwave

VMA% and VFB% results are cleared in Figures (5.4) and (5.5), respectively, which clears the significant enhancement in the resulted during heating mixture, for the same reasons.

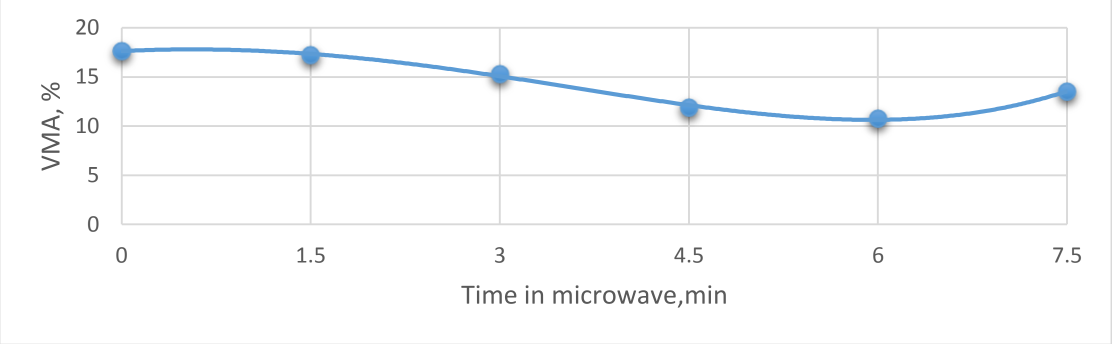


Figure 5.4 VMA% vs. heating time in microwave

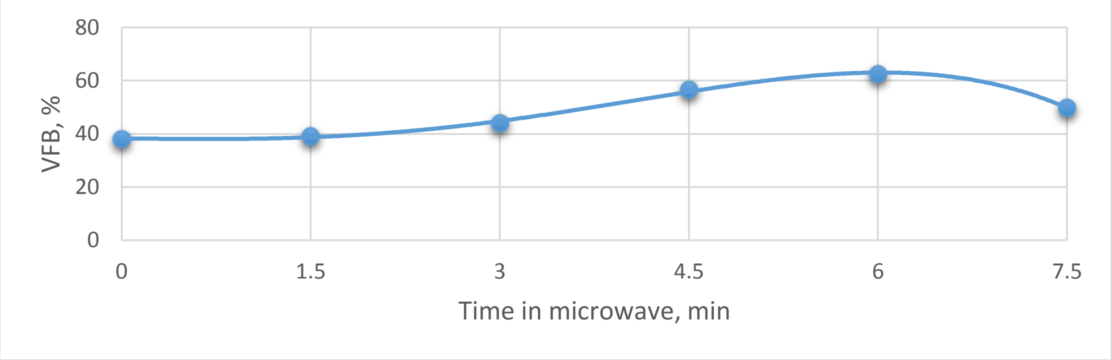


Figure 5.5 VFB% vs. heating time in microwave

5.2.2 Microwave Heating Time – Marshall Mechanical Properties Relationships

Figure (5.6) illustrates Marshall Stability of HWBEM. Marshall Stability increase very slightly with heating time gradually up to 3 min, as a result of the low internal evaporation rate of water. Then, a significant increases in the results were observed up to 6 min, followed by a drop in Marshall stability after 7.5 min heating time. In the first phase, the amount of water was decreased with the increase in the heating time, which is believed that the remaining water content is sufficient to complete cement hydration to produce the secondary binding, until 6 min heating time. Of course, this is led to further reduction in air voids and increase in density. Extra heating causes a removal in the required water for hydration process, which in its turn decrease Marshall stability. It is worth to mention that lowering bitumen viscosity helps in better coating and better characteristics of primary bonding agent, but it is still insufficient to resist deformation as the base bitumen grade is (100-150).

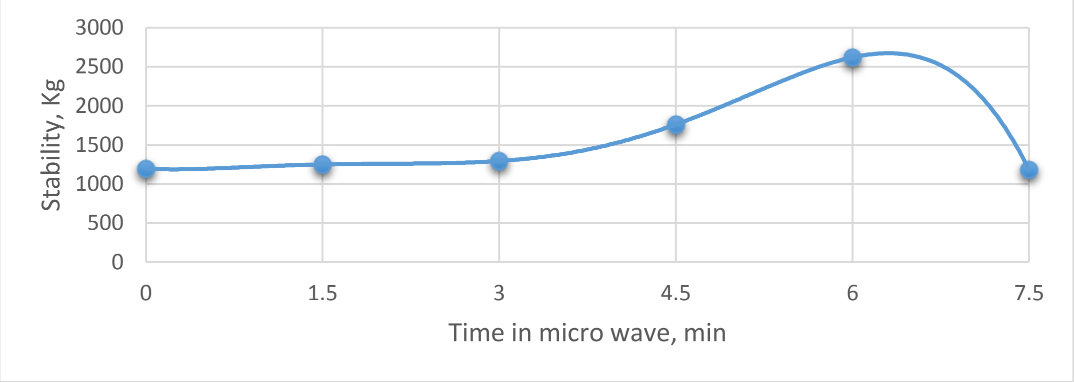


Figure 5.6 Stability vs. heating time in microwave

Marshall flow is illustrated in Figure (5.7), the values decreased with the gradual increasing in heating time. The resulted flow values ranged between 2-3mm, which reflects good indication of mixture resistance to plastic deformations. Heat enhances coating percentages, as mentioned previously, in which, good binder and aggregates coating lead to enhance the interface connection in more flexible media. In CBEM-OPC the interface between the binder and aggregates is gathered with less primary binder, where the secondary binder is brittle and has less flexibility.

Stability- flow curves are plotted in Figure (5.8), which clears that slope of microwave-treated mix (HWBEM) is relatively higher than other mixes in term of stiffness. However, it has to say that such mix behavior is better in contrast to other mixes, i.e. HMA, CBEM-OPC, and Conventional CBEM.

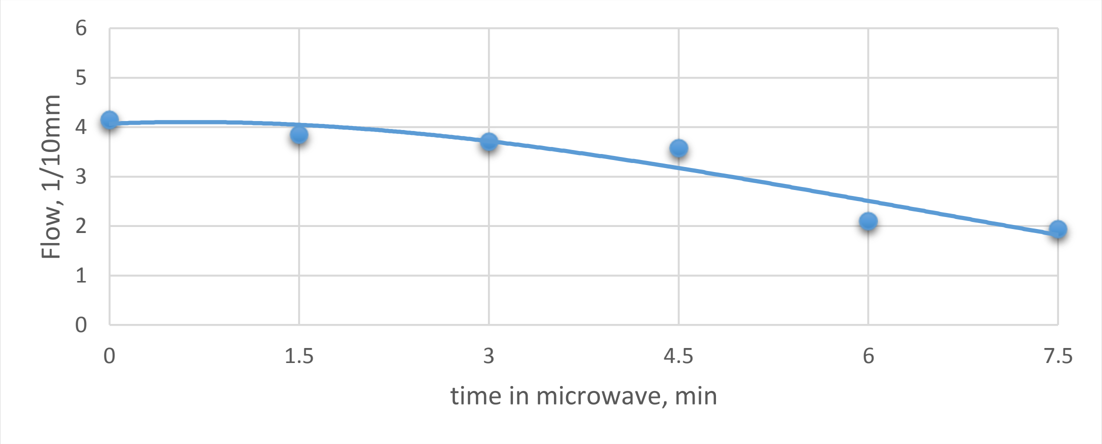


Figure 5.7 Flow vs. heating time in microwave

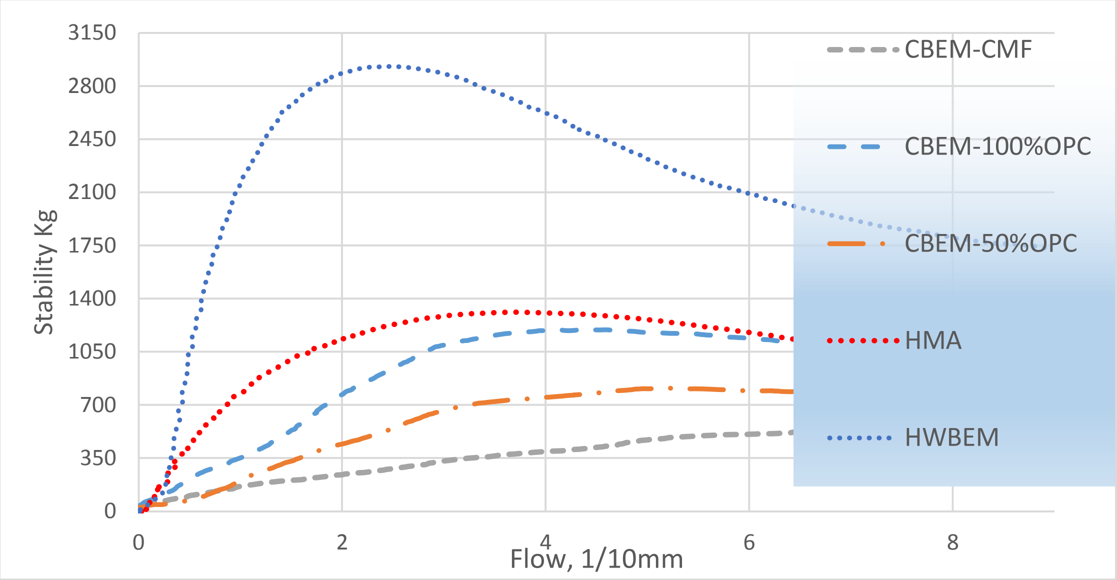


Figure 5.8 Stability-flow curves for HWBEM compared with CBEM-CMF, CBEM with diff OPC content, and HMA

Based on the mechanical and volumetric results, which were illustrated previously, the following points can be concluded:

- Optimum heating time of microwave (OPHTM) has been found to be 6 minutes, which associated to mix temperature of 91 °C.
- As heating in microwave for CBEM reflects 91 °C (<100 °C) mix temperature, the new mixture can be classified under half warm bituminous mixtures category.
- After selecting OPHTM the following sub points are observed as listened below:
    - Marshall Stability increased to triple compared to CBEM-OPC 100%, six times CBEM-CMF, and to double compared to HMA.
    - Marshall Flow property was enhanced perfectly, and the resulted value within limitations of GSRB (i.e., 2.5 mm). Flow property decreased by about 50% compared to CBEM-OPC100%, and about 290% compared to CBEM-CMF.
    - Air voids content of the new developed HWBEM was 4%, which is within GSRB requirements (3-5%). The AV% reduced about by 50% compared to CBEM-CMF and CBEM-OPC100%.
    - As a result, density, FBA, and VMA enhanced sufficiently.

Hence, 6 min heating in microwave was adopted for other tests and other modification processes, since it has been noticed that such level has significant enhancement on mix volumetric and mechanical properties.

5.2.3 Wheel Track Test

Wheel track test results are plotted in Figure (5.9). The results show high rutting resistance compared to CBEM-CMF and HMA mixes. The resulted rut depth after 1000 cycles was 0.7 mm. Rutting has decreased about 8.7 times compared to HMA, and about 15.6 times compared to CBEM-CMF. No noticeable difference between the new HWBEM and the CBEM-OPC was observed. The small value of rutting is an indication of high mix stiffness. From the other side, it is clear that the viscous phase of the new mix was rather poor, while the elastic phase was the controller one, and this is an unfavorable indication since mixture has become too brittle.

Dynamic Stability (DS) results are illustrated in Figure (5.10), which clears that treated mix with microwave improves the stiffness significantly. DS of the treated mix enhanced by about 8.38 times the HMA, and about 12 times than CBEM-CMF. The same explanation that mentioned in the previous section can be adopted here as the reasons for this enhancement in the new mix characteristics.

