Ministry of Higher Education & Scientific Research
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EVALUATING ASPHALT MIXTURES COMPRISING POLYMER

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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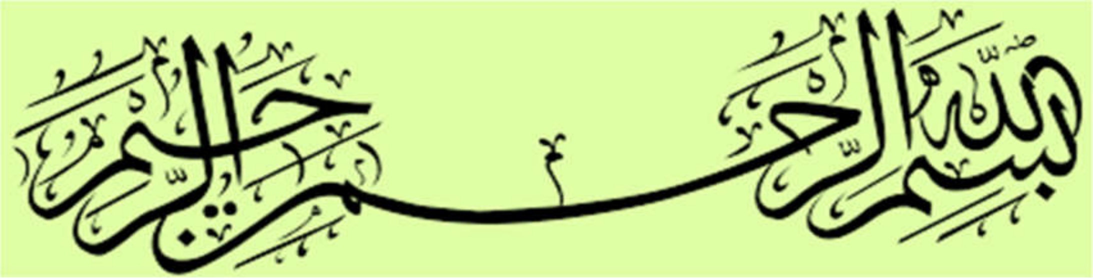

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ABSTRACT

The use of Hot Mix Asphalt (HMA) has been increased to cover high annual demand for new roads within the construction of the infrastructure projects. Although, HMA has obviously satisfactory engineering performance, its negative mix influence on environment encouraged researchers to look for other technologies such as Warm Mix Asphalt (WMA) and Cold Mix Asphalt (CMA) as successful alternatives. This study focused on developing Cold Bituminous Emulsion Mixtures (CBEMs) as a kind of CMA, modified by adding acrylic (AR) polymer.

The experimental program includes two stages; the first stage is to assess the performance characteristics of CBEMs with modified binder by acrylic (AR) polymer with two types of filler; Ordinary Portland Cement (OPC) and Conventional Mineral Filler (CMF) on the performance of CBEMs via several tests (e.g., Marshall test, indirect tensile strength, creep compliance, wheel tracking, and water damage). Acrylic (AR) polymer is utilized in percentages of 1.25, 2.5, 3.75 and 5 of the residual bitumen. Volumetric, mechanical, and durability improvement are investigated for such utilization. While the second stage includes assessing the influence of low energy heating (under 100 C°) by microwave technique on the developed CBEMs as a trial to improve the volumetric properties of CBEMs, without adverse effects on the mechanical and durability properties.

Results of stage one revealed that CBEMs with 1.25% AR polymer of residual bitumen introduce highest; stability, indirect tensile strength, creep stiffness and resistance to water sensitive. Also, rutting resistance (represented by rutting depth introduced) of CBEMs with OPC and 1.25% AR, is increased by 90 % and 93% compared with traditional HMA and CBEMs with CMF and 1.25% AR, respectively. Furthermore, durability property (represented by water damage) is increased by 109 % and 55 % in contrast with traditional HMA and CBEMs with CMF, respectively. Although, improvements in mechanical and durability property is achieved, problem of high air void content for CBEMs with OPC and 1.25% AR polymer is continued with polymer compressing.

In the stage two of the work, CBEMs with pre-compaction heating treatment by microwave technique, called Half Warm Bituminous Emulsion Mixture (HWBEM), is developed. This technique succeeded in reducing air void content of HWBEMs with OPC and 1.25% AR polymer by 6% in comparison with HWBEM with CMF and 1.25% AR polymer, while it showed almost same air void contents of traditional HMA. On the other hand, this mixture demonstrated significant improvements for the rutting resistance and durability properties; the rutting resistance of HWBEM with OPC and 1.25% AR is increased by 81 % and 80% in comparison with traditional HMA and HWBEM with CMF and 1.25% AR polymer, respectively. Furthermore, durability property (represented by water damage) is increased by 135% and 81% compared with traditional HMA and HWBEM, respectively.

Finally, it can be concluded that the modified HWBEM with OPC by 1.25% AR polymer may be considered as a vital sustainable alternative to HMA in road surface layer for the infrastructure projects of light and heavily trafficked highways. Several benefits are gained in term of; eco-friendly, cost- effectiveness, and less energy consumption.

SUPERVISOR CERTIFICATE

We certify that this thesis entitled "Evaluating Asphalt Mixtures Comprising Polymer" which is prepared by Muna Fadhil Al-kafaji under our supervision at the University of Kerbala in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering (Infrastructure Engineering).

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Muna Fadhil Al-kafaji

DEDICATION

- I dedicate this work to the master of martyrs and the destination of the Liberals Abu -Abdullah Al Hussein (peace be upon him).
- The deepest words of thanks and appreciation gratitude and dedication should go to the great people, if I am where I am today, you are the reason for that and you deserve a special mention, my mother and my father.
- My sincere appreciations go to my sister and brothers, I am so lucky to have them in my life.
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ABBREVIATIONS/ACRONYMS

AR	Acrylic
APP	Atactic polypropylene
BBR	Bending Beam Rheometer
CBEMs	Cold Bitumen Emulsion Mixtures
CMF	Conventional Mineral Filler
CMS	Cationic Medium- Setting
DS	Dynamic Stability
DSR	Dynamic Shear Rheometer
EBA	Ethylene–Butyl Acrylate
EMA	Ethylene–Methyl Acrylate
EPDM	Ethylene–Propylene–Diene Terpolymer
EVA	Ethylene Vinyl Acetate
FA	Fly Ash
FHWA	Federal Highway Administration
SCRB	State Corporation for Roads and Bridges
HDPE	High Density Polyethylene
HMA	Hot Mix Asphalt
HWBEM	Half Warm Bitumen Emulsion Mixture
HWMA	Half Warm Mix Asphalt
IEC	Initial Emulsion Content
IIR	Isobutene–Isoprene Random copolymer
IRAC	Initial Residual Asphalt Content
ITSM	Indirect Tensile stiffness modulus
ITSR	Indirect Tensile Strength Ratio
LDPE	Low Density Polyethylene
LVDT	Linear Variable Differential Transducer
MF	Marshall Flow
MPW-Indonesia	Ministry of Public Work Republic of Indonesia

MS	Marshall Stability
NCAT	National Center for Asphalt Technology
NR	Natural Rubber
OPC	Ordinary Portland Cement
OPWwc	Optimum Pre-Wetting Water Content
OAEC	Optimum Asphalt Emulsion Content
ORBC	Optimum Residual Bitumen Content
OTLC	Optimum Total Liquid Content at Compaction
PA, PPA	Phosphoric Acid, Polyphosphoric Acid
PAV	Pressure Aging Vessel
PBD	Polybutadiene
PE	Polyethylene
PFA	Pulverised Fuel Ash
PI	Polyisoprene
PIB	Polyisobutene
PMA	Polymer Modified Asphalt
PP	Polypropylene
PS	Polystyrene
PSA	Paper Sludge Ash
PU	Polyurethane resin
PVAR-E	Polyvinyl Acetate Emulsion
PVC	Polyvinyl Chloride
RAP	Reclaimed Asphalt Pavement
RHA	Rice Husk Ash
RMSR	Retaining Marshall Strength Ratio
S	Sulfur
C	Creep stiffness
SBE	Styrene–Butadiene Elastomer
SBR	Styrene–Butadiene Rubber
SBS	Styrene–Butadiene–Styrene elastomer (linear or radial)

SEBS	Styrene–Ethylene–Butadiene–Styrene elastomer
SEM	Scanning Electron Microscopy
SF	Silica Fume
SIS	Styrene–Isoprene–Styrene elastomer
VFB	Voids Filled with Binder
VMA	Voids in Mineral Aggregate
WD	Water Damage
WMA	Warm Mix Asphalt
WTT	Wheel Track Test

Chapter One

INTRODUCTION

1.1 Background

The human main commercial needs and development in modern transportation facilities were the main drive for the growth in road infrastructure construction. Development modern transportation facilities comprise the development of vehicles such as the increase in speed, safety and comfort requirements. Consequently, construction of new highways and roads, in addition to maintenance or rehabilitation of the existing roads network considered as a necessary demined, which will affect on pavement structure to provide this demand. Thus, various technologies have been utilized to construct the pavement structure such as Hot Mix Asphalt (HMA) technology, Warm Mix Asphalt (WMA) technology, and Cold Mix Asphalt (CMA) technology. HMA technology was the first successful try to construct the asphalt layer in the flexible pavement. However, this technology was not economical nor eco-friendly, as a result of high production temperature and high CO_2 emission. Therefore, recent orientations were toward utilized sustainable pavement construction, which can be defined as the optimum utilization of natural and man made resources through the pavement lifespan that can eliminate significant damage to the environment. Sustainability in the pavement construction, namely, is represented by the lower consumption of energy and efficient utilization of waste materials (Gambatese and Rajendran, 2005).

Cold Bituminous Emulsion Mixtures (CBEMs) is one of the cold mix asphalt technologies, which can be produced at ambient temperature that can be designated as a sustainable solution. Numerous countries were widely utilized this type of mixture, such as the USA and France since the 1970s (AL-HDABI, 2014). In construction, this mixture was not adequate in terms of long curing process and low early strength to be utilized in the UK due to the relatively wet/cold climatic conditions. Therefore, the utilization and development of this mixture was not advanced (Leech, 1994).

In asphalt pavement system, the bituminous mixture, which used for constructing and maintaining highways, roads and parking areas is incorporation of graded aggregates and bituminous materials as binders with or without additives. The aggregates used for asphalt mixtures could be crushed rock, sand, gravel or slags (Thives and Ghisi, 2017). Bitumen can be found in natural deposits or it can be obtained by refining crude oil; the standard product is called penetration grade bitumen. Also, it is sometimes referred to as asphalt-cement. It forms a mastic which adhesive the larger particles of the mineral aggregate together. The proportion of bitumen in bituminous mixtures varies depending on the type of mixture and application to be nearly within a ranges of 1% to 10% by mass (Ebels, 2008).

Asphalt mixture represents the whole pavement surface and binder layers, whereas the base layer could be an asphalt mixture or a crushed stone. All these layers work on distributing stresses caused by loading and protecting the underlying unbound layers from the effects of water. Additionally, these layers should resist the effects of air and water, permanent deformation, cracking caused via loading and environment to perform their functions over the pavement design life. Many factors affect the ability of a bituminous mixture to achieve structural requirements such as mixture design, construction practices, properties of component materials, and additives use (Epps et al., 2000). Plate (1-1) demonstrates the structure on which most asphalt pavements are based.

Plate 1-1 Typical Flexible Pavement Structure

1.2 Bituminous Mixture Technologies

At natural temperature, grade bitumen has high viscosity, which is relatively a hard semisolid material. Such material is very hard to coat all the aggregate particles to perform the binding constitution without increasing its workability. There are various ways to increase the workability and thus decreasing the highly viscous bitumen into low viscosity liquid suitable for producing a homogeneous bituminous mixture. Lowering bitumen viscosity could be achieved by either heating, fluxing, foaming, or emulsifying the bitumen. Accordingly, three main techniques are used to produce bituminous mixtures at different mixing and applying temperatures; namely, as Hot Mix Asphalt (HMA)), Warm Mix Asphalt (WMA) and Cold Mix Asphalt (CMA) technologies, Figure (1-1) illustrates the temperature ranges for these technologies.

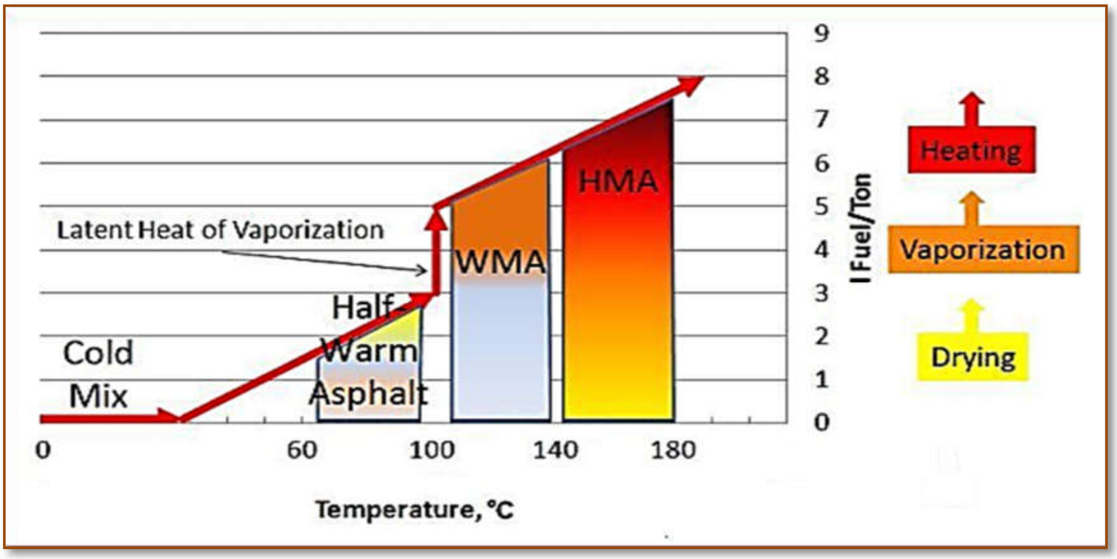


Figure 1-1 Different Technologies of the Bitumen Mixtures Production(AL-HDABI, 2014)

1.2.1 Hot Mix Asphalt Technology

This technology obtains from blending mineral aggregate and asphalt cement at high temperatures; it is usually produced at temperatures between (140 and 180°C) and compacted at about (80 to 160°C) (Kristjansdottir, 2006). The high temperatures are necessary to dry the aggregates, which form about 95% by weight of the mixture, and to reduce the viscosity of the binder to obtain proper and uniform aggregate coating and improve mix workability (Tutu and Tuffour, 2016).

Generally, the production process that comprises in the HMA technology is heating the mixture materials (asphalt binder and aggregate) and blending heat bitumen with the preheated aggregate mixture to obtain relatively a full coating for the aggregate. The bitumen and aggregate temperatures are in the range of (140 to 170 °C) based on the grade type of the used bitumen (AL-HDABI, 2014).

To date, HMA consumed by the majority of the paving industry market worldwide, which is mainly due to the high experience in dealing with such technology. However, some disadvantages are associated with this technology such as environmental impact, high energy consumption for heating, safety issue, limited paving season, and limited hauling distance (EAPA, 2015).

1.2.2 Warm Mix Asphalt Technology

WMA technology is manufacturing and blending at temperatures approximately between 100 and 140 °C; WMA is produced at temperatures lower by 20˚C - 40˚C compared with the temperature of conventional HMA (EAPA, 2015). Generally, the energy saving from manufacture process of this technology is estimated to be about 20 % compared with the traditional HMA (Rubio et al., 2012).

This technology possesses strength, durability, and performance characteristics similar to or better than HMA .The performance characteristics of WMA mix is at least equivalent to conventional mixes (Rubio et al., 2012). Actually, the low temperature of this technology is a result of the reduction in binder viscosity during rheological modification while still providing for the complete coating of aggregates and workability of the mix.

The benefits of WMA technology in contrast to HMA technology include (Tutu and Tuffour, 2016):

1) The ability to pave in cold weather and yet gain desired densities.
2) The ability to have good workability after long transfer.
3) The ability to reduced compaction effort.
4) The ability to blend higher proportions of reclaimed asphalt pavement (RAP).
5) The ability to place multiple lifts within a short time.

Half-Warm Mix Asphalt (HWMA) is a new generation of WMA where the mix preparation temperature does not exceed 100°C. Foam bitumen and heated aggregate in range between 75 °C to 90 °C are used successfully to produce comparative performance mixture (Jenkins, 2000).

The main advantage of utilizing half-warm foamed asphalt mixes is to enhance the coating of aggregate, Figure (1-2) demonstrates the relationship between aggregate temperature and aggregate coating for different maximum particle sizes of continuously graded aggregate. Also, same figure reveals three different coating regions, which are known as practically no coating, partial coating and complete coating. The practically no coating zone characterizes 20 % or less particle coating, whereas the partial coating zone characterizes a partial coating range between 21 and 99 %, and the complete coating zone characterizes particles that are 100 % coated (Jenkins, 2000).

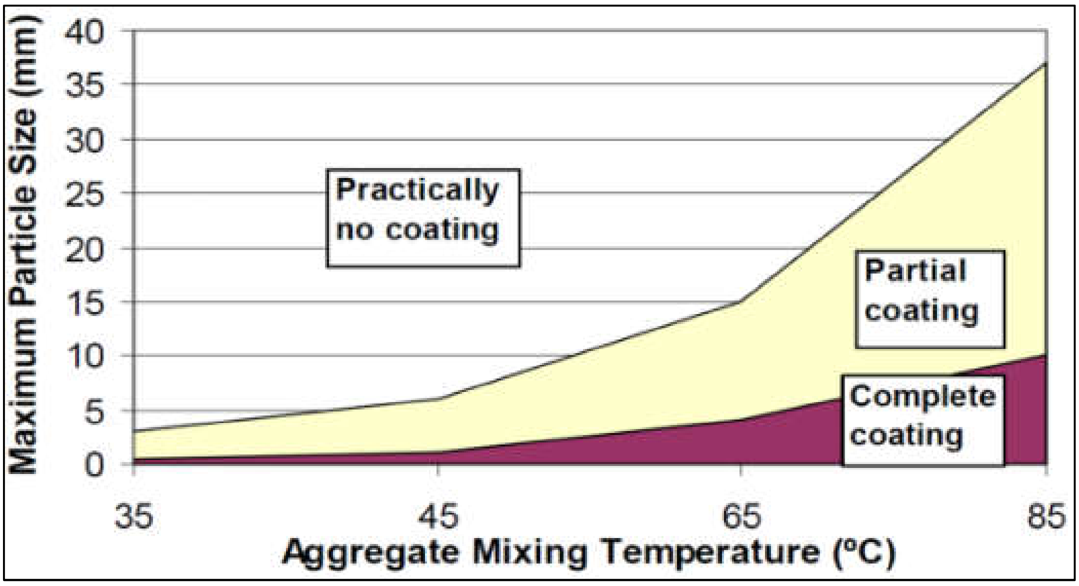


Figure 1-2 Coating Status According to Temperature of the Aggregate Mixing (Jenkins, 2000)

1.2.3 Cold Mix Asphalt Technology

This technology is obtained by mixing mineral aggregate and the hydrocarbon binder with or without additives at ambient temperatures. The hydrocarbon binder could be either cutback (produce from mixing the bitumen with flux oil), emulsified bitumen (produce from emulsification of asphalt emulsion with water), or foamed asphalt (produced from foaming process of hot asphalt with cold water). Currently, the cutback is restricted according to the modern global regulations; hazard and soil pollution could be the result of such use, while such worries are no associated with asphalt emulsion applications (Leech, 1994). However, when this mixture is used as paving mix, it can display the following advantages (Choudhary et al., 2012):

- Safety ؛ because no heating for aggregate or binder.
- Eco-friendly and conserves energy. It considers as green asphalt mix for rural road construction because CMA pavement can provide energy savings of over 50% compared with HMA.
- Simplicity in production; it can be easily prepared using small set up on site and can be produced manually for small-scale job. Laying of HMA for rural road construction is not sometimes economical because setting up of a hot mix plant for small-scale job increases the project cost.
- Long hauling distance; paving mix is suited for construction roads in remote and isolated areas of a country, whereas plant produced hot mix may have set before reaching the site.
- Longer paving season; because it can be placed through wet or humid conditions.
- Versatile; because available of large number of grades emulsion and cutback.
- Economical; lower cost of production with low investment in production plants.

1.3 Disadvantages and Statement of the Problem

According to the vital advantages of the CMA, such technology is looking very promising to overcome the disadvantages of the current prevalent technology, i.e. HMA. Unfortunately, CMA has also some distinct disadvantages. Mainly, the disadvantages are due to some inherent problems associated with its performance, which made to be regarded as "inferior" to conventional HMA mainly due to (Thanaya et al., 2009, Leech, 1994) :

- The low early life strength (as a result of trapped water between asphalt film and aggregate surface).
- The high air-void content of perfect compacted mixtures (as a result of the existence of the water during compaction from pre-wetting of aggregate and in the emulsion itself).
- The long curing period (trapped water or volatiles need a long time to evaporate).
- Additionally, other concerns regarding, as the coating percentage is insufficient because of the incompatibility between the aggregates and emulsion.

- The drainage of binder through storage because of the low viscosity of the emulsion.
- The binder stripping from the aggregate due to high water sensitivity and low adhesion.

Therefore, developing CBEM is in high demand, as its advantages are unique, and there is a hope by the available techniques to overcome the mentioned disadvantages.

1.4 Aim, Objectives, and Scope of the Research Work

The essential aim of this study work is an attempt to overcome some disadvantages of the conventional CBEM by two techniques. Firstly, suggest a polymer to modify the mechanical performance of the CBEMs. Secondly, suggest a low energy heating technique to modify the volumetric properties of the mix. Thus, to catch such goal, the following objectives have been drawn:

- Enhancing the performance of the recommended CBEM incorporating ordinary Portland cement (OPC) as a filler instead of conventional mineral fillers with different percentages.
- Selecting one of the available polymers to perform the development process.
- Comparing the mechanical and volumetric properties of the new developed CBEM with traditional CBEM and HMA comprising conventional mineral filler to ensure the feasibility of the development.
- Evaluating the new developed CBEM durability in terms of its sensitivity to water damage.
- Optimizing the percentage of the suggested polymer for the new developed CBEM, to reach the best practice of such development.
- Studying the effect of low energy (microwave) heating on the new developed CBEM mechanical, durability, and volumetric properties, to ensure further development.

However, within the limiting time and resources, the followings are the main scope of this research work:

1. Using locally available materials as much as it is available.
2. Using one type of polymer.

3. Using conventional testing methods such as Marshall test and indirect tensile strength, further to some modern testing such as creep compliance and wheel tracking.
4. Using home scale microwave oven.

1.5 Thesis Outline

The thesis has been designed to comprise six chapters, each one could be a phase to step the extension in the knowledge in the development of CBEM, whereas:

Chapter 1	Presents the background of the study, bituminous mixture technologies, CBEM's disadvantages and statement of the problem, aim, objectives and scope of thesis work, and thesis outline.
Chapter 2	Demonstrates polymer modified asphalt mixture, improving the performance for CBEM, curing protocols for CBEMs and design method for CMA.
Chapter 3	Presents materials, asphalt mixtures' preparation, laboratory tests and the research methodology.
Chapter 4	Portraits results and analysis for conventional HMA, and unmodified and modified CBEMs by AR polymer.
Chapter 5	Presents results and analysis for unmodified and modified CBEMs by using low energy heating.
Chapter 6	Presents the main conclusions and recommendations for future work.

Chapter Two

LITERATURE REVIEW

2.1 Introduction

This chapter presents a general overview on the polymer modified asphalt mixture and other methods for the improvement of CBEMs. Then, the chapter focuses on the curing systems and design methods for CBEMs.

2.2 Polymers Modified Asphalt

Asphalt cement, which is the predominant bitumen types, is normally a by-product material from the crude oil distillation. Although such materials showed a good performance as a binder through the last 100 years of usage still some of its characteristics need modifications. However, the modifier selection depends mainly on the final requested characteristic, namely, anti-stripping, anti-cracking, resistance to permanent deformation, etc. Accordingly, researchers have been tried extensively several modifiers to improve asphalt cement performance. Table (2-1) demonstrates the most recent asphalt cement modifiers. Meanwhile, polymers are the most common and effective modifier agents (Read and Whiteoak, 2003).

Table 2-1 Additives Used to Modify Bitumen (Read and Whiteoak, 2003)

Type of modifier	Examples	Abbreviation
Thermoplastic Elastomers	Styrene–butadiene elastomer Styrene–butadiene–styrene elastomer (linear or radial) Styrene–butadiene rubber Styrene–isoprene–styrene elastomer Styrene–ethylene–butadiene–styrene elastomer Ethylene–propylene–diene terpolymer Isobutene–isoprene random copolymer Polyisobutene Polybutadiene Polyisoprene	SBE SBS SBR SIS SEBS EPDM IIR PIB PBD PI
Latex Thermoplastic polymers	Natural rubber Ethylene–vinyl acetate Ethylene–methyl acrylate Ethylene–butyl acrylate Atactic polypropylene Polyethylene Polypropylene	NR EVA EMA EBA APP PE PP

Table 2-1 Additives Used to Modify Bitumen (continued)

Type of modifier	Examples	Abbreviation
Thermosetting polymers	Polyvinyl chloride	PVC
	Polystyrene	PS
	Epoxy resin	
	Polyurethane resin	PU
	Acrylic resin	
	Phenolic resin	
Chemical modifiers	Organometallic compounds	
	Sulfur	S
	Phosphoric acid, polyphosphoric Acid	PA, PPA
	Sulfonic Acid, sulfuric acid	
	Carboxylic anhydrides or Acid esters	
	Dibenzoyl peroxide	
	Silanes	
	Organic or inorganic sulfides	
	Urea	
Recycled materials	Crumb rubber, plastics	
Fibres	Lignin	
	Cellulose	
	Alumino-magnesium silicate	
	Glass fibres	
	Asbestos	
	Polyester	
	Polypropylene	PP
Adhesion Improvers	Organic amines	
	Amides	
Anti-oxidants	Phenols	
	Organo-zinc or organo-lead compounds	
Natural asphalts	Trinidad Lake Asphalt	TLA
	Gilsonite	
	Rock asphalt	
Fillers	Carbon black	C
	Hydrated lime	
	Lime	
	Fly ash	
Reactive polymers	Random terpolymer of ethylene, acrylic ester and glycidyl methacrylate	
	Maleic anhydride-grafted styrene–butadiene styrene Copolymer	
Viscosity modifiers	Flux oils (aromatics, napthenics, parrafinics)	
	Fischer–Tropsch waxes	

2.2.1 Types of Polymers Modifier

The polymer is chains of smaller, simpler repeating molecules called monomers. Monomers or starting molecules based to determine the physical properties of polymers. The composition of jointing two or more different monomers called "copolymer" (Stroup-

Gardiner and Newcomb, 1995). Generally, the copolymers construction is with various forms such as repeat or random in blocks of polymers "block copolymers", as shown in Figure (2-1). Polymer structures consist straight, radial, cross-linked, and irregularly branched chains. Many factors influence the behavior and performance of polymers such as bonding types, structure, chemistry, and the manufacturing process (Shafii et al., 2011).