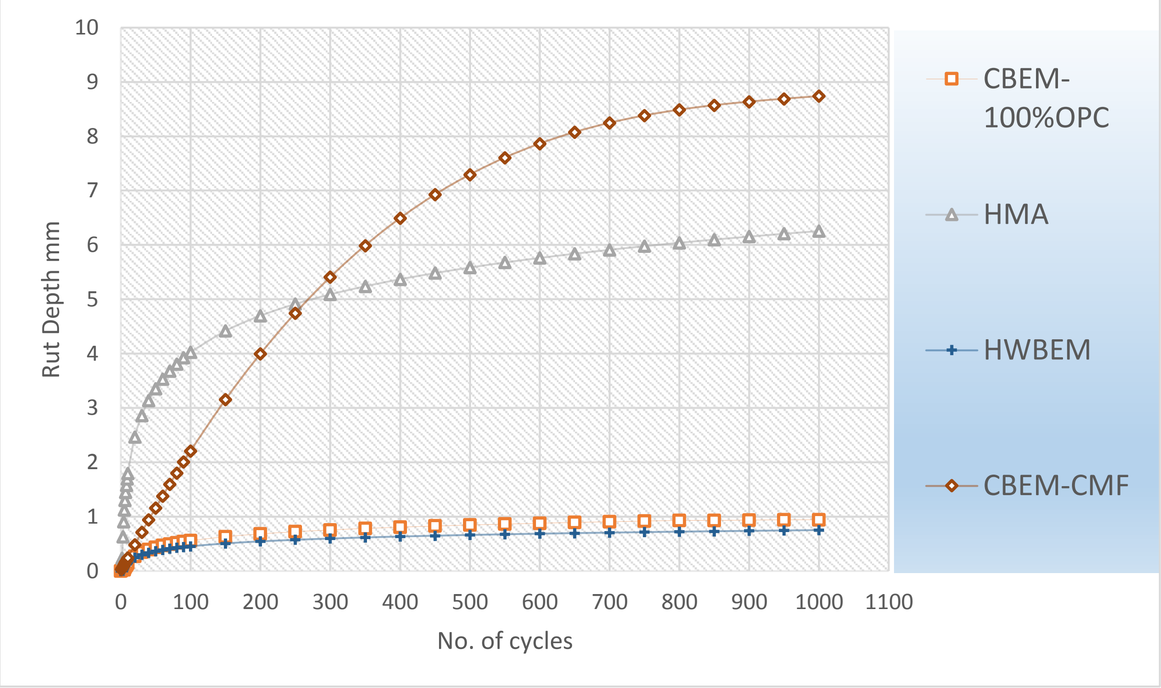


Figure 5.9 Rutting vs. number of cycle’s curves for HWBEM compared with HMA, CBEM-CMF, and CBEM-100%OPC

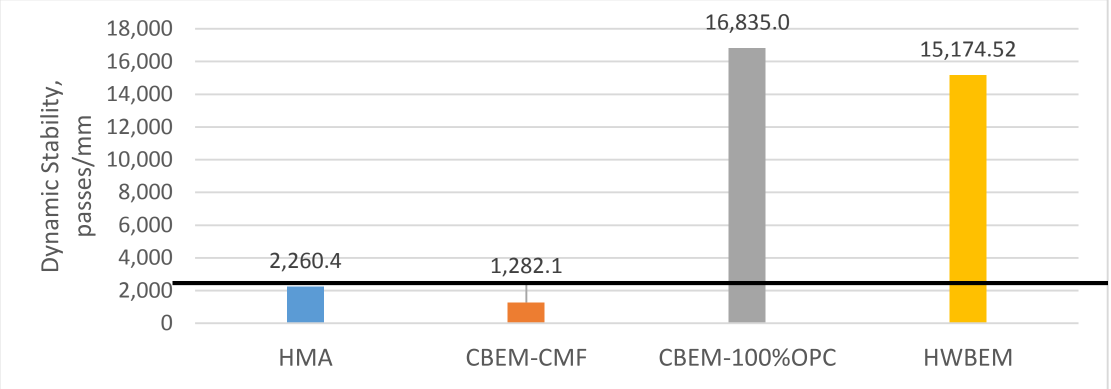


Figure 5.10 Dynamic stability for HWBEM compared with HMA, CBEM-CMF, and CBEM-100%OPC.

5.2.4 Creep Compliance and Creep Stiffness

Test results of CC is cleared in Figure (5.11), which shows that there is a noticeable reduction in CC behavior for HWBEM, and reflects an enhancement in crack progression characteristics. Also, HWBEM curve behavior was similar to HMA. HWBEM enhanced by about 2.87 times compared to CBEM-CMF, but HMA still have lower CC than other mixes.

CS of HWCBEM are plotted in Figure (5.12). CS for the HWBEM has enhanced, but it still lower than HMA creep tensile crack stiffness. This could be related to grade of the base binder.

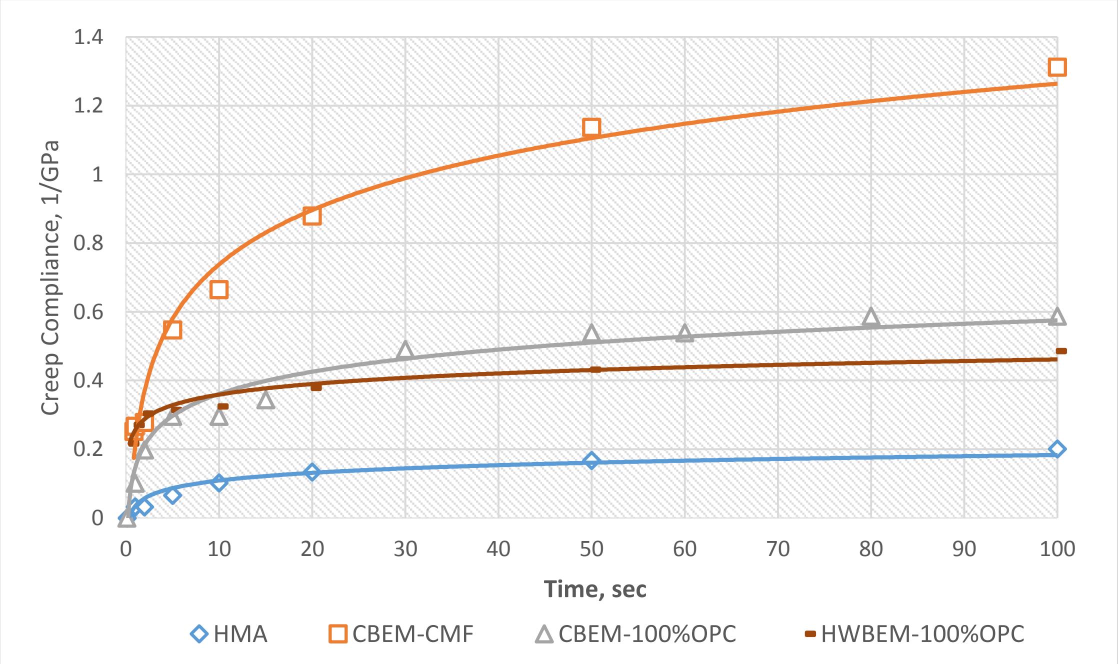


Figure 5.11 Creep compliance for HWBEM compared with other mixes

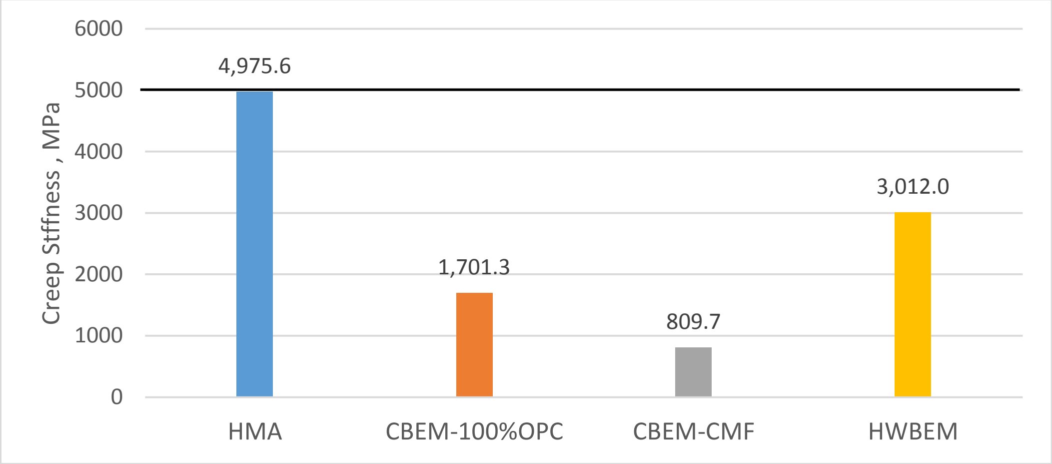


Figure 5.12 Creep stiffness after 100 sec for HWBEM compared with HMA and CBEM-CMF mixes.

5.2.5 IDT Test Result

IDT test results have shown that HWBEM has higher tensile resistance than HMA and CBEM-CMF, as can be seen in Figure (5.13). Max tensile cracking resistance improved by about 1.34 and 7.24 compared HMA and CBEM-CMF, respectively.

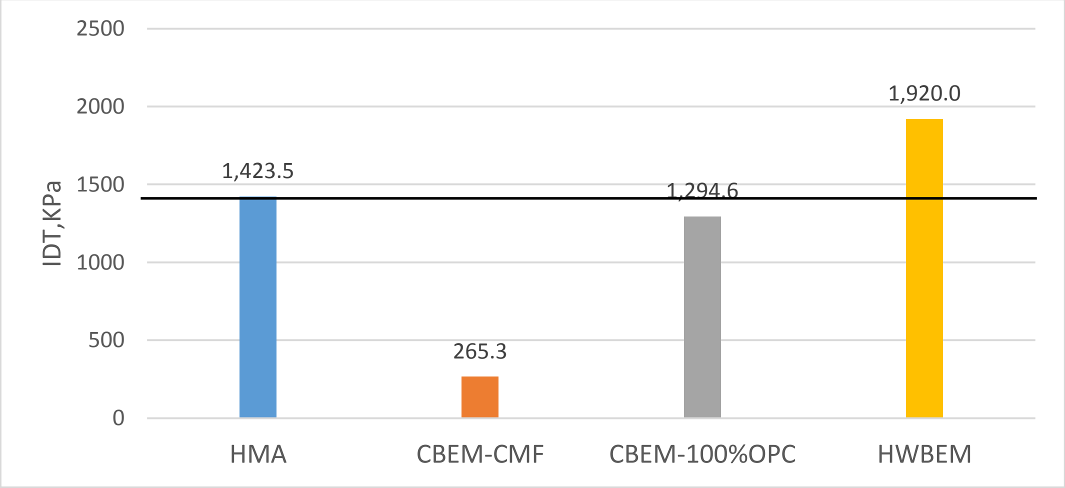


Figure 5.13 IDT for HWBEM compared with HMA, CBEM-CMF, and CBEM-100%OPC

5.2.6 RMS Results

In term of retained Marshall Stability, resistance to water action of the developed mix has improved significantly as can be seen in Figure (5.14). The mix improved by about 1.47 and 2.88 times HMA and CBEM-CMF mixes, respectively. This is mainly as a reflection of the improvement in the volumetric characteristics, which prevent the stripping by prevent ingress of water during conditioning.

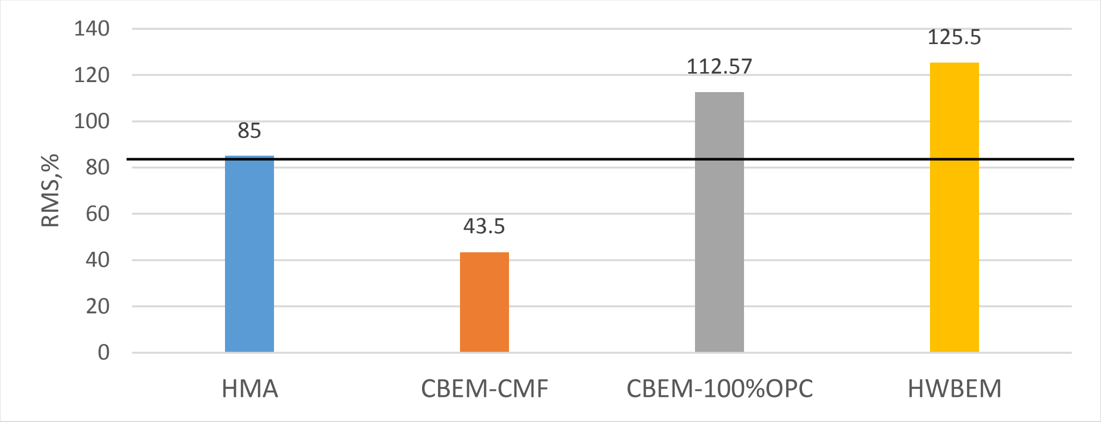


Figure 5.14 RMS% for HWBEM compared with HMA, CBEM-CMF, and CBEM-100%OPC

5.3 HWBEM Comprised FGA

In this section, results of an attempt to prepare heated CBEM incorporated FGA are described. The preparation of mix includes the same points mentioned in section (5.2) with one modification, which is subjected the loose mixture to heating in house microwave device for 6 min, as this time was determined previously as an optimum. The results are plotted and compared with untreated mixes.

5.3.1 HWBEM – FGA% Volumetric Properties

Density results are plotted in Figure (5.15) for both treated and untreated CBEM contained FGA. The treated density results were higher than untreated ones, for all GFA percentages, and they ranged between 2.205-2.26 g/cm^3. Also, a gradual reduction in density value of compacted specimens was observed with increasing amount of FGA%, which could be due to the increase in the angularity that resists compaction efforts and accompany be a low density of glass particles to virgin fine aggregates. Nevertheless, at 100% FGA, average incensement in density due to heating is 9.6%. The resulted value of density is comparable to HMA, and higher than CBEM-CMF and CBEM-OPC100%.

Air voids content results are presented in Figure (5.16). A significant improvement was observed compared to the untreated mix. The new mix has AV% ranges between 2.69-6.33%, while the untreated mix has AV% ranges between 9.02-14.28%. The resulted values were comparable to HMA, and within GSRB limits. About 55.6% enhancement was achieved in term of AV% compared to untreated mix having 100% FGA. Such enhancement could be back to the improvement in workability of the mix, as explained previously.