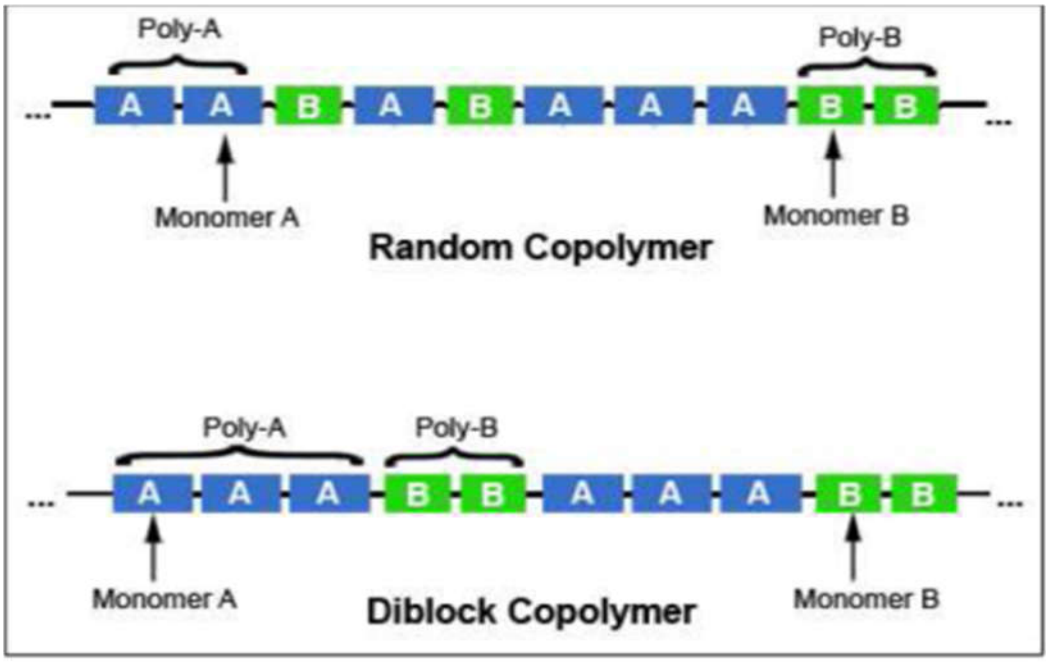


Figure 2-1 Examples of Copolymers (Deb, 2012)

Generally, polymers are classified into two major categories that are used in improving asphalt for road applications; namely, elastomer and plastomer (Johnston and Gayle, 2009):

2.2.1.1 Elastomer Polymer

These polymers are recognized by their capacity to withstand permanent deformation and cohesive failure by expanding, and subsequently returning their initial shape when the applied load removed. Elastomer polymers have a high elastic response and, thus, withstand permanent deformation by expansion and returning their initial shape (Airey, 2002).

2.2.1.2 Plastomer Polymer

These polymers obtain very high strength at a quick rate, also have characteristic brittle and more resistance to permanent deformation at low temperature. Also, these polymers modify the asphalt binder to resist permanent deformation by shaping a rigid, tough, three-dimensional network (Shafii et al., 2011). Under heavy loads, this network transfers quick early tensile strength. Mixtures comprise plastomer offer high moduli in low strain tests as a resilient modulus. However, high early tensile strength is compared with lower strain tolerance (King et al., 1999).

Additionally, elastomer and plastomer are again separated into two other classes based on their temperature rearranged structural characteristics (Deb, 2012):

- Thermoset polymers: those polymers that do no dissolve once heated.
- Thermoplastic polymers: those polymers that dissolve once heated.

Initially heated of thermoset polymers lead to develop a complex, cross-linked structure that is remained on cooling, but it cannot be inverted when reheated. Unlike thermoplastic polymers, which develop a well-defined, linked matrix when cooled, but the resultant structures can be inverted by reheating (Stroup-Gardiner and Newcomb, 1995).

2.2.2 Significance of Polymer Modified Asphalt (PMA)

In flexible pavement, polymer modified asphalt (PMA) utilized to reduce distresses such as permanent deformation and cracking (Chen and Huang, 2007). The increase attention towards the use of PMA, for the reason that conventional asphalt mixtures cannot withstand the heavy axle loads and tire pressures (Abd-Allah et al., 2014). The modification method with polymers is the most cost- effective alternative than conventional bitumen because it enhances targeted aspects of the performance of roads. In addition, the polymers utilized to modify bitumen are easily available at sensible cost. This has led to the development of a wide range of proprietary asphalts made with PMA and a range of PMA that can be added to generic asphalts (Read and Whiteoak, 2003).

Generally, The National Center for Asphalt Technology (NCAT) showed reasons for the use of asphalt modification (King et al., 1999), which will clear the validation of the modification processes:

- High temperatures lead to stiffen binders and mixtures, consequently reduce the rutting and the detrimental effects of load induced moisture damage.
- Low temperatures lead to soften binders that enhance the relaxation properties and strain tolerance, consequently decreasing non-load associated thermal cracking.

- Enhance fatigue resistance when higher strains are imposed on the asphalt concrete mixture.
- Reduce stripping by enhance asphalt-aggregate bonding.
- Reduce raveling by improving abrasion resistance.
- Reduce each of tender mixes, drain down, or segregation through construction.
- Regenerate aged asphalt binders.
- Substitute the asphalt cement as an extender.
- More durability because it allows to thicker films of asphalt on open-graded aggregates.
- Reduce flushing or bleeding.
- More resistance to aging or oxidation.
- Harden the layers for HMA, consequently reduce required structural thickness.
- Enhance the durability of pavement with an attending clear decrease in life cycle costs.
- Enhance total performance as observed by the highway user.

2.2.3 Asphalt Emulsion Modification Techniques by Polymer and Rate of Dosages

For bitumen emulsion, many factors can affect on the performance of polymer modifiers such as: blending techniques, the percentage added, the types of aggregate used, and the methods and temperatures of emulsion storage(Shafii et al., 2011).

2.2.3.1 Polymer Modification Techniques

Normally, the composition of polymer modified asphalt emulsion (PMAE) is comprised of asphalt emulsion and polymer emulsion or a product formed from emulsifying asphalt that has been modified with the polymer (Deb, 2012). Also, PMAE has various construction techniques. Significantly, these modification techniques have an influence on polymer network distribution and on the performance of polymer modified asphalt emulsions (Deb, 2012). Forbes et al. (2001) studied the effect of polymer modification techniques on asphalt binder microstructure at high temperatures. In general, four techniques are commonly used for modifying the asphalt binder. These modification techniques are brief as below:

1. Pre-blending–squarely, the polymer is added to the hard asphalt before emulsification. This technique used for the solid forms of the polymer.
2. Co-milling–composite materials as polymer, asphalt, and emulsifier solution are provided by separated streams and are incorporated together instantaneously.
3. Soap Pre-batching–In this technique, the polymer modifier is mixed with water and emulsifier before crunching together hard asphalt cement.
4. Post-blending hence, the polymer modifier is mixed with the asphalt emulsion in the plant or in the site.

Forbes et al. (2001) study showed that the first technique "pre-blending technique" provides a monophase emulsion in which globules of polymer modified asphalt demonstrate clearly single phase, as can be seen in Plates (2-1). Whereas, other techniques provide bi-phase emulsions, which are combined of asphalt and polymer droplets, as can be seen in Plates (2-2). In bi-phase emulsion, manufacture process of polymer no utilized temperatures above (85-90°C). Conversely, monophase emulsions in which the manufacture temperature reach up to 180 °C to provide enough distribution of the polymer in asphalt. Plate (2-3) illustrates a single stage in which the latex added pre or post-emulsification process.

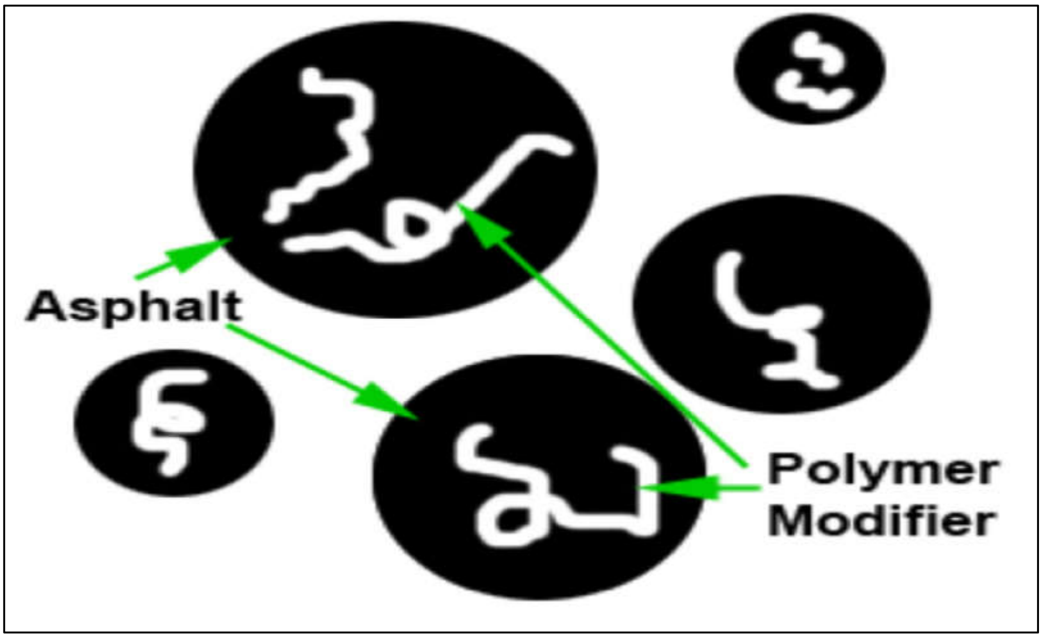


Plate 2-1 Pre-Blended Asphalt-Polymer Monophase (Forbes et al., 2001)

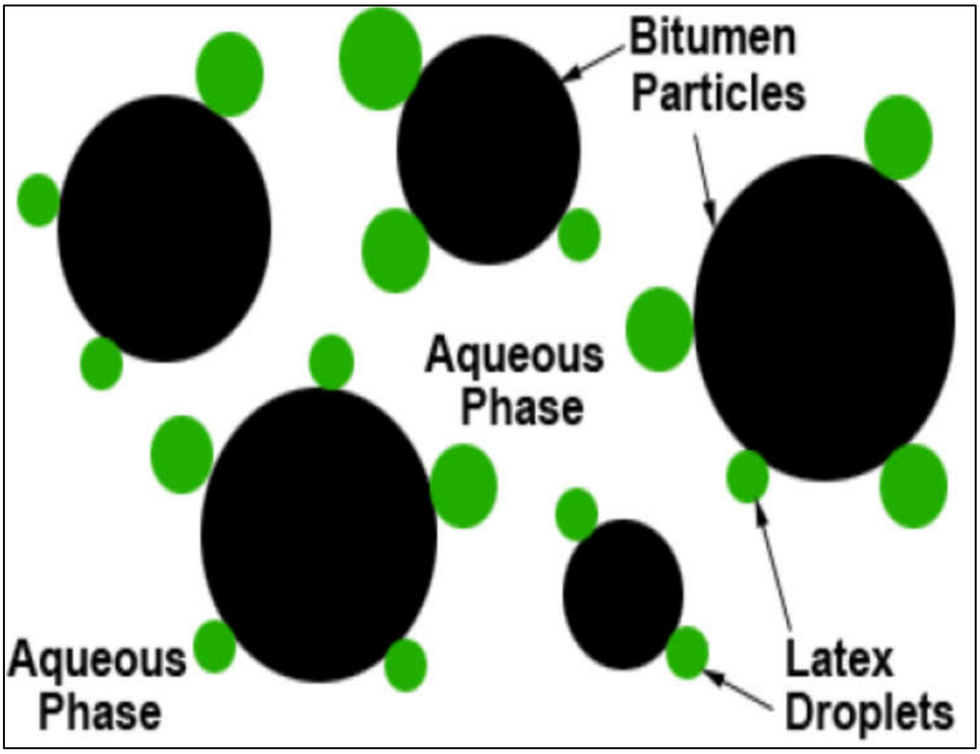


Plate 2-2 Bi-Phase Modified Emulsion (Takamura, 2000)

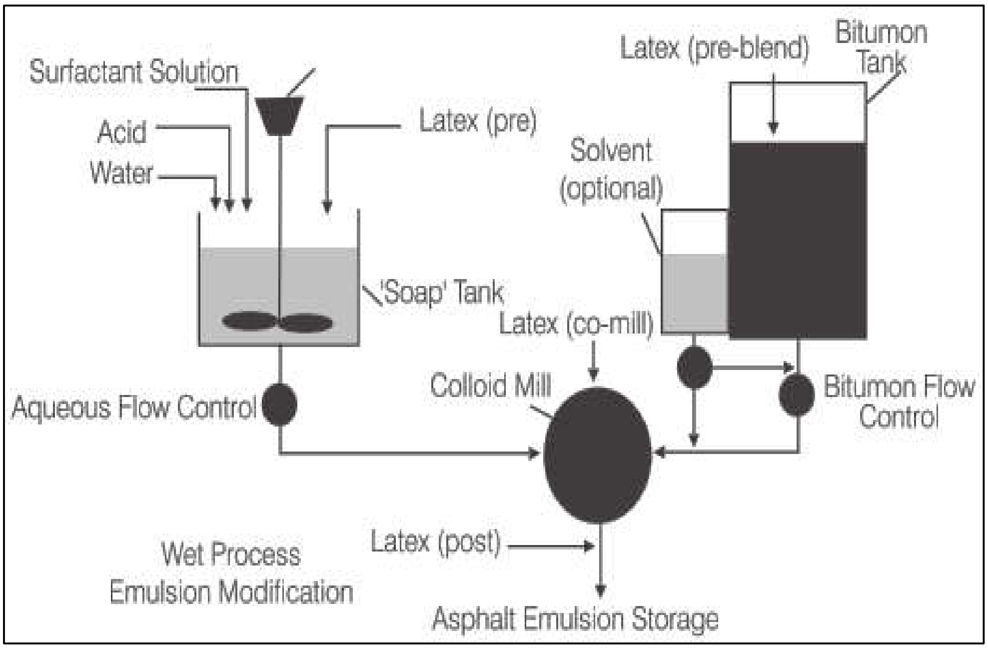


Plate 2-3 Typical Processes of Emulsion Modification (Abd-Allah et al., 2014)

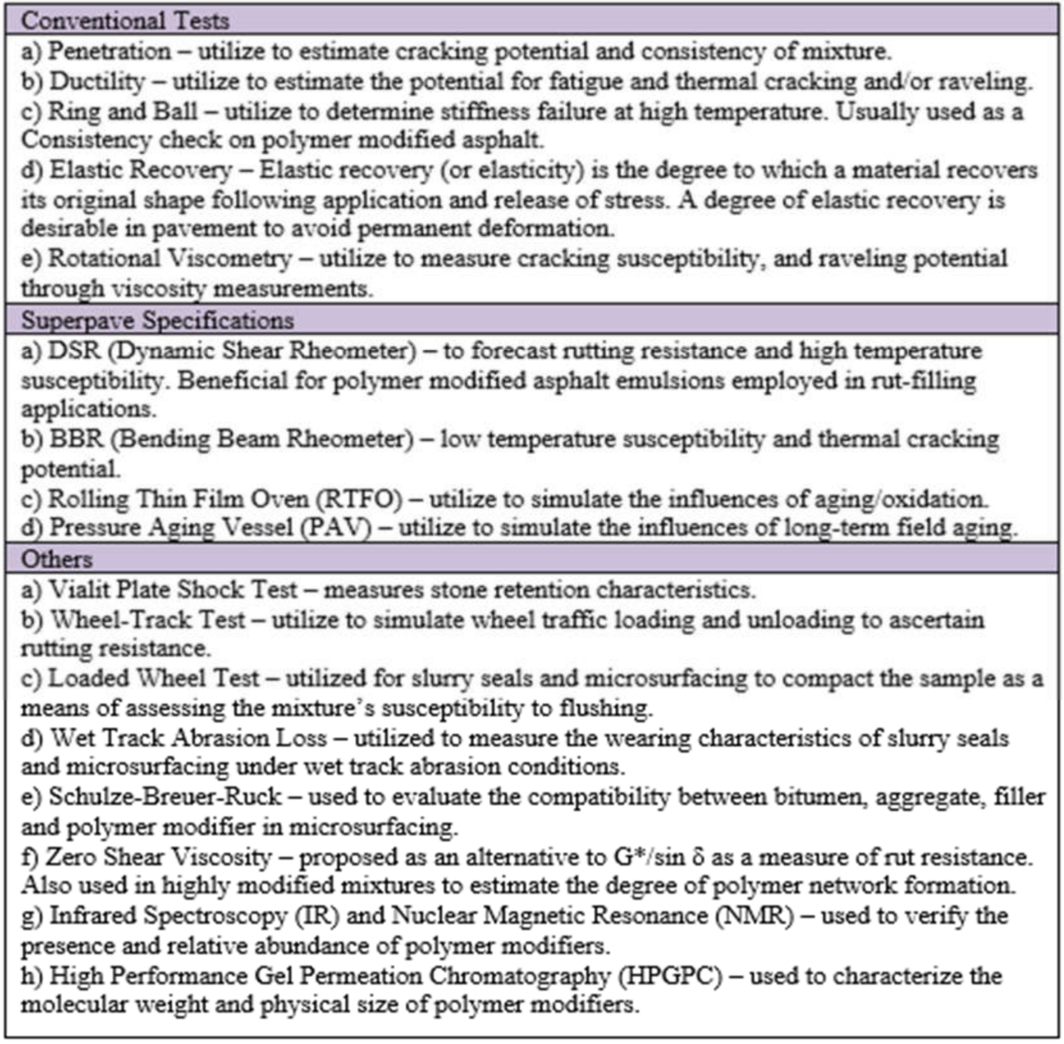
2.2.3.2 Polymer Dosage Rates

Federal Highway Administration (FHWA) stated that the polymer dosage rates are (1-5%) by weight of asphalt, and the most common dosage rate is (2-3%) for slurry seal and chip seal application (Shafii et al., 2011). Other researchers recommended that the most polymer dosage rates applications varies between (2-10%) of the residual asphalt content (Johnston and Gayle, 2009). The polymer concentration that recommended by standard and manufacturer specifications is (3-5%) (Johnston and Gayle, 2009). Several factors are dependent to select the optimal percentage, such as the polymer type, asphalt type and their interaction. Additional, the polymer with a percent of (2.8% - 3.0%) causes a slight influence on the response of stress-strain relationship for the residue emulsion at low temperatures. Whereas, temperatures above 25°C leads to increase the stiffness of emulsion (Anderson et al., 1992). On the other hand , addition of the styrene–butadiene-rubber (SBR) latex in a dosage of 3.0-3.5% for microsurfacing formulation (which compose from 100 portions of aggregates, 8-15 portions of water and 0.5-2 portions of Portland cement) revealed a significant mix characteristics (Takamura, 2000).

2.2.4 Characterization of Polymer Modified Asphalt

Previous researchers stated that a variety of test methods and equipment can be utilized to evaluate the physical properties of asphalt binders and emulsion residue. These test methods are divided into three groups, these are conventional test, superpave specifications and other tests, as can be seen in Table (2-2). The first group concentrated on determinations the viscosity, penetration, ductility, and softening point temperature. Nevertheless, these tests are often unsuccessful to describe the accurately and comprehensively the performance characteristics related with PMAE (Takamura, 2005, Airey, 2004). While, the second tests method include Dynamic Shear Rheometer (DSR), Bending Beam Rheometer (BBR), Rolling Thin Film Oven Test (RTFO) and Pressure Aging Vessel (PAV). Currently, most researchers encourage utilizing oscillatory DSR testing as a method of select the distinction viscoelastic properties of modified binders and residue (Airey, 2004).

Table 2-2 Typical Tests of Polymer Modified Asphalt (Shafii et al., 2011)



Conventional Tests
a) Penetration – utilize to estimate cracking potential and consistency of mixture. b) Ductility – utilize to estimate the potential for fatigue and thermal cracking and/or raveling. c) Ring and Ball – utilize to determine stiffness failure at high temperature. Usually used as a Consistency check on polymer modified asphalt. d) Elastic Recovery – Elastic recovery (or elasticity) is the degree to which a material recovers its original shape following application and release of stress. A degree of elastic recovery is desirable in pavement to avoid permanent deformation. e) Rotational Viscometry – utilize to measure cracking susceptibility, and raveling potential through viscosity measurements.
Superpave Specifications
a) DSR (Dynamic Shear Rheometer) – to forecast rutting resistance and high temperature susceptibility. Beneficial for polymer modified asphalt emulsions employed in rut-filling applications. b) BBR (Bending Beam Rheometer) – low temperature susceptibility and thermal cracking potential. c) Rolling Thin Film Oven (RTFO) – utilize to simulate the influences of aging/oxidation. d) Pressure Aging Vessel (PAV) – utilize to simulate the influences of long-term field aging.
Others
a) Vialit Plate Shock Test – measures stone retention characteristics. b) Wheel-Track Test – utilize to simulate wheel traffic loading and unloading to ascertain rutting resistance. c) Loaded Wheel Test – utilized for slurry seals and microsurfacing to compact the sample as a means of assessing the mixture's susceptibility to flushing. d) Wet Track Abrasion Loss – utilized to measure the wearing characteristics of slurry seals and microsurfacing under wet track abrasion conditions. e) Schulze-Breuer-Ruck – used to evaluate the compatibility between bitumen, aggregate, filler and polymer modifier in microsurfacing. f) Zero Shear Viscosity – proposed as an alternative to $G^*/\sin\delta$ as a measure of rut resistance. Also used in highly modified mixtures to estimate the degree of polymer network formation. g) Infrared Spectroscopy (IR) and Nuclear Magnetic Resonance (NMR) – used to verify the presence and relative abundance of polymer modifiers. h) High Performance Gel Permeation Chromatography (HPGPC) – used to characterize the molecular weight and physical size of polymer modifiers.

2.2.5 Polymer Modified Asphalt Mixture

The process includes the present of one of the additives that used in wet modification method, which is added the additives to asphalt emulsion prior to production of mix asphalt.

2.2.5.1 Hot Mix Asphalt (HMA) Modified by Polymer

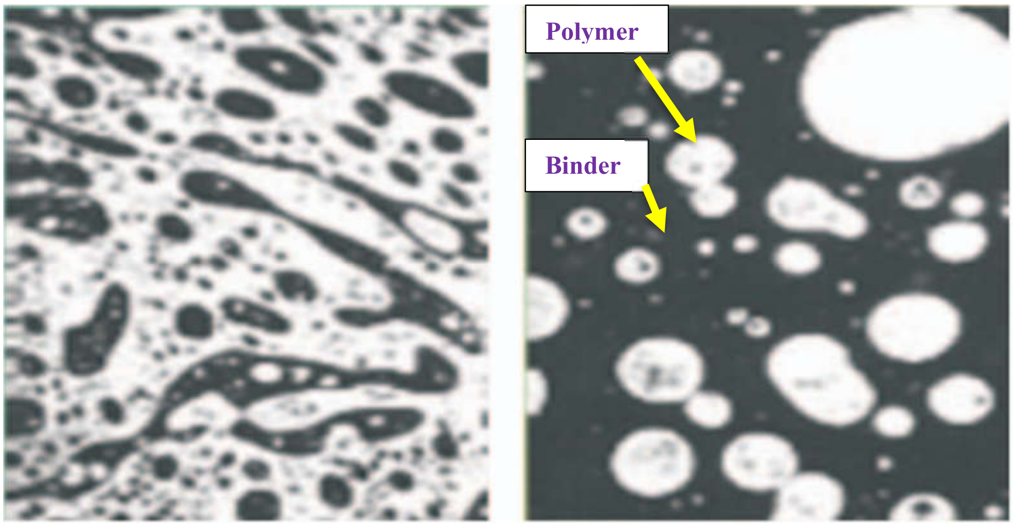
Rutting is one of the most common forms of distress for asphalt concrete pavement (Tayfur et al., 2007). This type of distress increases with the high summer temperatures and heavy trucks. On the other side, cracking is the most common form of distress that increases due to low temperature and/or high axle load. Consequently, various types of polymer modifiers asphalt were utilized to enhance both the rutting and thermal cracking problems of HMA by changing the properties of the asphalt binder(Albritton et al., 1999). Attention has been grown towards the use of polymer modified asphalt (PMA), because traditional asphalt mixtures cannot resist the modern increase in axle loads and tire pressures (Abd-Allah et al., 2014). Also, bitumen showed high temperature sensitivity due to seasonal temperature variation. It softens in summer and cracks in winter, therefore polymers have been used significantly to produce modified bitumen with better properties; such as wide temperature susceptibility range, as well as, better rheological properties (Bulatović et al., 2012). In HMA, PMA consider as one of the additives that might be used collectively or individually for the followings; (Karakas et al., 2015):

- Overcome shortage of raw materials.
- Need for a longer service life of roads.
- Need for better physical and mechanical properties of asphalt pavement and Reduction in the maintenance and repair costs.

However, PMA demands temperatures normally exceed 160ºC and very frequently approaches 180-190 ºC (Yuliestyan et al., 2016). The pavement with PMA shows better resistance to low temperature cracking, rutting deformation, reduce the effect of fatigue damage, the occurrence of stripping and susceptibility of temperature. Which used with success in the high stress locations as intersections of busy streets, airports, vehicle weigh stations, and race tracks (King et al., 1999). In addition, it shows enhanced in cohesion and adhesion properties (Awwad and Shbeeb, 2007). El-Batal et al. (2000) stated that mixtures modified with high-density polyethylene (HDPE) exhibited higher stability, air voids and higher voids in mineral aggregate than conventional mixes. The highest mix stiffness was obtained in creep test for mixes with 4% HDPE by asphalt weight (Abd-Allah et al., 2014). Roberts et al. (1996) stated that the typical content of low density polyethylene (LDPE) was about 4-6 % by weight of the modified binder and addition of LDPE to asphalt cement decreases its penetration, and increases its kinematic viscosity, absolute viscosity and softening point (Abd-Allah et al., 2014).