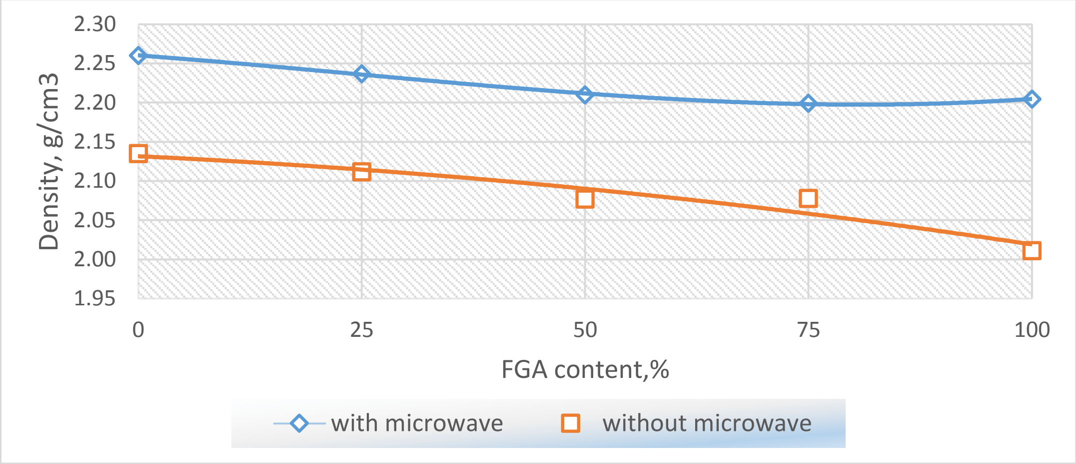


Figure 5.15 Density vs. FGA% content for HWBEM compared with CBEM mixes

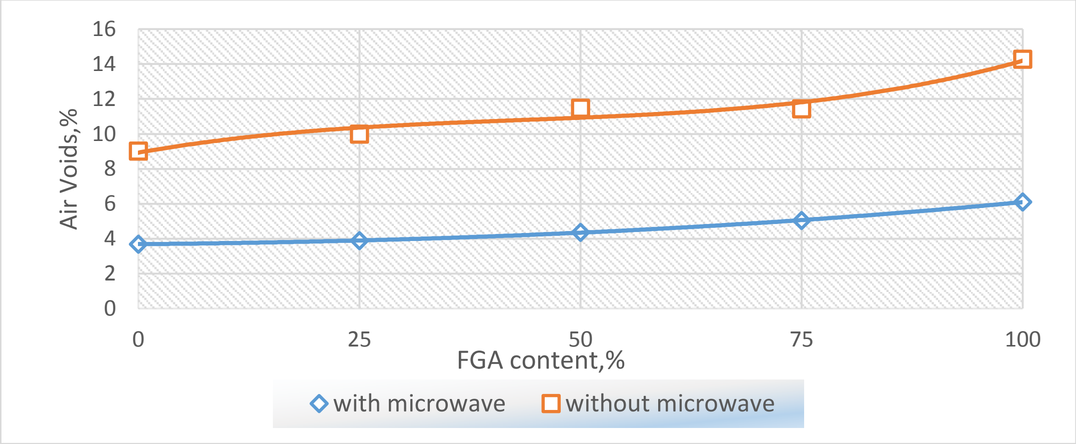


Figure 5.16 AV% vs. FGA% content for HWBEM compared with CBEM mixes

VFB and VMA were also enhanced, as cleared in Figures (5.17, and 5.18). VMA% values of the developed mix are within GSRB requirements, unlike what was found in the untreated mix. While, the VFB% property values were unfavorable for both mixes.

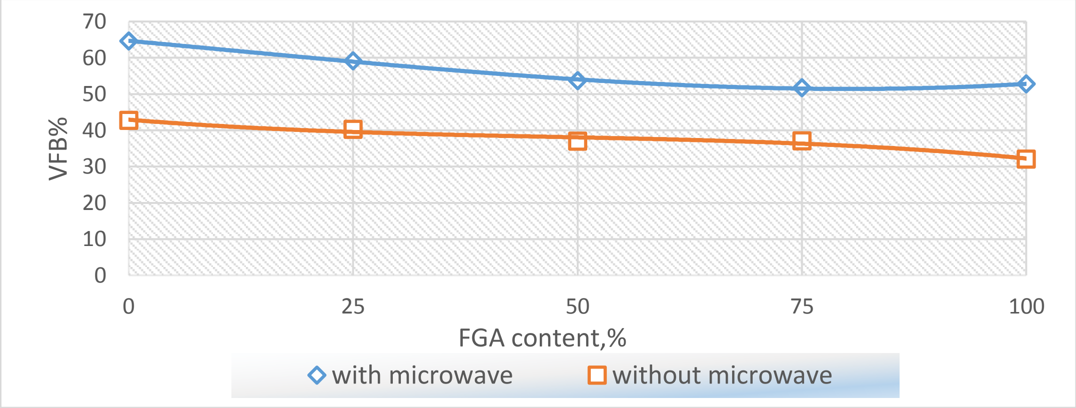


Figure 5.17 VFB vs. FGA% content for HWBEM compared with CBEM mixes

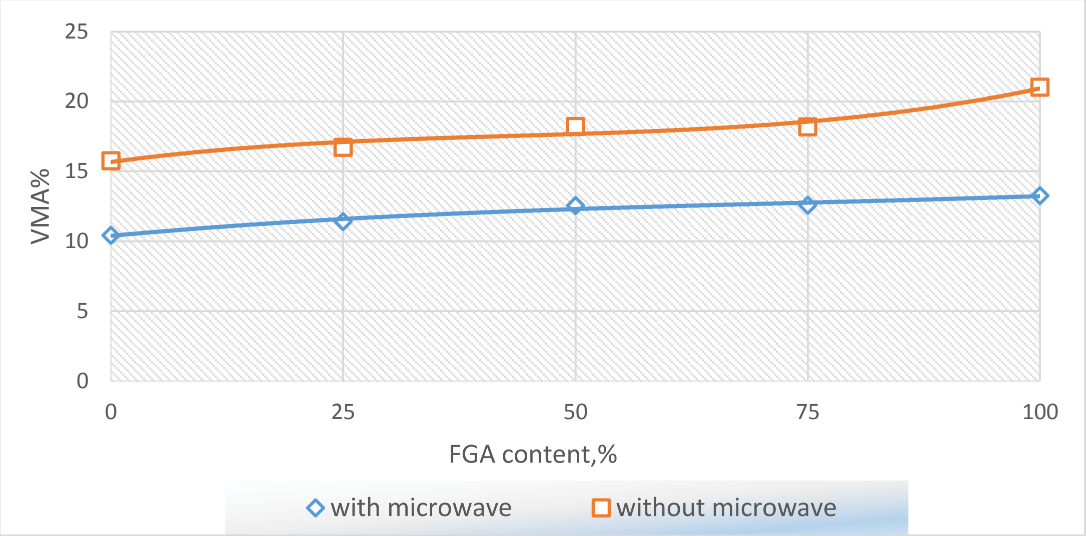


Figure 5.18 VMA% vs. FGA% content for HWBEM compared with CBEM mixes

5.3.2 Mechanical Properties of the HWBEM Incorporated FGA

The mechanical tests in term of Marshall Stability and flow, IDT, WTT, and CC are performed and will be illustrated in the next subsections.

5.3.2.1 Marshall Mechanical Properties

Marshall Stability results are shown in Figure (5.19). The Figure clears a noticeable reduction in stability value at a higher amount of FGA up to 75% FGA content, followed by a slight increase at 100% FGA content. Also, an improvement in result has observed when compared to untreated mixes. For 100% FGA content, the stability was improved about 94% compared to untreated mix, about 69% compared to HMA, and about 370% compared to CBEM-CMF.

Marshall Flow results were graphed in Figure (5.20) indicating A significant reduction in the flow curve. The flow curve trend took the same shape of untreated mixture flow curve, but with shifting down. The flow values were improved and in the acceptance to GSRB. Flow values of the new mix were improved by about 44% in case of incorporation of 100% GFA. Such improvement could be a result of lowering the brittleness of the mix due to increasing the coating, which is in its turn activate the primary binder over the secondary.

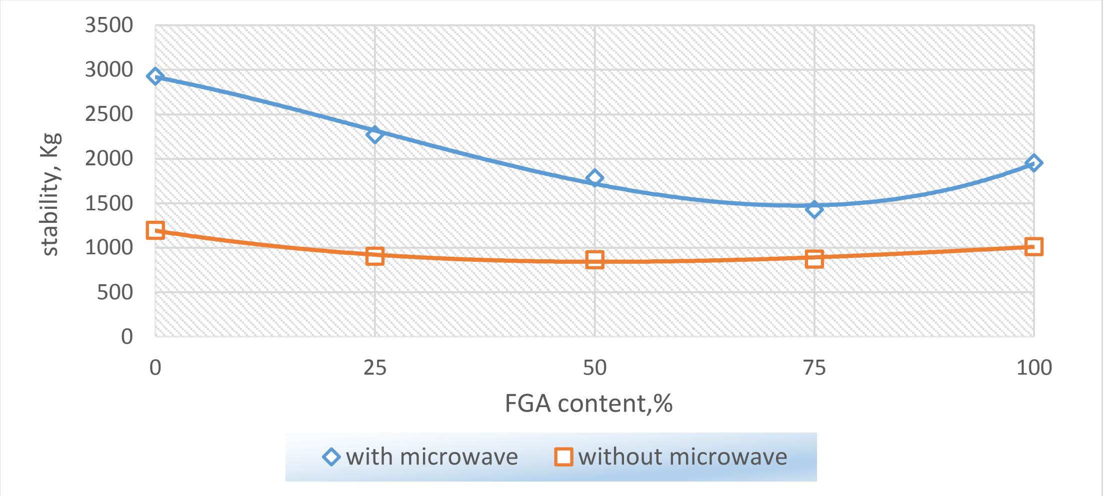


Figure 5.19 Stability vs. FGA% content for HWBEM compared with CBEM mixes

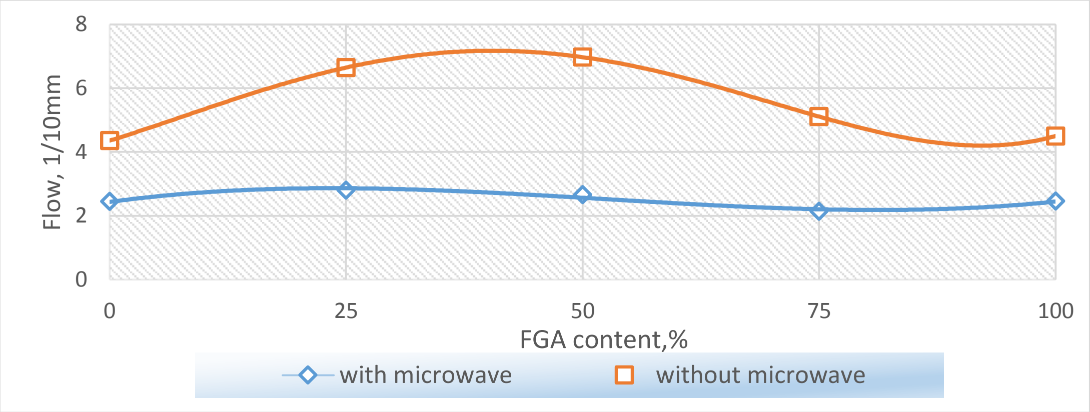


Figure 5.20 Flow vs. FGA% content for HWBEM compared with CBEM mixes

Stability-Flow curves have been constructed for all replacement FGA ratios as plotted in Figure (5.21), where all values above 800 Kg in stability, and flow no more than 4 mm, or less than 2 mm. Indeed, almost all behaviors of the treated curves were much better that HMA curve.