2.2.5.2 Cold Bitumen Emulsion Mixtures (CBEMs) Modified by Polymer

Polymer modified asphalt emulsion offers a binder with safer and more eco-friendly characteristics, further to enhancement to road material performance (Haverkamp, 2001).This enhancement is by forming a continuous network within the binders. Therefore, compatibility between polymers and binders must be satisfied, in order to create a uniform connected network. Otherwise, in the incompatible case the polymers will collect themselves and are not linked, as demonstrated in Plate (2-4) (Deb, 2012).



(a) Compatible (b) incompatible

Plate 2-4 Compatibility and Incompatibility between Polymers and Binders(Deb, 2012)

Obviously, the addition of polymers to asphalt binders results in the modification of physical properties. PMAE has benefits compared with unmodified asphalt emulsion can be summarized as follows (Johnston and Gayle, 2009, Donald, 1986):

- Improve the resistance to low temperature cracking and rutting deformation.
- Improve the resistance to the occurrence of bleeding.
- Improve the resistance to fatigue characteristics.
- Improve the resistance to retention of the aggregate particles.
- Earlier time to open the road after constructions or repair.
- Increase the pavement lifespan with same cost of equivalent, as a result of a reduction in fatigue and thermal cracking, decreasing in high temperature susceptibility (e.g., rutting and shoving).

Polymer modifier is used to expand the lower and/or upper effective temperature operating ranges of pavements and to add elastic components that allow it to recover after loading stress (Read and Whiteoak, 2003). Khalid and Eta (1997) used two polymers, Ethylene Vinyl Acetate (EVA) and Styrene-Butadiene-Styrene (SBS) admixtures with two gradations; namely, close graded wearing course and dense graded base course with cationic emulsion. Their results showed a significant improvement of stiffness and permanent deformation compared with unmodified mixtures, where the use of 4% of SBS and 6% EVA increased the fatigue life of CBEM by 45 and 35 times, respectively.

Chavez-Valencia et al. (2007) studied the effect of polyvinyl acetate on the CBEM in terms of compressive strength. They utilized two methods: the first was coating the aggregates with a film of the modified emulsion with polyvinyl Acetate (A-PVAC); and the second was, before the A-PVAC binder was applied, the aggregate was covered with the polymer by mixing the aggregate in a diluted PVAC-E. The second method showed an improvement in void content, which in turn reflected on compressive strength, i.e. compressive strength increased by 31%, Figure (2-2) demonstrates the reduction in air voids content with various polymer introducing technique. Other study proved that utilizes SBR with the asphalt emulsion reduced temperature susceptibility. Consequently, this effected rutting resistance at high temperature and cracking at low temperature (Zhang et al., 2010). In addition, SBR utilized with slow setting emulsion to improve the performance of emulsion asphalt, which demonstrates improvement in the rutting resistance of binder, as can be seen in Figure (2-3,), where G* / Sin δ (rutting factor) and G*. Sin δ (fatigue resistance) (Warid et al., 2015).

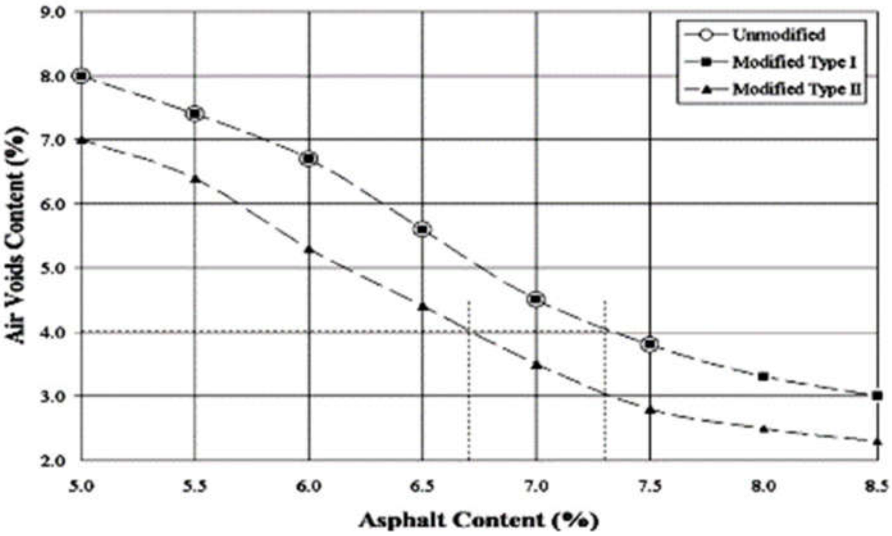


Figure 2-2 Air Voids Content Decrease with Different Polymer Introducing Technique (Chávez-Valencia et al., 2007)

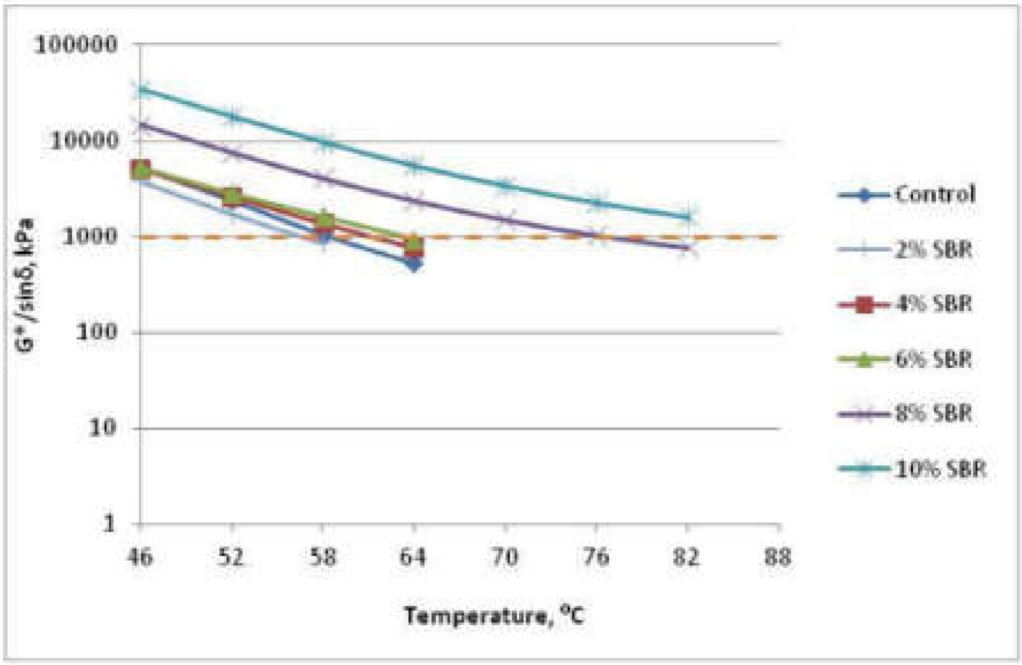


Figure 2-3 Phase Angle as Function of Temperature(Warid et al., 2015)

As a comparison between modified asphalt emulsion and hard asphalt has been conducted in another research work, used SBS to evaluate the performance of modified HMA and asphalt emulsified in thin surface treatments by using laboratory tested as rheological properties, cohesion, stone retention, tensile strength, and durability. The results from this study concluded that (Serfass et al., 1992):

- SBS modified HMA is not suitable in cooler weather because it exhibits poor adhesion to aggregate and requires the use of an anti-stripping agent. On the other hand, the use of anti-stripping agents with SBS modified HMA produces only modest improvements, which decrease under more adverse climatic conditions. Also, SBS modified asphalt emulsions show a longer application season, good performance under cool and damp conditions. SBS-modified asphalt emulsions require a much longer set time than do their hot mix Counterparts.
- In addition, high contents of SBS may be used in asphalt emulsions, while higher SBS concentrations in HMA show decreased adhesion and problematically high viscosities.

2.3 Improving CBEMs' Performance

Although polymer showed obvious improvement in the CBEM, as it is demonstrated in the previous sections, but the mechanical and volumetric properties of such mix still incomparable to HMA. Thus, extensive review to other practices that associated in other improvements of CBEM is in high demand, on the hope of use these contributions of improvement collectively in this research work, which could lead to upgrade CBEM to the level of HMA performance. However, large number of the studies have been achieved to characterize the behavior of CBEMs and to enhance their performance. Whereas, various methods suggested improving the performance of these mixtures; namely, dry method, wet method and other techniques. The first method includes incorporating the utilized improvements with aggregate during the preparation process of the CBEM. While, the second method in which the improvements are incorporated with asphalt emulsion prior to production of CBEMs (which is the main consideration in this research). The third method includes different preparation techniques, i.e. compaction and heating technologies. Hereafter is the most significant attempts to improve CBEMs:

2.3.1 Cement and Lime

There are many of virgin active materials that have been used successfully to improve the mechanical properties of CBEMs; such as cement and lime. Cement and lime are the most extensively utilized cementitious components for CBEMs. OPC and lime are considered as active filler. Consequently, they provide the following purpose (Ebels and Jenkins, 2007):

- Stimulated factor for breaking process for emulsion asphalt.
- Accelerate obtain initial strength and cementitious links.
- Acting as a modifier that leads to reduce the plasticity index (PI).
- Acting as a factor for anti-stripping.

Previous studies of using OPC in the CBEMs concluded that the mechanical properties such as stiffness modulus, permanent deformation resistance, fatigue cracking (at an initial strains below 200 micro strain), and resistance to water damage are enhanced with Portland cement addition (Brown and Needham, 2000b), as can be seen in Figures (2-4) to (2-6).

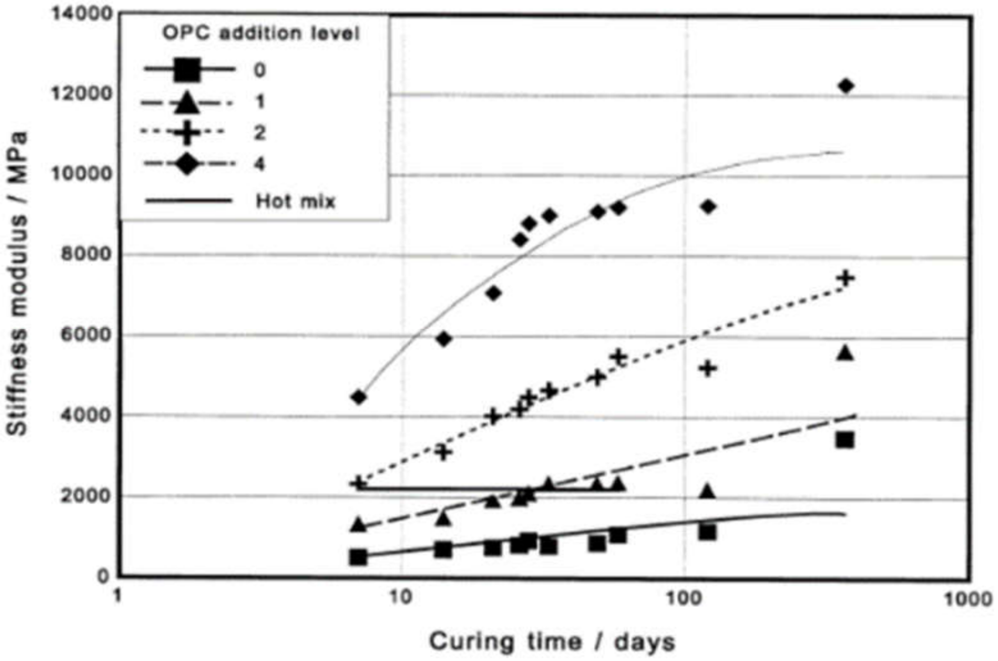


Figure 2-4 Influence of OPC on Stiffness Moduli for Cold Mix Asphalt(Brown and Needham, 2000b)