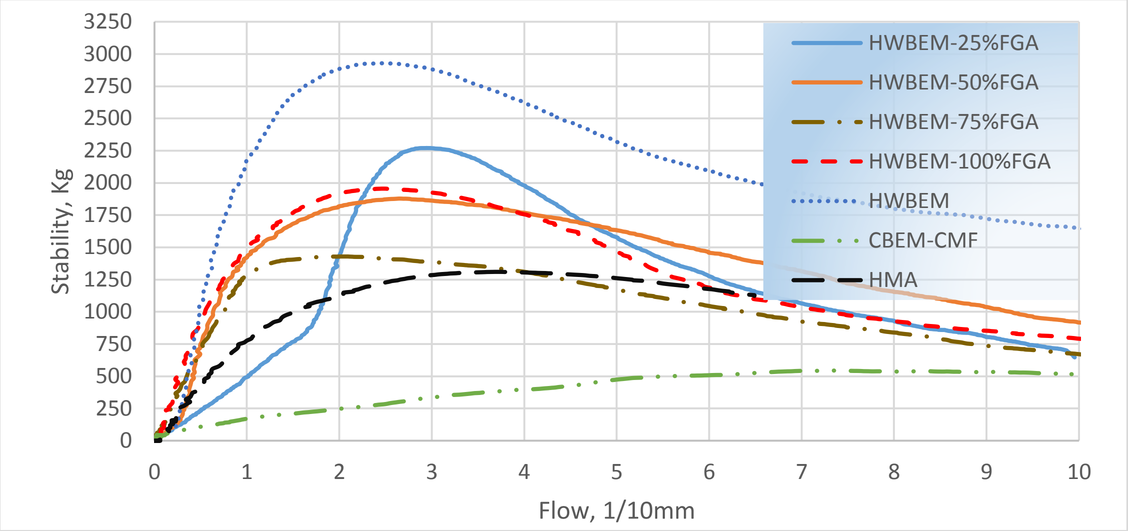


Figure 5.21 Stability-flow curves for HWBEM comprised FGA compared with untreated HWBEM, CBEM-CMF and HMA mixes

5.3.2.2 Wheel Track Test

WTT results are illustrated in Figure (5.22). The test was applied for all FGA percentages and compared to untreated one. Test result cleared good indication for resistance to permanent deformation in term of rut depth, although the microwaved cold mix with FGA has higher rut depth compared to untreated one after 1000 cycles. Maximum rutting value can be observed in a heated mix with 100% FGA, which was found to be 1.85 mm. Based on the results in Figure (5.22), the following points can be noticed:

- Rut depth of 75% FGA heated mixture is lower than what has observed in 25 and 50% FGA treated mixes.
- Rut depth values for all heated mixes contained FGA are much lower than what has noticed in HMA. Mix with 100% FGA has improved about 3.41 and 4.78 times HMA and CBEM-CMF mixes, respectively.
- HWBEM with 50% and 100% FGA showed the highest value of rutting compared to other plotted mixes in the same graph.

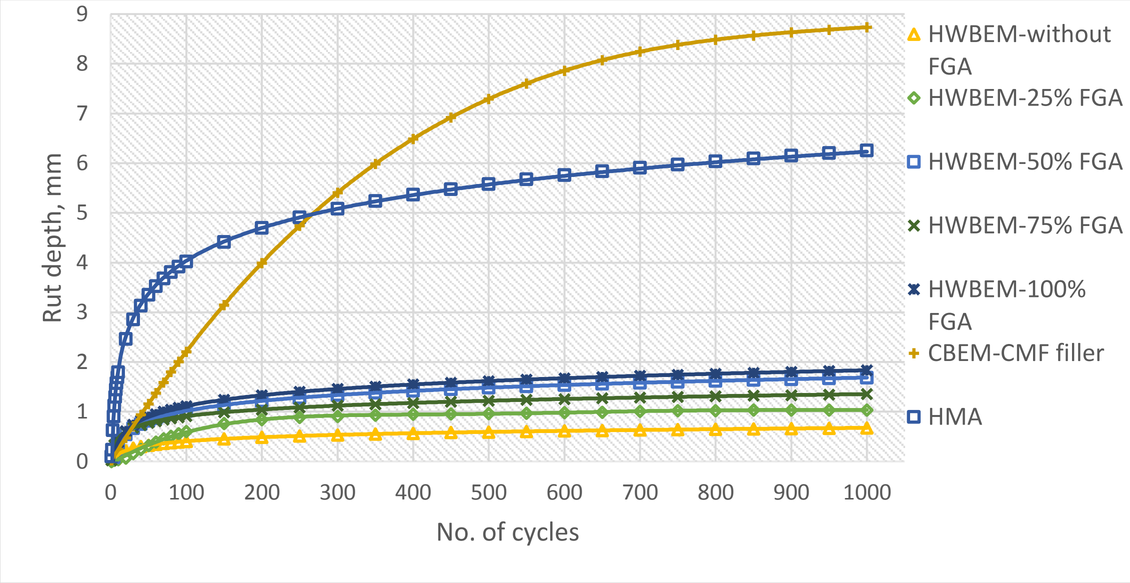


Figure 5.22 Rutting vs. number of cycle curves for HWBEM comprised FGA compared with untreated HWBEM, CBEM-CMF and HMA mixes

The dynamic stability of the new mixtures improved compared to HMA and CBEM-CMF as plotted in Figure (5.23). Also, it has been observed that HWBEM comprised FGA has lower resistance to rutting compared to untreated mix (HWBEM), however it still has higher resistance compared to HMA and CBEM-CMF. Heating led to evaporate internal mix moisture, reduce air voids content, as result, the internal interface between aggregate and bitumen has increased which has direct effect on improve bonding and enhance stiffness.

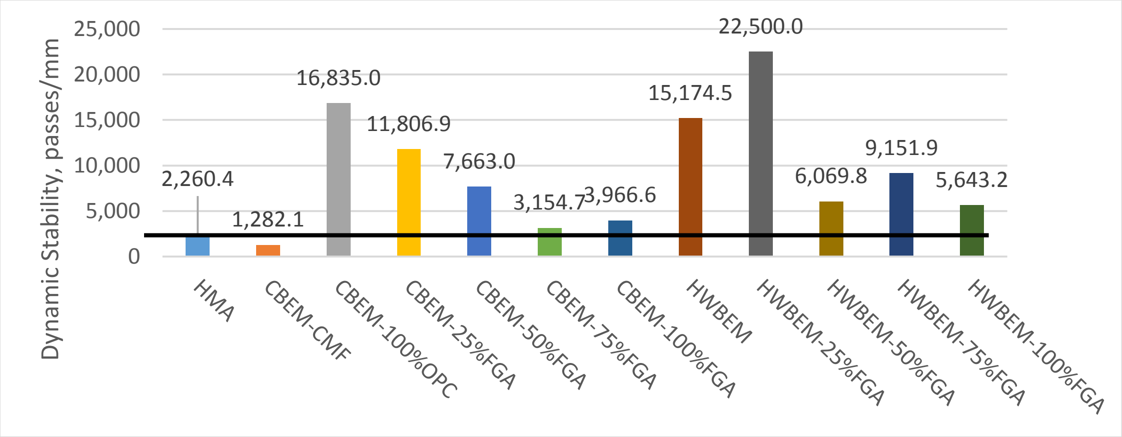


Figure 5.23 Dynamic stability for HWBEM comprised FGA compared with untreated HWBEM, CBEM-CMF and HMA mixes

5.3.2.3 Creep Compliance Test

Test results in Figure (5.24) for HWBEM incorporated FGA showed that increasing FGA resulted in slight rising in compliance values compared to untreated one up to 50%

FGA, followed by the gradual reduction for 75 and 100% FGA values. Tensile creep after 100 sec is still higher for HMA compared to other mixes.

HWCBEM-FGA mixes improved in term of crack resistance stiffness compared to CBEM-CMF, but it still lower than HMA, as can be seen in Figure (5.25), which could be due to the base bitumen grade as mentioned previously.

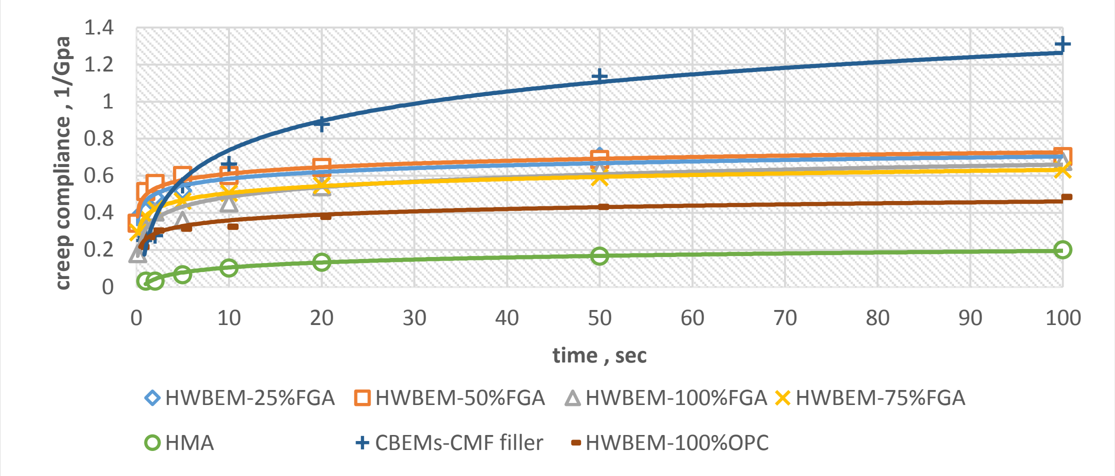


Figure 5.24 Creep compliance curves for HWBEM comprised FGA compared with untreated HWBEM, CBEM-CMF and HMA mixes

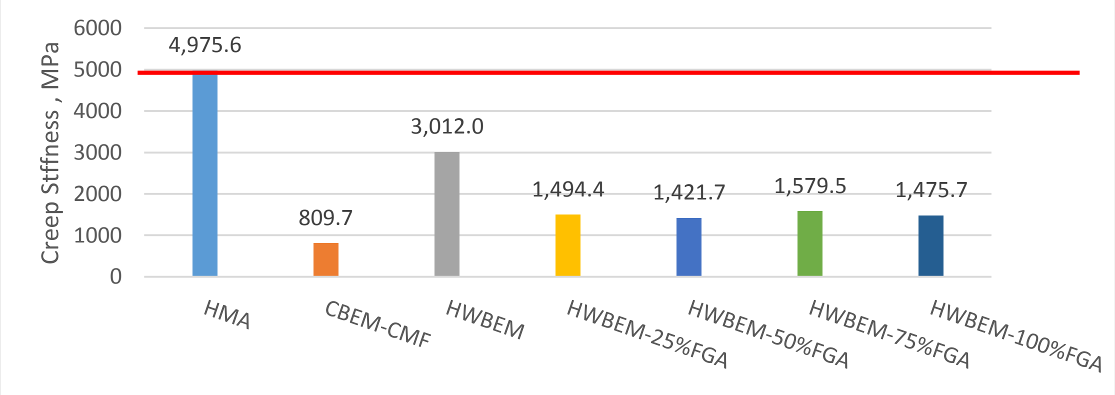


Figure 5.25 Creep stiffness after 100 sec. curves for HWBEM comprised FGA compared with untreated HWBEM, CBEM-CMF and HMA mixes

5.3.2.4 IDT Test

Test results of HWBEM dosed FGA are plotted in Figure (5.26). Results provided an indication of sufficient improvement in resistance to tensile crack failure compared to HMA and CBEM-CMF. Also, results cleared that increasing amount of FGA in HWBEM mix resulted in a reduction of tensile crack resistance, but it still comparable to HMA. The weakest resistance has been observed in HWBEM-100% FGA mix, which was better than CBEM-CMF by about 4.72 times.

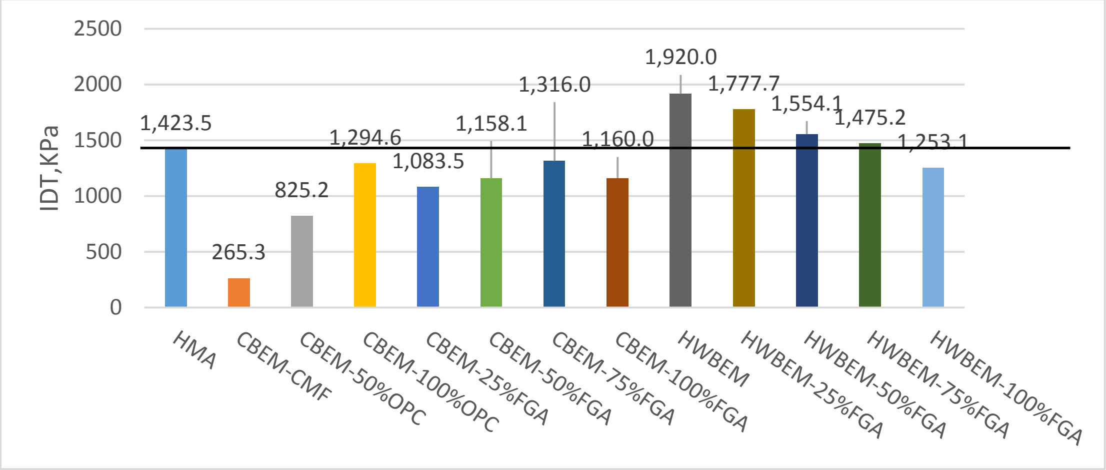


Figure 5.26 IDT% for HWBEM comprised FGA compared with untreated HWBEM, CBEM-CMF and HMA mixes

5.3.2.5 RMS Test Results

Significant positive change has been observed when mix comprised FGA compared to CBEM-CMF and HMA mixes as illustrated in Figure (5-27). The Figure shows that mix resistance to water damage in term of Marshall stability increased with increase in FGA content, up to 75%, followed by a noticeable reduction when 100% FGA is incorporated. In general, all HWBEM mix with FGA showed excellent results compared with HMA and CBEM-CMF. Such result could be a result of reducing air void and increasing density, in addition to improving the coating of the primary binding materials.

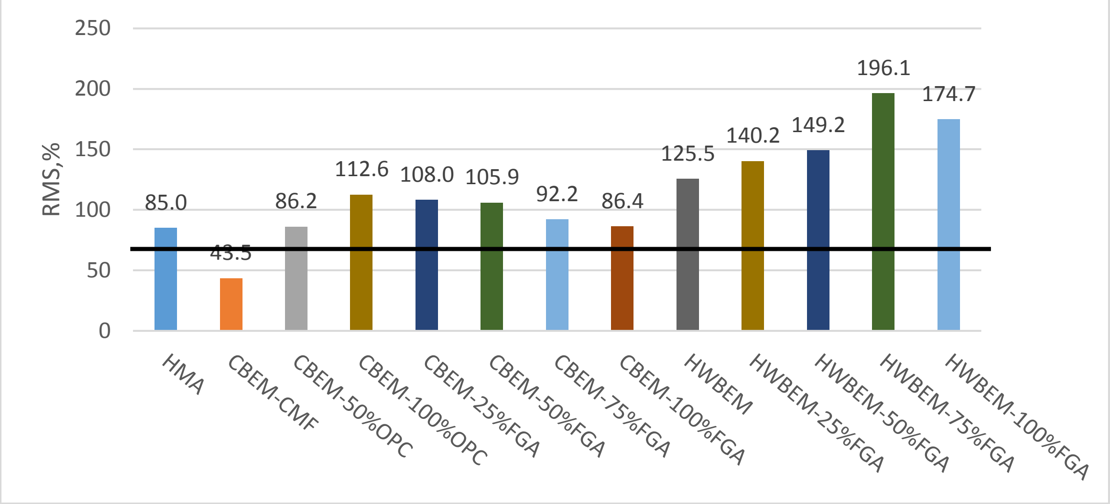


Figure 5.27 RMS% for HWBEM comprised FGA compared with untreated HWBEM, CBEM-CMF and HMA mixes

5.4 Overview of the results

In this section, all results obtained during research work are collected for all mixes, and for different treatment techniques to simplify research summary and make it easier for comparison.

5.4.1 Volumetric Properties

Results of mixes volumetric properties are illustrated in Figures below:

- Density, Figure (5.28)
- Air void, Figure (5.29)
- Void in mineral aggregate, Figure (5.30)
- Void filled with bitumen, Figure (5.31)
-

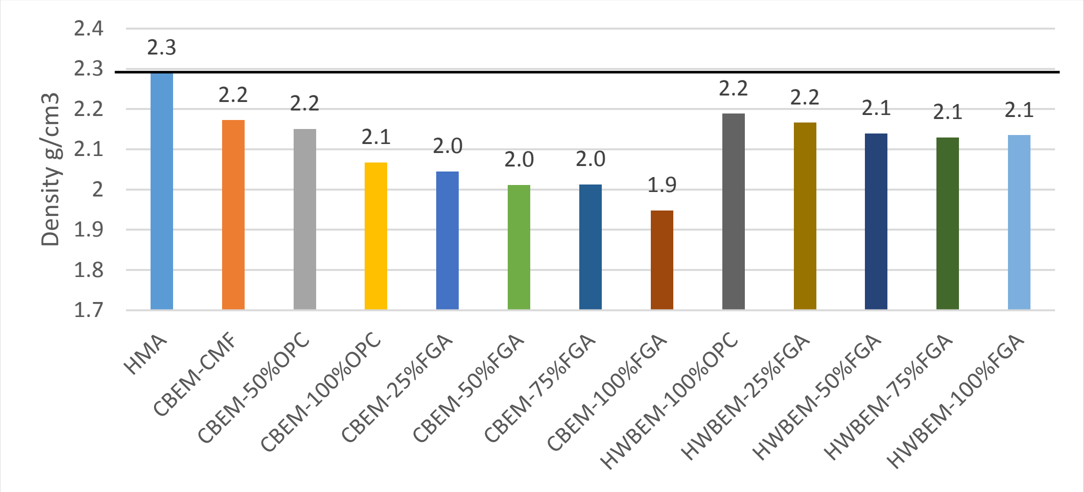


Figure 5.28 Density results for different mixtures types

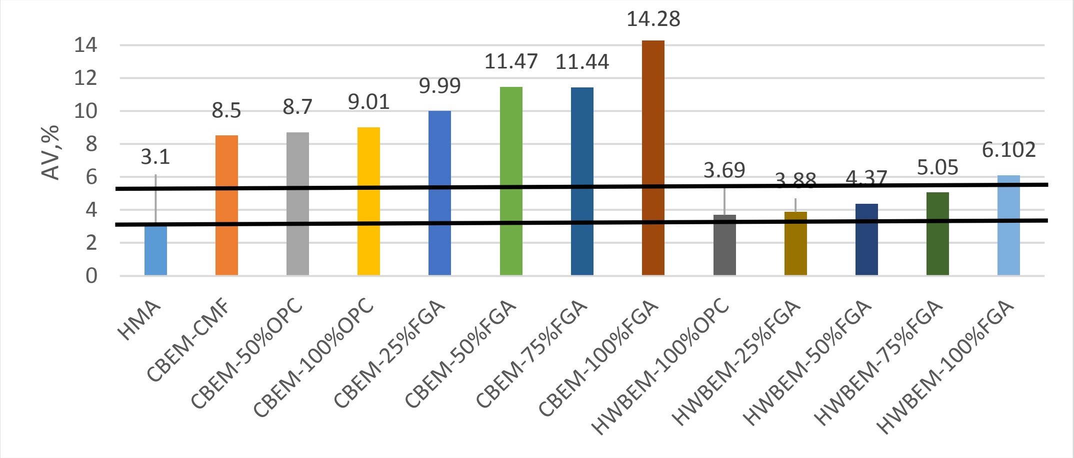


Figure 5.29 AV% results for different mixtures types

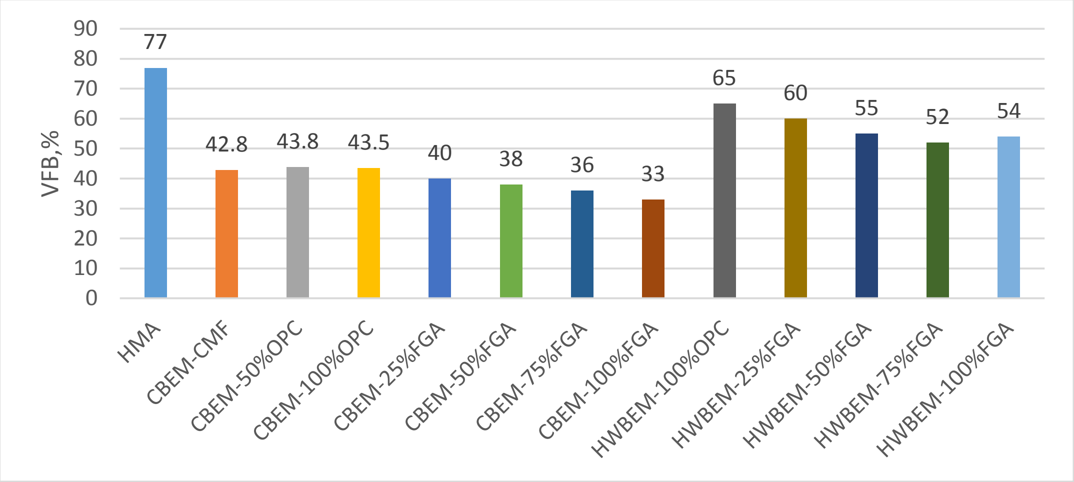


Figure 5.30 VFB% results for different mixtures types

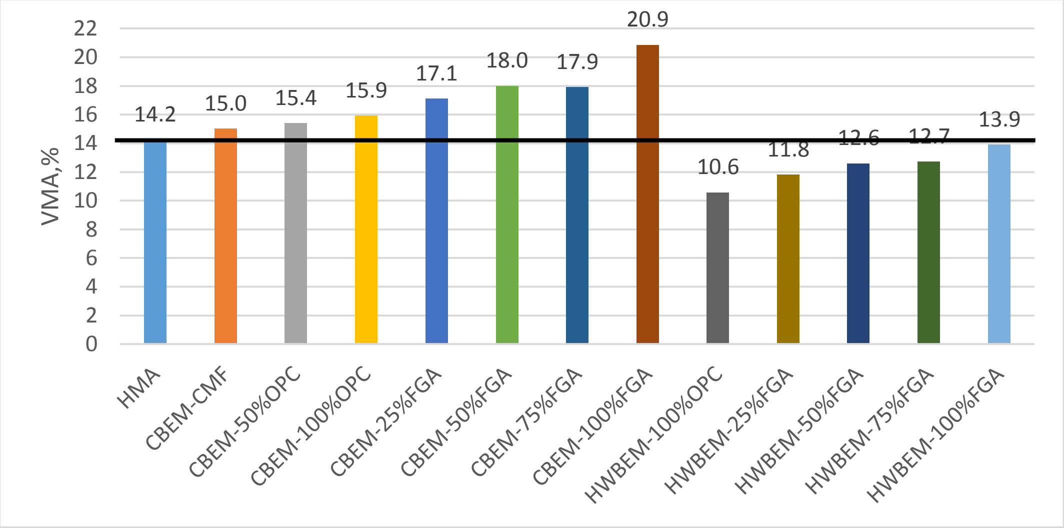


Figure 5.31 VNA% results for different mixtures types

5.4.2 Mechanical Tests Results

The Mechanical testing results include the following category

5.4.2.1 Marshall Stability and Flow

Marshall stability- flow curves are plotted in Figure (5.32), Marshall Stability and Flow are cleared in Figures (5.33) and (5.34), respectively.