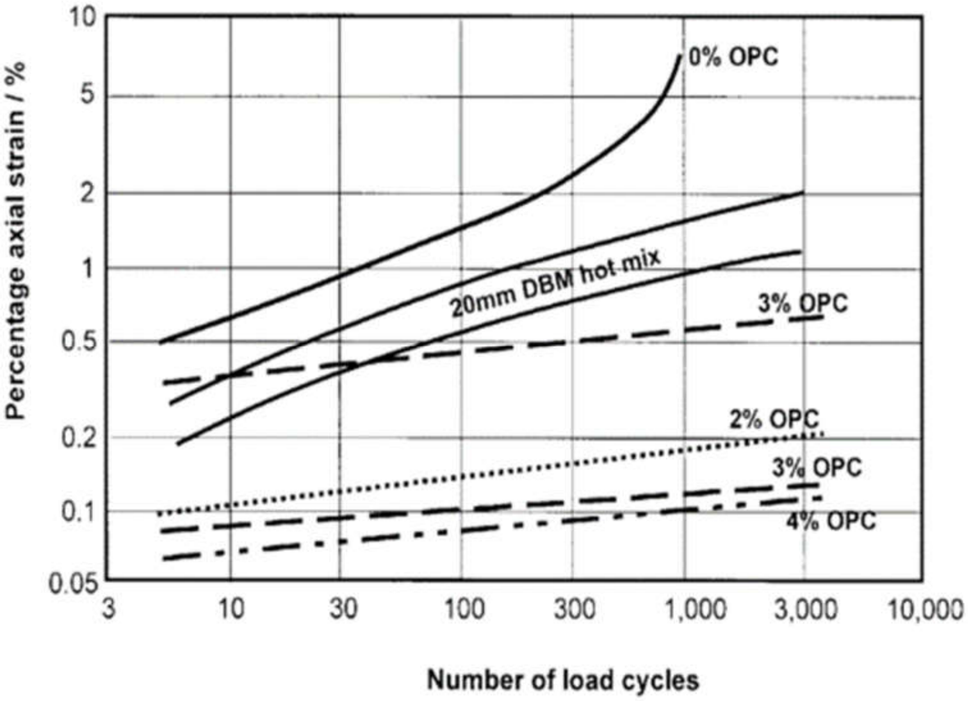


Figure 2-5 Resistance of Permanent Deformation of Cold Mix Asphalt with Different Percentages of OPC(Brown and Needham, 2000b)

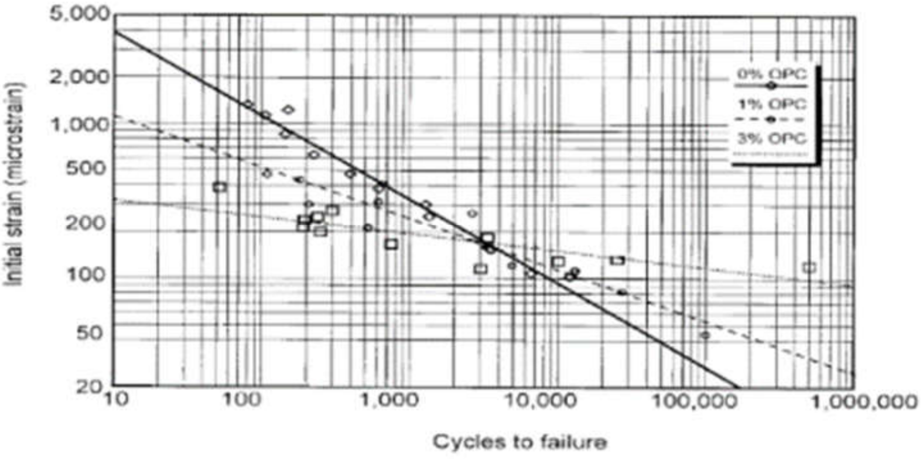


Figure 2-6 Cycles of Failure Versus Initial Strain for Mixtures with Range of OPC Addition Levels(Brown and Needham, 2000b)

Addition the cement into the emulsion improves the performance of the treated mixtures compared with conventional HMA and it proved to be a regulating element of the emulsion breaking by increasing the viscosity of the bitumen and contributing to the creation of new bonds in the mixture. It also effects on physical and chemical properties of asphalt even with slight doses and has useful action in producing an excellent creep performance and a high stiffness modulus even after submerged in water (Giuliani, 2001).

Addition Portland cement with percentages between 1 to 6 % were improved to mechanical properties, resilient modulus, temperature susceptibility, water damage, creep and permanent deformation resistance (Oruc et al., 2007),as can be seen in Figures (2-7) and (2-8).

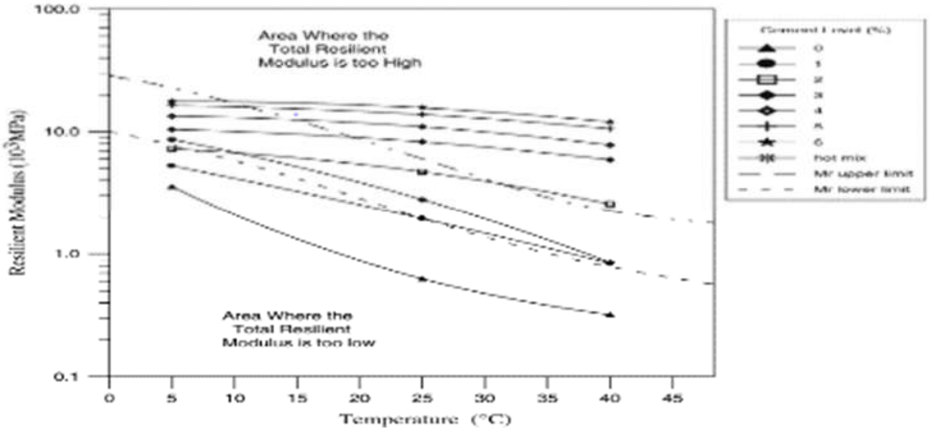


Figure 2-7 Effect of Cement on Resilient Modulus for Temperature Susceptibility (Oruc et al., 2007)

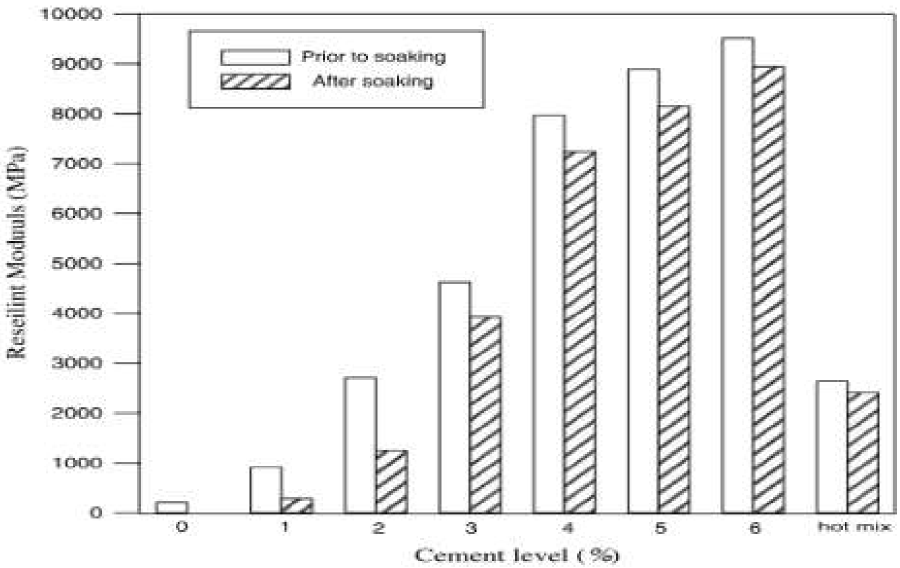


Figure 2-8 Influence of Cement Level on The Resistance to Water Damage (Oruc et al., 2007)

Brown and Needham (2000b) used different added materials, as OPC, lime and cacl2. This study showed that hydrated lime and cacl2 have less effect in comparison with OPC on stiffness modulus values, in which OPC improves the stiffness of a mixture by stiffening the binder.

The interaction between cement and asphalt emulsified can be demonstrated in Figures (2-5a,b), which shown that the initial asphalt emulsion is spherical separately; whereas, emulsified asphalt with cement particle produced an inorganic–organic interpenetrating structure after adding the cement (Xu et al., 2017).

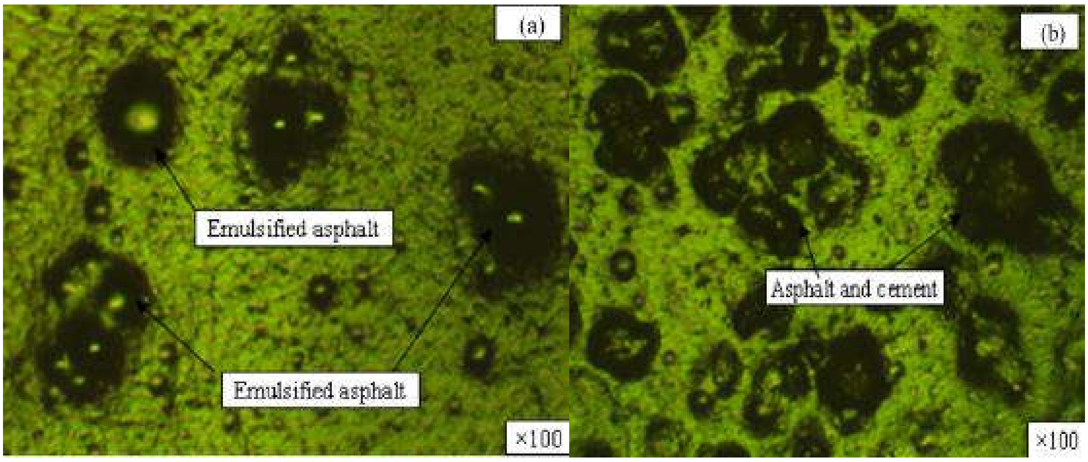


Plate 2-5 Interaction between Cement and Asphalt Emulsified: A) without Cement; B) with Cement (Xu et al., 2017)

2.3.2 By–Product and Waste Materials

These materials were utilized with the CBEM to improve the minor mechanical properties such as low early strength and high porosity. Whereas, the advantages of these materials include improvement of final strength relate to influence of the cementitious, economic advantages and impact environmental (Thanaya, 2003b). Also, these materials less of the water content in the mix by the hydration method, chemical characteristics and powder physical (Al-Busaltan et al., 2012). Previously, the researcher study utilized these materials with the CBEMs as lists:

2.3.2.1 Fly Ash Material

This modification type utilized as a filler material. In road pavement, it was utilized as a stabilizer factor to sub-grade, sub-base and the granular bases of the road (Dash, 2013). Generally, four main benefits can be obtained when using fly ash material with CBEM's (Al-Busaltan et al., 2012):

- Absorption of the trapped water via the hydration process.
- Enhancement mechanical properties in mixture.
- Cost effectiveness.
- The ecological benefit factor.

Pulverised Fuel Ash (PFA) is a pozzolanic material that is generally used as an increment-based materials to improve long-term strength, workability, resistance to sulphates attack and durability in concrete (Owaid et al., 2012). Thanaya et al (2006) studied the effect of addition coal fly ash to CBEMs which lead to increase stiffness of mixture comparable to HMA after full curing conditions.

Al-Busaltan et al (2012) improved the mechanical properties of CBEM's as indirect tensile stiffness modulus and creep stiffness by using (LIMU), which is a waste domestic fly ash, as can be seen in Figures (2-8 and 2-9).

Rice husk ash (RHA) is another by-product material produced from the burning of rice husk and its production is about 20 million tones worldwide yearly (Zemke and Woods, 2009). It creates with cellular microstructure and extremely pozzolanic action when rice husk is burnt at temperatures lower than 700 ºC. RHA contains a high amount of silicon dioxide, and its reactivity related to lime depends on a combination of two factors, namely the non-crystalline silica content and its specific surface. However, this material has been proven as a vital material in improving CBEMs(AL-HDABI, 2014).