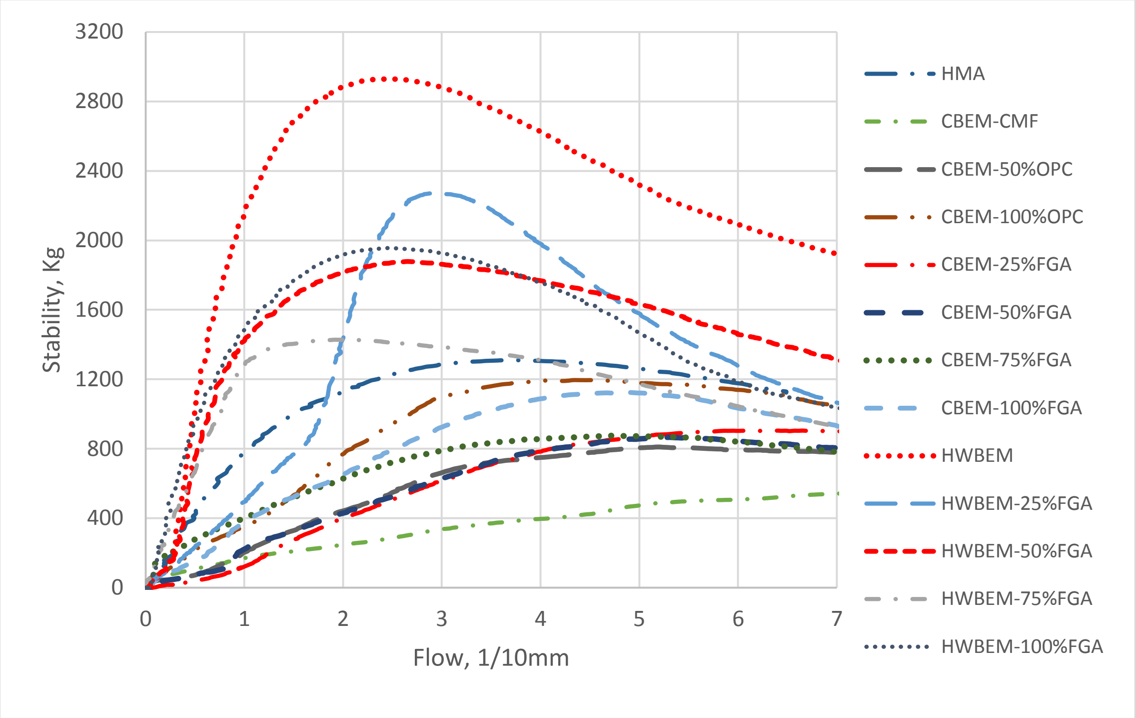


Figure 5.32 Stability-flow curves results for different mixtures types

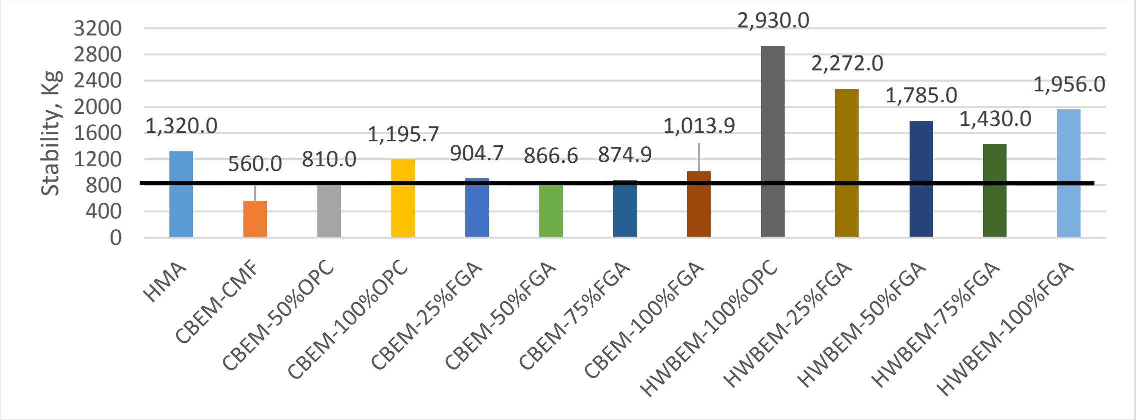


Figure 5.33 Stability results for different mixtures types

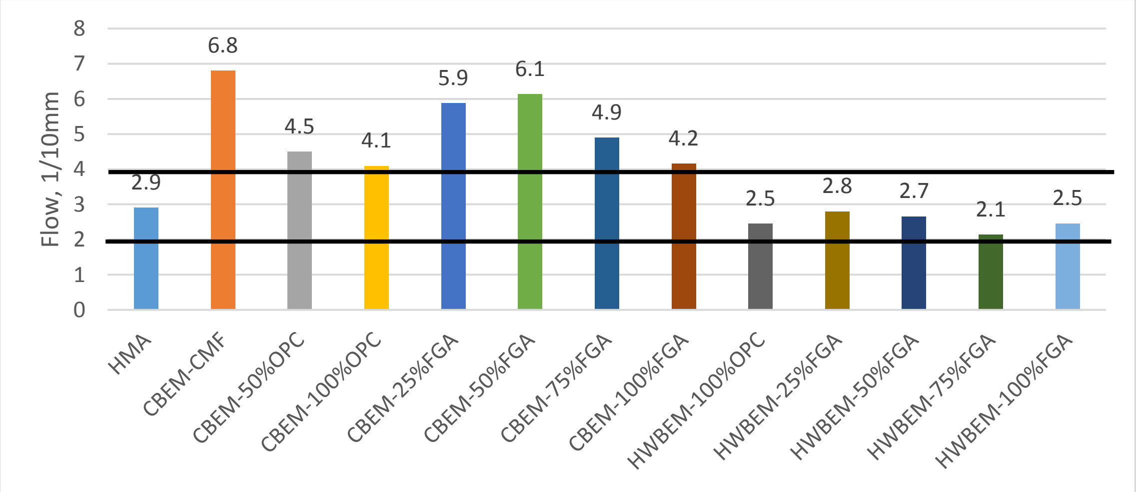


Figure 5.34 Flow results for different mixtures types

5.4.2.2 Permanent Deformation (Rutting)

Tests results for rut depth are plotted in Figure (5.35), and dynamic stability results are shown in Figure (5.36).

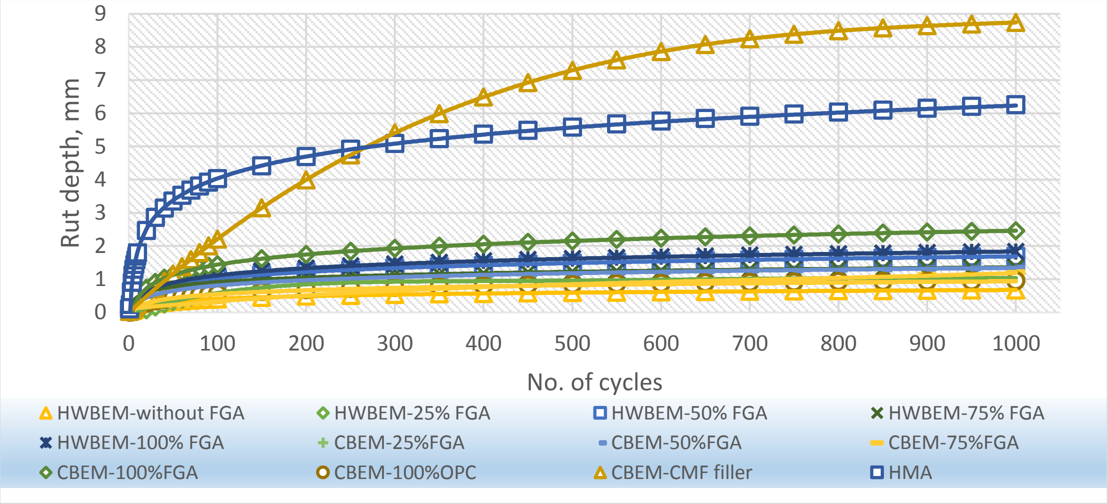


Figure 5.35 Rutting curves results for different mixtures types

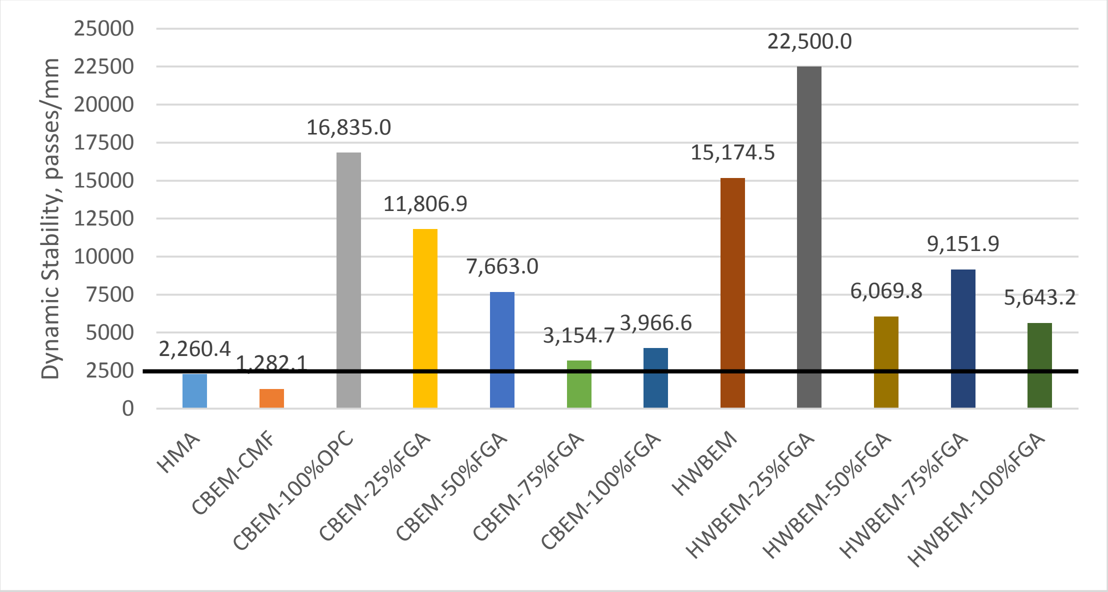


Figure 5.36 Dynamic stability results for different mixtures types

5.4.2.3 IDT Results

Tests results of IDT is cleared in Figure (5.37).

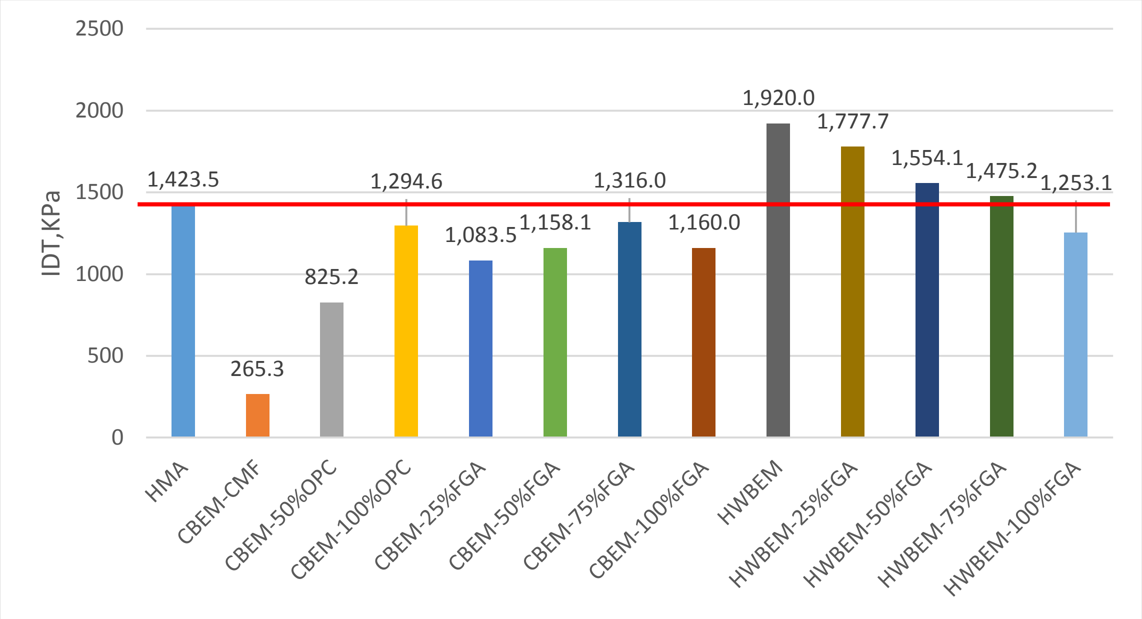


Figure 5.37 IDT results for different mixtures types

5.4.2.4 Creep Compliance

Creep compliance data results for different mixes are cleared in Figure (5.38), Creep Stiffness is plotted in Figure (5.39).

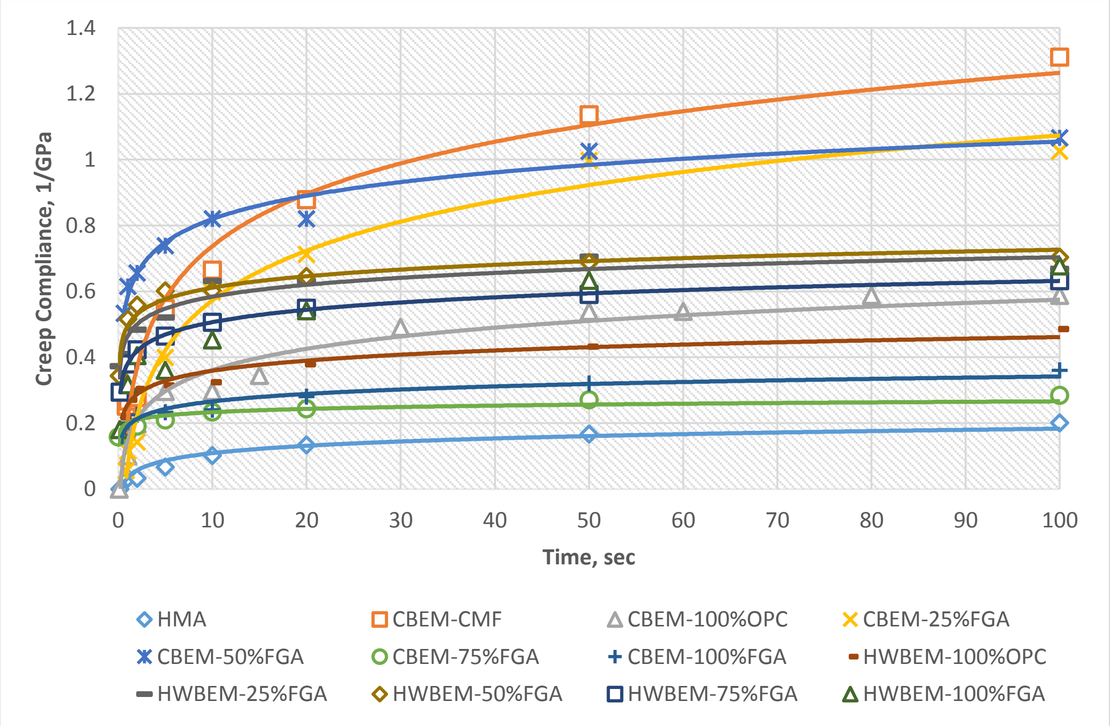


Figure 5.38 Creep compliance curves results for different mixtures types

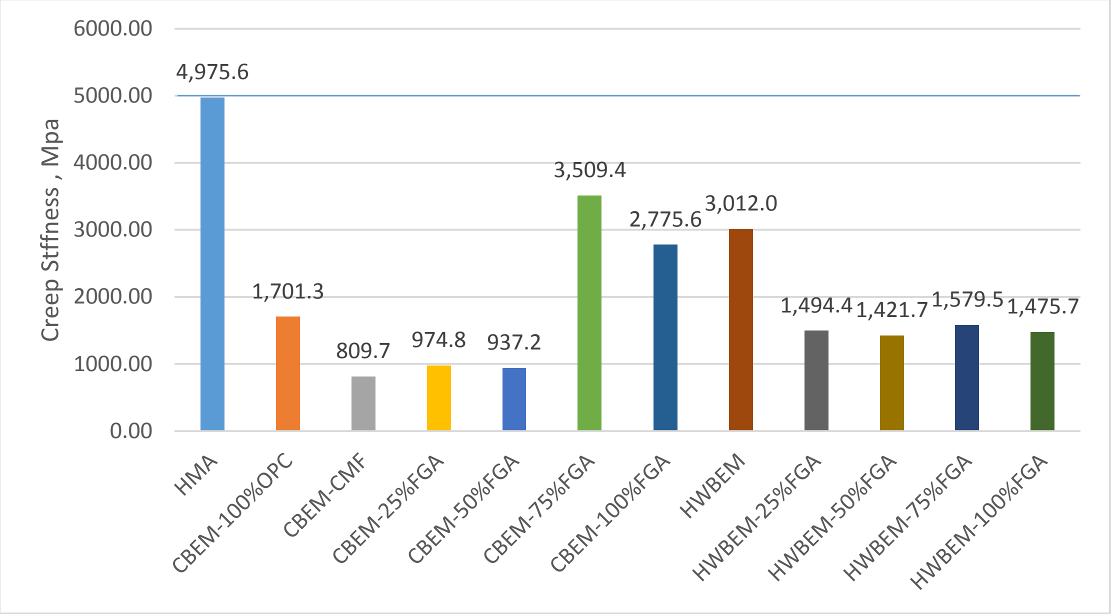


Figure 5.39 Creep stiffness results for different mixtures types.

5.4.2.5 Water Sensitivity Tests

RMS test results are plotted in Figure (5.40)

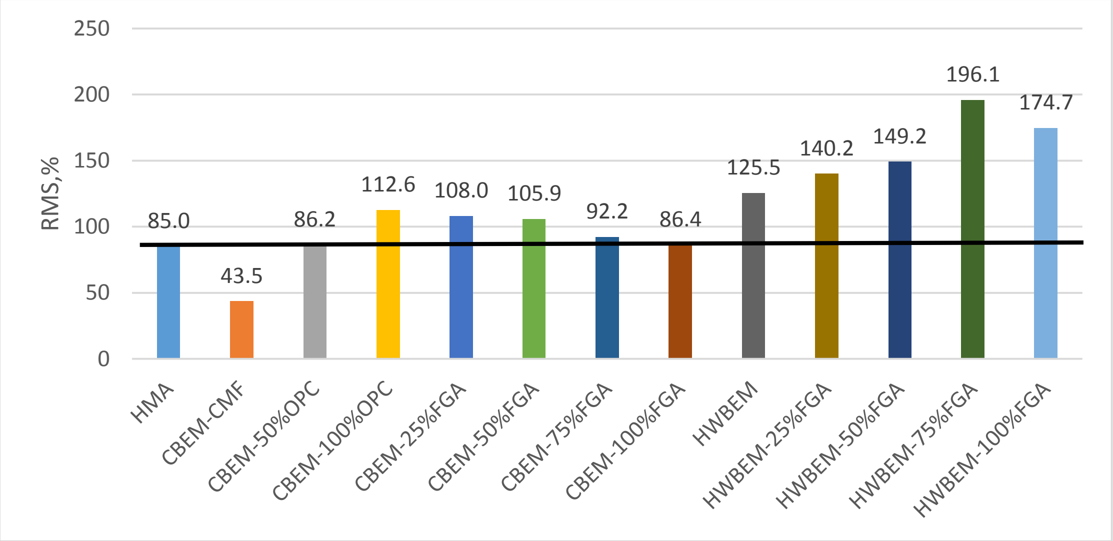


Figure 5.40 RMS% results for different mixtures types

5.5 Summary

As mentioned previously, active filler like OPC has approved its efficiency for improving CBEM in term of mechanical and durability properties, but no enhancement was observed with volumetric properties. Also, more sustainable approaches are in high demand to improve asphalt concrete industry. Thus, incorporation waste glass with the existence of OPC as stabilizer agent has shown acceptable mechanical and durability properties, and negative effect on voids content. Therefore, through this chapter a low energy post-heating process has shown its effectiveness for improving volumetric properties, further to extra mechanical and durability properties. As a result, the new developed HWBEM comprised waste glass fine aggregates present a superior and sometimes comparable to the sustainable alternative for HMA.

Chapter Six

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In this study, an attempt has been conducted to develop CBEMs’ mechanical and volumetric weak properties, and makes it comparable to traditional HMA within the requirements of GSRB for surface layer and heavy traffic conditions. However, after an extensive lab works and analysis, the following conclusions can be drawn:

1. According to the Iraqi GSRB requirements, CBEM-CMF (cold bituminous emulsion mixtures without any additives) absolutely unsuitable as a structural surface layer for heavy traffic load at early life since it has very weak volumetric, mechanical, and durability properties.
2. Existence of ordinary Portland cement (OPC) played an important role in CBEM improvement in term of mechanical and durability properties, but no enhancement has observed for mixture air voids contents. OPC has enhanced significantly mixture strength at early life, and reflected a stiffer, and more brittle mixture than CBEM-CMF and hot mix asphalt (HMA). OPC has reduced risks of water damage and higher rutting potentials. Also, incorporation of OPC resulted in a higher amount of water required for coating because of the higher surface compared with conventional limestone filler (CMF). Where CBEM-100%OPC improved by about 2.15, 2.1, 9.28, 13.13, 1.74, 4.88, and 2.1 times of CBEM-CMF in terms of Marshall stability (M-S), Marshall flow (M-F), rutting resistance, dynamic stability (DS), creep stiffness (CS), Indirect tensile strength (IDT), and retained Marshall stability (RMS), respectively.
3. Replacing fine aggregates even up to100% by FGA with the existence of 100% OPC showed good results in term of mechanical, durability, and workability properties, and within requirements of the Iraqi GSRB specifications. But air voids content is increased with the higher amount of FGA up to 14.5% in term of 100%FGA replacement.

4. Heating by microwave energy was very efficient to reduce air voids by up to 4% after 6 min heating (associated mix temperature of 91°C), and resulted in a new mixture with mechanical and volumetric properties within the requirement of GSRB for the surface layer. In addition to air voids reduction enhancement, the mix has been improved significantly in term of mechanical and water sensitivity properties compared to CBEM-CMF and HMA. Where the half warm bituminous emulsion mixtures (HWBEM) was improved by about 2.2, 8,9.7, 1.3, and 2.9 times of HMA in terms of M-S, rutting resistance, DS, IDT, and RMS.
5. As the optimum heating process was under 100 °C, the new developed mix can be defined as Half Warm Bituminous Emulsion Mixture (HWBEM).
6. Replacing fine aggregates even up to100% by FGA in the HWBEM results in a novel mixture as it showed superior characteristics to conventional CBEM and HMA in term of overall mix properties.
7. The newly developed mixes (i.e., HWBEM and HWBEM incorporated 75% FGA) are very suitable to work as structural surface course layer according to GSRB requirements.
8. No enhancement was observed while increasing compaction effort to double using vibrator compactor. The existence of trapped water made the specimens bouncing during compaction and distorted its particles instead of reducing volume and increasing density. Also, heavy compaction effort using Marshall Hammer resulted in 8-14% air voids content, which considers as an unacceptable range compared to HMA.
9. Combination of a virgin with higher amount of FGA aggregates created a sloppy mixture, which resulted in higher air voids content and some difficulties in compaction process (higher amount of moisture led to squeeze out fine materials from mold during compaction).

6.2 Recommendations for Further Studies

Several recommendations for further studies are presented below:

1. It is highly recommended to evaluate the developed mixes (HWBEM, and HWBEM-75%FGA) in the site and verify what have been concluded in the lab studies.
2. Trying to incorporate other municipal waste materials in addition to crushed glass in CBEM mixture is highly recommended for sustainable benefits.

3. Modifying CBEM mix design procedure is in high demand, especially the curing protocol to be compatible to local environment.
4. Studying the environmental and cost effectiveness for the new developed CBEM and comparing with traditional HMA.
5. The proposed microwave technique, which proved its efficiency in this study, requires further experimental optimization studies, in terms of moisture content and heating time, a frequency used and its effect on binder properties, and time required to reach full mixture strength.

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Appendix A – HMA mechanical and volumetric results

- Marshall Stability cleared in Figure (A.1)
- Marshall Flow cleared in Figure (A.2)
- Density cleared in Figure (A.3)
- AV% cleared in Figure (A.4)
- VFB% cleared in Figure (A.5)
- VMA% cleared in Figure (A.6)