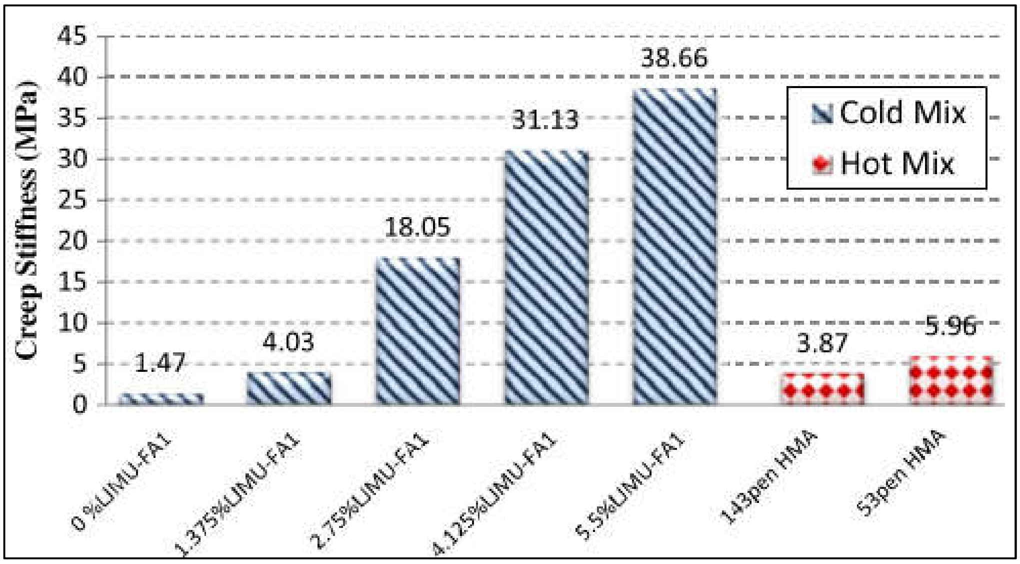


Figure 2-9 Influence of % LJMU-FA1 on Creep Stiffness Al-Busaltan et al (2012)

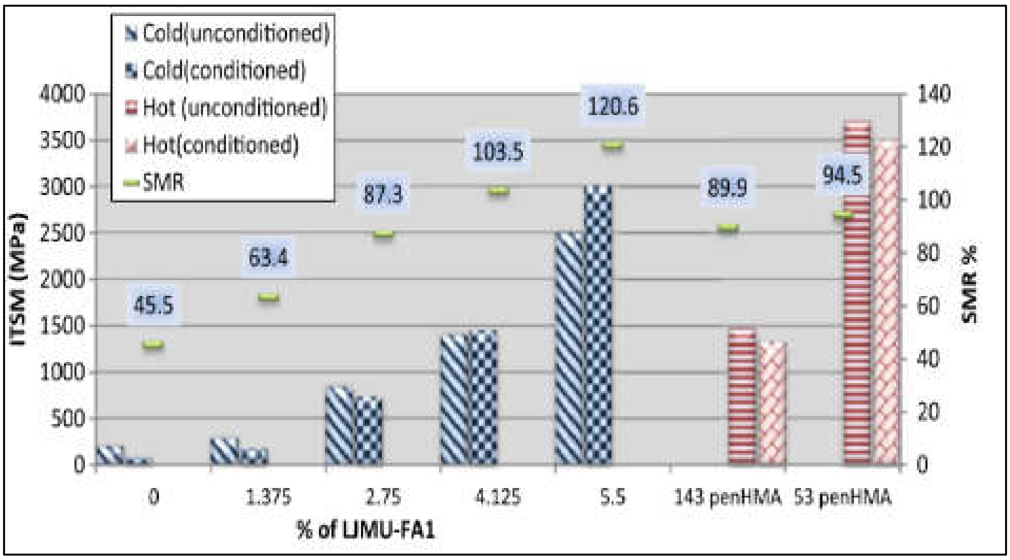


Figure 2-10 Influence of% LJMU-FA on Stiffness Modulus Al-Busaltan et al (2012)

2.3.2.2 Reclaimed Rubber Tires

Reclaimed tires rubber is a fine ground shreds produced by the mechanical cutoff of truck tire treads at ambient temperatures. Rubber shreds were subjected to no further processing except screening to the required particle sizes.

Using reclaimed rubber from discarded tires have several economic and practical benefits such as (Al-Abdul-Wahhab and Al-Amri, 1991):

- disposal rubber tires present a serious environmental problem.
- using the reclaimed rubber is economically cheaper than using the natural rubber or the addition of an-other polymer.
- reclaimed rubber tire contains additives as antioxidants and antiozonants that retard oxidative aging of asphalt.

Thanaya (2003b) proved unsuitability for combination this material in CBEMs. Cracks were observed to occur in the freshly compacted mixtures, as a result the rebound of the highly elastic crumb rubber particles, soon after compaction.

2.3.2.3 Fibers and Other Reinforcement

Utilized fibers as polypropylene with the CBEMs lead to improve many characteristics such as decrease Marshall stability, resilient moduli and the dry density compared to the unmodified mixture (de S. Bueno et al., 2003). Other study used plastic cells successfully for reinforce the CBEM, whereas results indicated a decrease in stiffness modulus for all curing ages, while improvement in permanent deformation resistance was recognized, as can be seen in Figures (2-10) (Thanaya, 2003b). Nevertheless, inclusion fibers or reinforcement cells for CBEM required additional investigations to overcome the cutoff, as the mixtures with fibers do not act as an integral mass (Thanaya, 2003b).

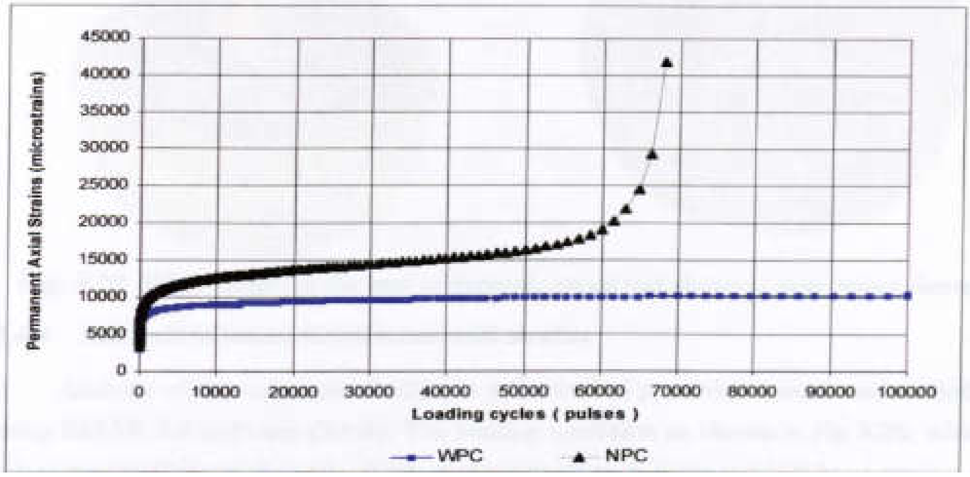


Figure 2-11 Permanent Axial Strains versus. Number of Load Cycles, at Age 3 Days (Thanaya, 2003b)

2.3.3 Compaction

Generally, compaction is a significant element, which affects the mechanical, and performance characteristics of asphalt mixture and the suitable compaction ensure the optimally performance of mixtures. Therefore, it is essential to choose the suitable compaction technique that reflects the experienced conditions and achievable in the field (Ojum, 2015). The increase in the compaction degree for CBEM results in an increase in the stiffness of the mixtures (Serfass et al., 2004). However, several compaction techniques were utilized to evaluate this characteristic, such as Marshall hammer, the roller compactor and the gyratory compactor (Kim and Lee, 2006). Results showed that the compaction with the gyratory technique lead to a higher density value than the Marshall compaction technique, but the specimen prepared by the gyratory compactor have lower resilient modulus values compared with specimen prepared using the Marshall compactor (Leech, 1994).

Thanaya (2007) stated that extra heavy compaction with at least 240 gyrations leads to obtained air void content between 5-10%. Whereas, heavy compaction is inevitable in cold mix asphalt to ensure the emulsion sets and the mixes stiffen properly. Also, the study acted simulation between the Gyratory compaction and Marshall compaction as lists (Thanaya, 2007a).

- Heavy level of compaction: In this level of gyratory compaction, 120 revolutions is equivalent to 75 blows for each side of the specimen in Marshall compaction.
- Medium level of compaction: In this level of compaction, 80 revolutions is equivalent to 50 blows for each side of the specimen in Marshall compaction.

2.3.4 Microwave Energy

Processing the materials by microwave technology is a relatively new development and show benefits in reduced processing times and energy savings (Thostenson and Chou, 1999). Principally, microwave heating is various from conventional heating in conventional heating thermal energy is received to the material surface by radiant and/or convection heating to be transmitted to the bulk of the material by conduction. Whereas, microwave energy is received instantly to the material through molecular interaction with the electromagnetic field. Microwave heating is transmit the electromagnetic energy to the thermal energy and this energy conversion rather than heat transmit. Consequently, microwaves can penetrate the material and provide energy; heat can be produced during the volume of the material resulting in volumetric heating. Therefore, it is possible to attain heating of thick materials is quick and uniform (Das et al., 2008). Additionally, the observed benefits with microwave processing warrant serious and the interest concentrated on this technology. Sensible benefits that produced by microwave material research comprise(Clark et al., 2000) :

- Decrease processing costs.
- Better production quality.
- New materials and products.
- Enhance human health.
- Decrease danger to humans.
- Environment and enhanced quality of life.

Clark and Sutton (1996) stated that heating specimens with microwave energy by microwaves penetrate during the material instead of concentrating the heat on the surface.

In CBEM, the microwave is used to reduce the air void where it is not acceptable by pavement engineers for use in road surfacing layers without affecting the obtained improvement in mechanical properties, and other environmental and economic issues. High air void content of CBEM is because the low workability through the compaction compared with HMA; CBEM workability is based on the pre-wetting content water and emulsion bitumen. Whereas, HMA workability based on the viscosity of the bituminous binder that in turns based on temperature of the mixture. Thus, increase temperature of CBEM leads to increasing the workability causing obtained the required air void content. Furthermore, microwave heating increase the coalescence of emulsion bitumen and accelerate the adhesion between bitumen and aggregate. (Al-Busaltan, 2012). Microwave treatment (few minutes) for CBEM with short time application displays significant improvement to CBEM in terms of porosity reduction, whilst long time (few hours) is harmful, because it leads to ageing the bitumen (Bishara et al., 2003). Microwave energy utilized to treat CBEMs comprising PSA (Paper sludge ash) and PSA with SF (Silica-fume), this attempt concluded that (Al-Busaltan, 2012):

- Decreasing the porosity of CBEMs to an acceptable limit, which identifies by road engineers. This decrease is due to the decrease in the bitumen viscosity, which in turn increases the workability and facilitates compaction.
- Increasing the resistance to permanent deformation comparative with conventional HMA.
- Increasing resistance to the water damage and ageing comparative with HMA.
- Enhancing the fatigue characteristics for control CBEMs and slightly effects on comprising PSA.

2.4 Curing Protocols for CBEMs

Curing is process loss of the moisture content in mixtures and returns the bitumen to a continuous phase at elevated temperatures (Ojum, 2015). Jenkins (2000) defined the curing of cold bituminous mixes as process discharges the water from the mixture by evaporation, particle charge repulsion or pore-pressure induced flow paths. The curing process of CBEMs is influenced via several factors such as temperature, curing time, humidity, and cement content. The high curing temperature leads to increase the rate of water evaporation, subsequently increase the strength gain process and it is responsible for additional stiffness gain via increasing the binder stiffness due to ageing and by increasing the moisture loss by evaporation during the curing process. Whereas, studies by Chevron Research Company in California decided that full curing of cold asphalt mixtures on site may occur between 2 - 24 months depending on weather condition (Leech, 1994).

However, at high curing temperature the moisture loss by evaporation may hinder the hydration of cement. Bocci et al., (2002) reported that as curing temperature and time increased, the performance of the mixtures improved significantly (Ojum, 2015). Also, the high relative humidity level influences the stiffness modulus of negatively (Ruckel et al., 1983). While the cement has an important positive role in improving the stiffness modulus, especially during the early life of CBEM and accelerate the emulsion breaking process, increase the rate of bitumen coalescence and reduce the amount of evaporable water (Needham, 1996). To evaluate CBEM during service life, researchers proposed, assessed and compared different curing protocols to accelerate representative mixtures' life with respect to the following (Al-Busaltan, 2012) :

- Laboratory curing must be related to field curing.

- The binder film must not be brought to an artificial state.
- No binder ageing must be caused by curing.

Thus, different curing protocols have been suggested, as showed in Table (2-3).

Table 2-3 Curing System for CBEMs

System	Oven conditioning		In situ equivalent
	T (°C)	t (days)	
Brown and Needham (**Brown and Needham, 2000a**)	20	100 + 1 @60 C	1 year
Kishore Kumar (**Kishore Kumar et al., 2008**)	60	2	28 days
Asphalt Institute Ms-14 (**Asphalt Institute, 1989**)	38	1	7-14 days
Thanaya(Thanaya, 2003b)	40	14	Full curing
Jenkins (**Jenkins, 2000**)	40	1	7-14 days
Maccarrone.(Houeran and MaCCarrone, 1994)	60	3	1 year
NRA (2011) (**Doyle et al., 2013**)	40	28	1 year
NRA (2011)(**Doyle et al., 2013**)	20	28	1 month

2.5 Design Method for Cold Mix Asphalt

Currently, cold mix design procedures are under continuing development, where different methods are proposed with some modification from the main one, i.e., Asphalt Institute Method. Such modifications are incorporated to associate the spot environment of the developer. However, hereinafter are the most well known methods:

2.5.1 Asphalt Institute Design Method

Asphalt Institute design method MS-14 stated two methods for cold mix design (Asphalt Institute, 1989):

- Modified Hveem method

This method not commonly utilized needs because it required some particular apparatus, which is not commonly available in asphalt laboratories.

- Marshall Method

Mainly, this design method is consisted of several steps such as:

1) Determine the suitable gradation of mineral aggregate.

2) Determine the Initial Residual Bitumen Content (IRBC)

IRBC is determined by two methods Centrifuge Kerosene Equivalent (C.K.E) test or may be followed the empirical formula for dense graded.

$$P = (0.05A + 0.1B + 0.5C) * 0.7 \qquad \textit{Equation 2-1}$$

Where:

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

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

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

C = mineral aggregate amount passing (No.200).

The initial emulsion content (IEC) value can be determined by dividing P by the percentage of the residual bitumen content in the bitumen emulsion

$$IEC = \frac{P}{X} \qquad \textit{Equation 2-2}$$

Where:

IEC = Initial Emulsion Content of total mass mixture %

X = content of residual bitumen in bitumen emulsion, which may be gained by heating emulsion until evaporation the total water content, then calculation its percentage from total bitumen emulsion.