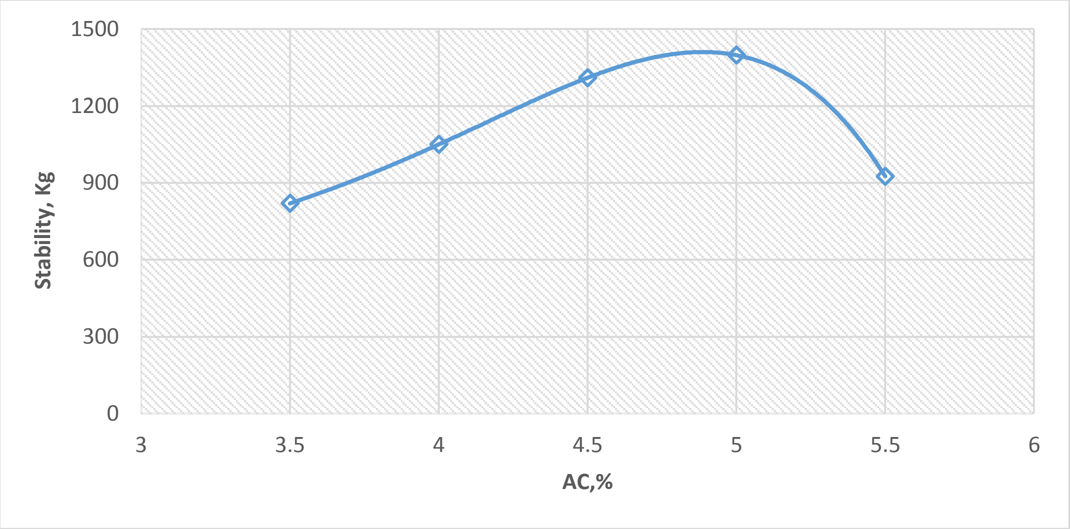

Figure (A.1) Stability vs. asphalt content for HMA

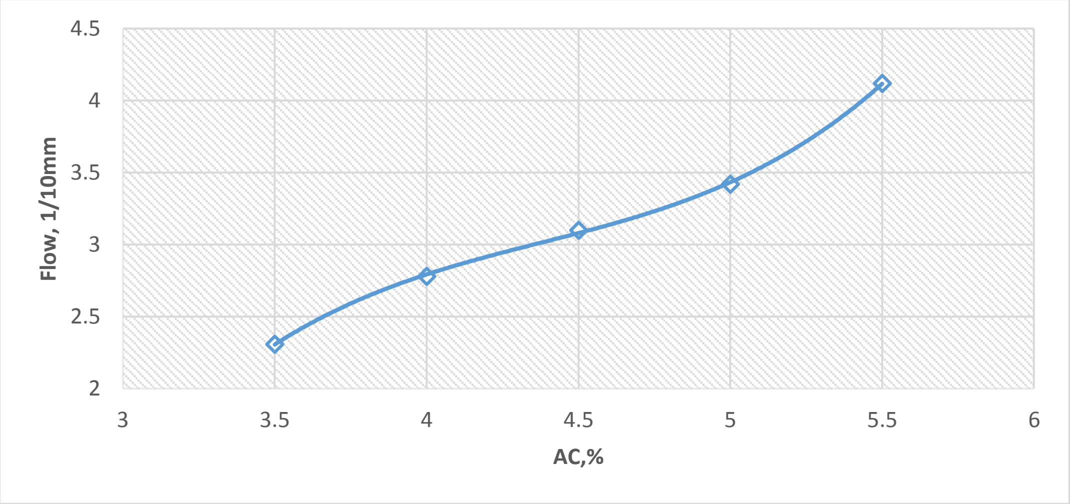

Figure (A.2) Flow vs. asphalt content for HMA

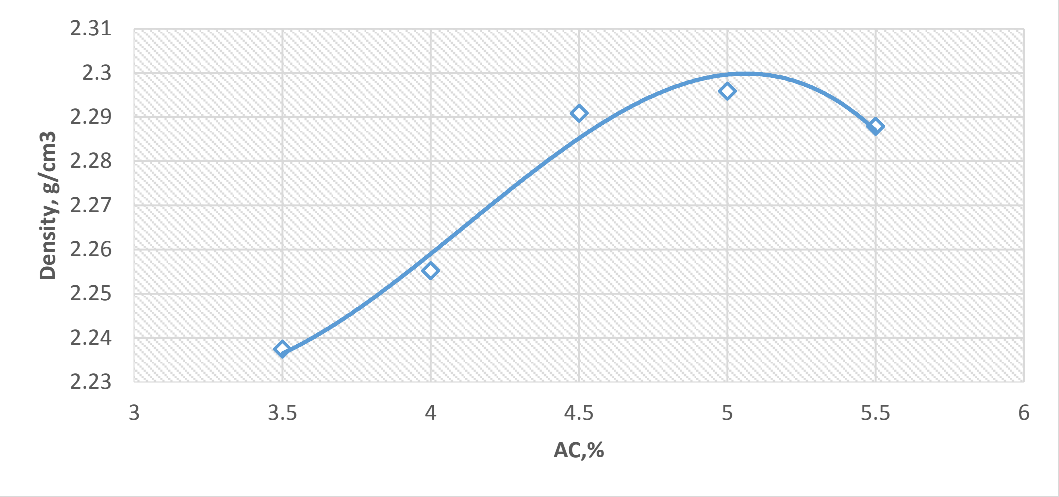

Figure (A.3) Density vs. asphalt content for HMA

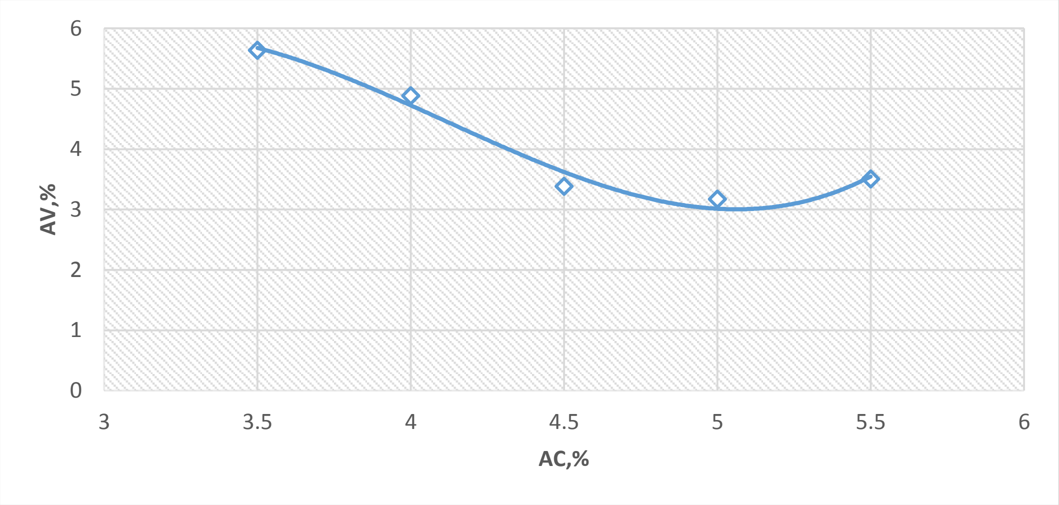

Figure (A.4) Air void vs. asphalt content for HMA

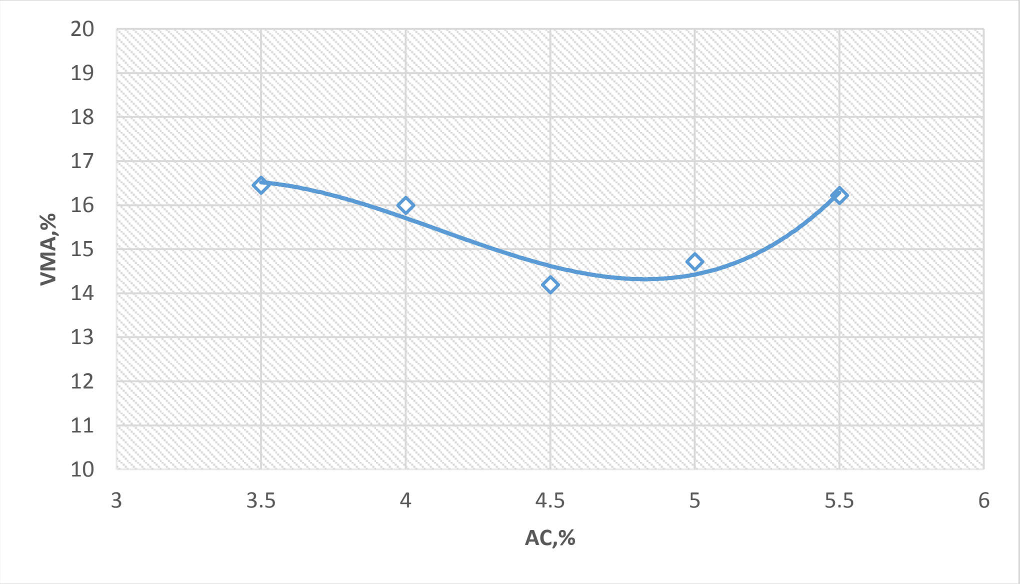

Figure (A.5) V.M.A vs. asphalt content for HMA

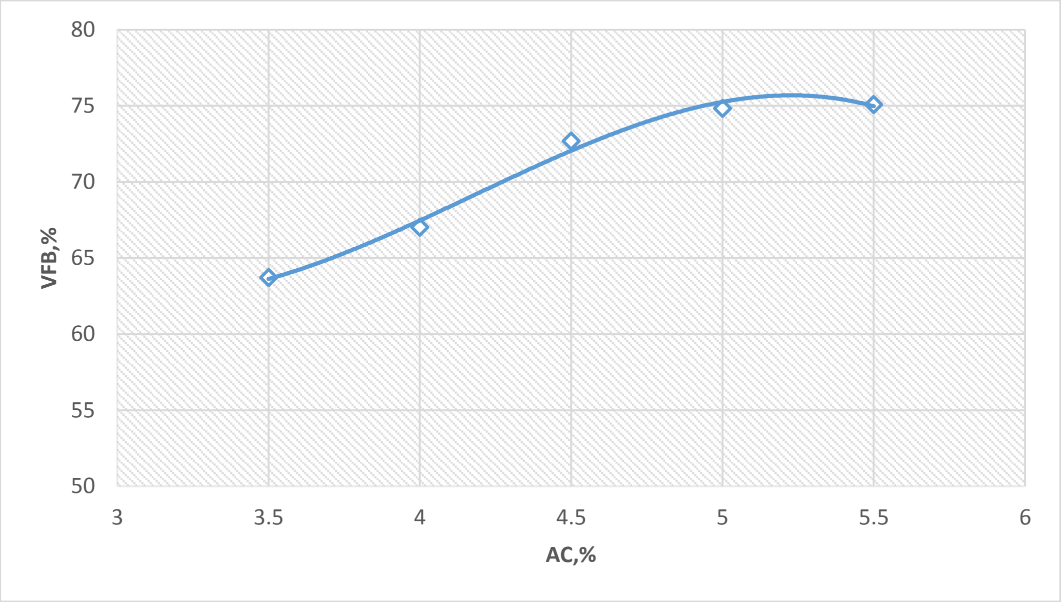

Figure (A.6) V.F.A vs. asphalt content for HMA

الخلاصة

في الوقت الحاضر كل شيئ يتوسع بشكل سريع، ينمو ويتطور لتلبيه حاجه المجتمع، ويشمل ذلك شبكات الطرق. العدد المتزايد من السيارات مصحوبا بزياده الاحمال المحوريه للمركبات الحديثة ادى الى تعجيل تضرر التبليط. التكنلوجيا الحالية لتبليط وصيانه الطرق باستخدام الخلطه الاسفلتيه الحاره قد يكون حل غير اقتصادي للمستقبل. على كل حال مثل، هذ النوع من الخلطات تمتلك العديد من العيوب والتي لا تتوافق مع متطلبات الاستدامه، الاقتصاديه، والصديق للبيئة. من جانب اخر، الخلطه الاسفلتيه البارده، او بشكل ادق خلطات المستحلب البتيوميني البارده، تمتلك العديد من المزايا البيئية والاقتصادية مقارنة بالخلطات الاسفلتية الحاره، لاكن تبقى الخصائص الميكانيكية والحجمية متدنية في العمر المبكر اذا تركت بدون معالجة. يهدف هذا البحث الى انتاج خطلة اسفلتية مستدامة من خلال تضمين مخلفات النفايات الصلبة بالاستفادة من التعريض الواطئ للحرارة للخلطة الاسفلتية ذات المستحلب البتوميني البارد.

في هذه الدراسه، جرت محاوله لتطوير الخصائص الميكانيكية والحجمية للخلطات المستحلب البتوميني الباردة باجراء معالجة مزدوجه. تضمن الطور الاول للمعالجة تحسين الخصائص الميكانيكية للخلطات البارده من خلال تعويض المادة المالئة التقليدية بالسمنت البورتلاندي الاعتيادي بثلاث نسب (0,50, 100%). بدلاله الخواص الميكانيه والديمومة بينت الدراسة ان اضافه 7% من الاسمنت البورتلاندي الاعتيادي من وزن اركام للخلطة CBEM ادى الى تطوير الخصائص المذكورة. حيث ان الخلطة CBEM-100%OPC تحسنت بمقدار 2.15 2.1, 2.28, 13.13, 1.74 4.88, و 2.1 مره مقارنة بالخلطة CBEM-CMF بدلالة ثبوتيه وانسياب مارشال M-F, M-S مقاومة التخدد , DS الثبوتية الديناميكية, مقاومة الزحف CS ,مقاومة الشد الغير مباشرIDT , و القوه المتبقية لثبات مارشال RMS على التوالي.

بعد ذلك، تم استخدام مخلفات البلدية الصلبة (مخلفات الزجاج) كركام ناعم بخمسه نسب (100,75,50,25%) محل الركام الناعم بوجود 7% من الاسمنت البورتلاندي الاعتيادي، و باستخدام طرق فحص مختلفة للخصائص الميكانيكية والديميومة كمؤشر للتغاير الحاصل في خصائص الخلطات الباردة نتيجه مثل هكذا تعويض. هذه الفحوصات هي: ثبوتيه وانسياب مارشال، مقاومة الشد الغير مباشرة، الزحف ،مقاومة التخدد ، الصلادة الديناميكية ،و تأثير الماء باستخدام نسبه الشد الغير مباشر. بدلالة الخصائص الميكانيكئة والديميومة، اوضحت الدراسة ان استبدال 100% من ركام الزجاج الناعم بوجود 7% من السمنت البورتلاندي الاعتيادي كمادة مالئه، كان له خواص

ميكانيكية وخواص ديمومة مقبولة وضمن المواصفات، لكن تبقى بعد التحسين حاوية على نسب فراغات هوائية عالية.

تم اقتراح المرحلة الثانية من المعالجة (الطور الثاني) للحصول على المستوى الامثل للفراغات الهوائية باستخدام التسخين اللاحق. الخلطة المطوره تم تسميتها بمزيج المستحلب البتوميني النصف دافئ HWBEM ، كون تم تحضريها بدرجه حرارة المختبر ورصها في درجه حراره 91 درجه مئويه. اظهرت الخلطة الجديده البتومينية النصف دافئة خصائص تفوق خواص الخلطة الحارة. حيث ان الخلطة المذكوره HWBEM تطورت بمقدار 2.2، 8، 9.7، 1.3، 2.9 مره مقارنة بالخلطة الحاره من ناحية M-S ، مقاومة التخدد ،الثبوتية الديناميكية ،مقاومة الشد الغير مباشر ، والقوه المتبقية لثبات لمارشال. وكانت نسبة الفراغات ضمن المواصفة العرقية 3-5%

اما بالنسبة لخلطات المستحلب البتوميني النصف دافئه HWBEM الحاوية على 75% من زجاج الركام الناعم بوجود التسخين المسبق اعطت خصائص ميكانيكية وديمومة وحجمية مبتكرة، تفوق (وفي بعض الاحيان مكافئة) للخلطات الحارة، وتفي بمتطلبات مواصفات الهيئه العامه للطرق والجسور العراقية GSRB الخاصه بالطبقة الاسفلتية السطحية، والحجوم المروريه العاليه. وبناء على ذلك، تم تحقيق الهدف الرئيسي، ويمكن أن يكون خليط الأسفلت المستديم الجديد مقارناً للخلطة الاسفلتية الحاره المعروفه.

أن الغرض من هذا العمل البحثي هو توصيف الخصائص الميكانيكية والحجمية للخلطات المذكورة، ومن الجدير بالذكر أن الخلطة الاسفلتية المستحدثه فعالة من حيث التكلفة وصديقة للبيئة لأنها تتوافق مع مبدئين اساسيين في الاستدامة هما :الكلفة الواطئة و توفير استهلاك الطاقة.

جمهورية العراق
وزارة التعليم العالي والبحث العلمي
جامعة كربلاء
كلية الهندسة
قسم الهندسة المدنية

تطوير تقنيات مختلفة في التبليط باستخدام مخلفات الزجاج

رسالة
مقدمة إلى كلية الهندسة في جامعة كربلاء
وهي جزء من متطلبات نيل درجة ماجستير في الهندسة المدنية
(هندسة البنى التحتية)

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