3) Optimum Pre-Wetting Water Content (OPWwc)

Emulsion asphalt's ability to coating the aggregate is ordinarily susceptible to Pre-Wetting Water Content of the aggregate; therefore, MS-14 suggested using different percentages of pre-mixing water to find the lowest pre-mixing water content that ensures the highest coating percentage. The coating degree must be greater than 50 % by visual observation. OPWwc is obtained accordingly, which is the lowest pre-wetting water content, which is show highest coating. There are several advantages of adding the pre-wetting water as decrease the viscosity consequently promotes workability and provides best distribution of bitumen emulsion on the aggregate surface (Thanaya, 2003b).

4) Determine Optimum Residual Asphalt Content (ORAC)

ORBC is determined by utilizing IRBC and OPWwc values with various of residual bitumen content at two points on each side of the IRBC in increase step of 0.5% (Asphalt Institute, 1989). ORBC is determined according to results of volumetric characteristic and Marshall Stability for the curing specimens with particular curing system.

5) Determine of Optimum Total Liquid Content at compaction (OTLC)

In CBEMs, the water content plays a significant role in the density of mix that is indicated to necessary OTLC to obtain the high properties for the mix. The TLC represent in the utilized mixture at compaction by OTL.

$$TLC = OPWwc + OBEC \qquad \text{Equation 2-3}$$

2.5.2 Design Method Depended by MPW-Indonesia(1990)

Basically, this method was included AASHTO and Marshall method that described in MS-14 with other adjustments to environmentally considerations (Thanaya, 2003b).

2.5.3 Design Method Depended by Nikolaides

Actually, this method was collected of the American Standard and the specifications of the Ministry of Public Work Republic of Indonesia (MPW- Indonesia, 1990), and introduced a method of distinction the permanent deformation performance (Thanaya, 2003b).

2.5.4 The Nynas Tests Procedure

This method was introduced by the Nynas Company. Three tests are suggested on the loose mixtures during storage or before laying of cold mixtures; these tests are runoff, washoff and workability tests. The runoff value refers to the quantity of asphalt emulsion mixture material runoff in a specific time from a specific mesh, whereas the washoff test is achieved immediately after the runoff test to check if the bitumen has washed off through the runoff test. Lastly, the workability test is achieved by utilizing the Nynas workability tester. The test is carried out by scraping the upper few mm of an uncompacted cold bituminous mixture through storage or just before laying, and the maximum force required to eliminate the top of the mixture by shear is measured (AL-HDABI, 2014).

2.6 Summary

Although, CBEM positively influences on the environment, cost and safety compared to HMA, but it is still need some improvements to overcome its shortcomings such as low early strength, and high air void. Previous studies suggested three methods for modification. The first way was to utilize additives or replacement conventional mineral aggregates by other material such as active materials, waste or by-product materials. While the second way was utilized the higher performance for asphalt emulsion by various additives such as a polymer. These two methods demonstrated essential improvements in mechanical and durability properties, but they still have not overcome the inherent problem in CBEM, which is the high air void content. Therefore, the third method was suggested to overcome this problem, which includes various techniques for increasing compaction. However, the range of air void still un-comparable to that recommended for HMA. Therefore, this study work will attempt to adopt the three methods collectively to evaluate the gain in performance of CBEM. In other words, using an active filler with polymer plus subjected the new low energy technique, all will be the main propose way to overcoming the inferiority of CBEMs, as will be seen in the next chapters.

Chapter Three

Experimental Investigation Program and Research Methodology

3.1 Introduction

This chapter includes a brief to the experimental work that achieved through this work. Experiments achieved of the raw materials and asphalt mixtures to evaluate their properties and correlate its properties to mechanical, volumetric, and durability properties of the asphalt mixtures. In addition, a detail description of the testing methods are presented in this part, with the research methodology that has been adopted for this study.

3.2 Asphalt Mixture Material

The materials used for this study include:

- Virgin Aggregates.
- Filler: Conventional Mineral Filler (CMF), and Ordinary Portland Cement (OPC).
- Asphalt binders: grade asphalt cement and bitumen emulsion.
- Polymer Modifier: Acrylic (AR) polymer with chemical composition (CH 2 CHCOOH).

To achieve the objectives of this study, five percentages of the AR polymer as a percentage of residual asphalt content used with each type as categorized below, the selection of such dosages is dependent of the ranges suggested by previous research works as reported by FHWA (Shafii et al., 2011):

- **Category 1:** 0%
- **Category 2**: 1.25%
- **Category 3:** 2.5%
- **Category 4:** 3.75%
- **Category 5:** 5%

3.2.1 Virgin Aggregates

Virgin aggregates (coarse and fine aggregate) were supplied from local Karbala quarries. They were sieved, isolated and graded as can be seen in Plate (3-1) to achieve the required gradation for surface course type IIIA according to General Specification for Roads and Bridges (GSRB), section R9 as illustrated in Table (3-1) (GSRB, 2003).

Coarse aggregate was consisted of limestone, crushed angular close to whiteness, while fine aggregate was consisted of crushed and normal sand; normal sand is less than 25% of the total fine aggregates according to GSRB. Table (3-2) demonstrates the physical properties of fine and coarse aggregates, which were gained from experiments carried out in the laboratory of Kerbala University.

The dense gradation, which is nominated by GSRB, section R9, for HMA (GSRB, 2003), was adopted for this study work, because no local standard gradation available to date, and dense gradation was adopted successfully by many agencies and researchers for CBEM (Asphalt Institute, 1989, Thanaya et al., 2009, Thanaya, 2007b, Oruc et al., 2007, Nikolaides, 1983, Al-Mishhadani and Al-Baid, 2014, Al-Mishhadani et al., 2013). Figure (3-1) shows the used gradation.

Plate 3-1 Sieving, Isolating and Grading of Virgin Materials

Table 3-1 Gradation of Virgin Aggregate for Surface Course Type IIIA (GSRB, 2003)

Sieve or Particle Size(mm)	% by Mass Passing Specification Range	% by Mass Passing Mid
¾ (19.0)	100	100
½ (12.5)	90-100	95
⅜ (9.5)	76-90	83
No. 4 (4.75)	44-74	59
No. 8 (2.36)	28-58	43
No. 50(300 µm)	5-21	13
No. 200 (75 µm)	4-10	7

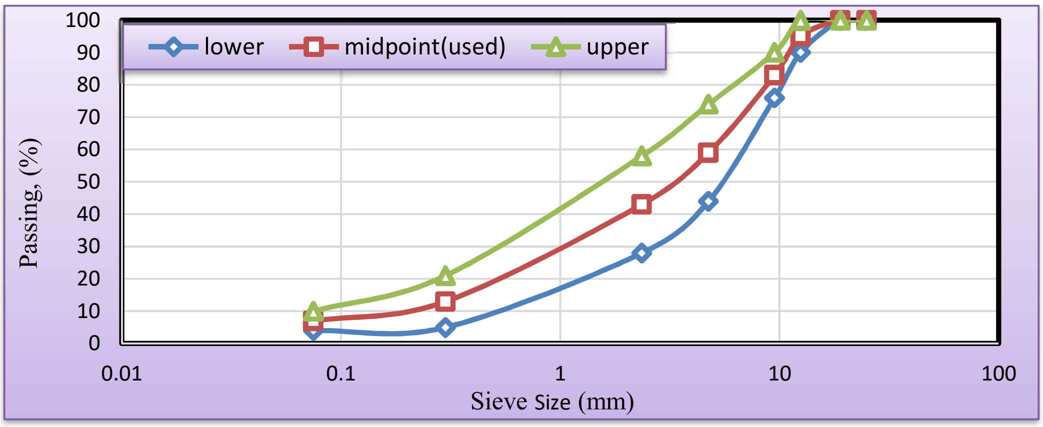


Figure 3-1 Distribute of Particle Size of the Used Gradation for Virgin Aggregate of Type IIIA Dense Graded Wearing Course

Table 3-2 Virgin Aggregates' Physical Properties.

Coarse Aggregate			
Property	**Value**	**Specification**	**CSRB,2003 Specification for Surface Course**
Bulk Density, gm /cm^3	2.543	C127 (ASTM, 2015d)	-
Apparent Density, gm /cm^3	2.634	C127	-
Water Absorption, %	1.36	C127	-
Percent Wear by Los Angeles Abrasion, %	9.1	C131(ASTM, 2014b)	30% Max
Soundness (Loss by Sodium Sulfate), %	4.1	C88 (ASTM, 2013d)	12% Max
Clay Lumps, %	0.05	C142(ASTM, 2010b)	-
Fine Aggregate			
Bulk Density, gm /cm^3	2.64	C128 (ASTM, 2015e)	-
Apparent Density, gm/cm^3	2.65	C128	-
Water Absorption, %	0.71	C128	-
Clay Lumps, %	1.9	C142	-
Passing Sieve No.200, %	3.52	C117(ASTM, 2013c)	-

3.2.2 Filler

Filler represents the very fine materials (< 0.075 mm) of mixture skeleton, which is added to provide certain physical and chemical properties that play a vital role in final mix properties. However, it acts either as inert or active material depending on its chemical composition, fineness, and surface characteristic (Dash, 2013). In this study, two type of fillers were utilized; namely, Ordinary Portland Cement (OPC) as active, and Conventional Mineral Filler (CMF) as inert fillers. The selection was based on economic and performance basics to optimize the behavior of polymer modifier CBEMs. CMF produced from crushing process of virgin aggregate in crushing plant, while OPC provided from Karbala Cement Plant. The two filler types were used for both mixture techniques; i.e. HMA and CBEMs. Table (3-3) demonstrated the physical and chemical properties of the mentioned fillers.

Scanning Electron Microscopy (SEM) test was achieved for two types of filler to recognize their morphology properties. Actually, SEM has been utilized highly to examine the microstructure of two type fillers. It is worth to mention that the results of SEM test in this study work were adopted from *(Ahmed, 2017)* because he adopted the same materials in his research. Plate (3-2) shows SEM analysis of CMF and OPC.

Table 3-3 Morphology Properties of the Utilized Fillers

Physical Properties of Fillers		
Properties	*Filler Type*	
	CMF	*OPC*
Specific Surface Area (m^2/kg)	225	410
Density (gm./cm^3)	2.610	2.987
Chemical Properties (XRF)		
SiO_2	81.15	24.91
Al_2O_3	3.78	2.324
Fe_2O_3	1.92	1.125
CaO	6.37	64.148
MgO	2.90	1.326
K_2O	0.73	0.760
Na_2O	0.19	1.714

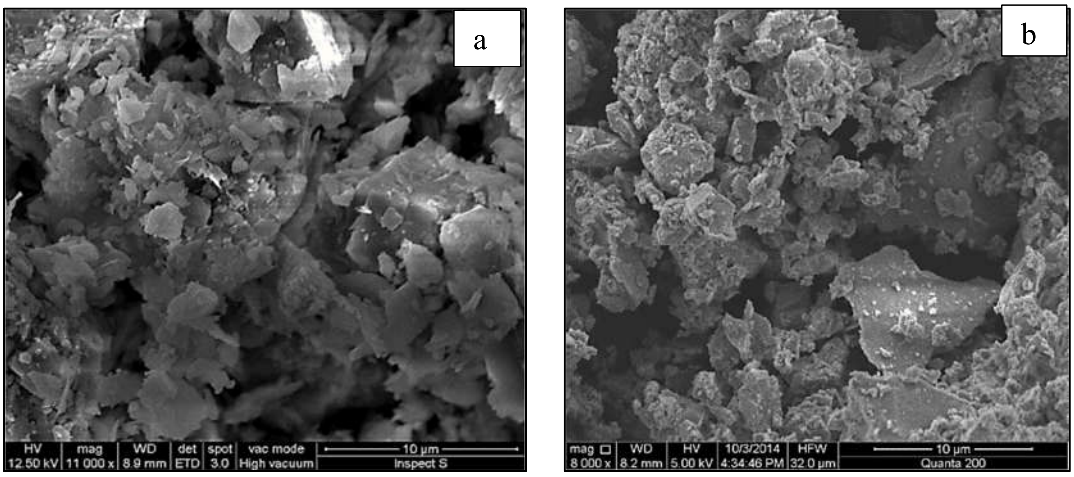


Plate 3-2 SEM of the Utilized Fillers: (a) CMF, (b) OPC(Ahmed, 2017).

3.2.3 Polymer

In this study, acrylic (AR) polymer is utilized as a modifier for asphalt emulsion, with different dosages as shown in Table (3-4). The material was supplied from the local market and it is manufactured by Conmix Company with characteristics shown in Table (3-5). This type of polymers was selected and for the first time to investigate it significant in improving CBEM, such polymer was used successfully to improve concrete mixture (Aggarwal et al., 2007, Wang and Shi, 2014). The hydration temperature and hydration degree of cement with AR polymer distribution are less than the control ones within 3 days (Wang and Shi, 2014). Also, addition of acrylic (AR) polymer to cement mortar enhances workability, increases compressive and flexural strengths, and reduces water absorption, carbonation and chloride ion penetration (Aggarwal et al., 2007).

It was blended with the asphalt emulsion by hand at the laboratory temperature for about (5) minutes to achieve the consistency of the polymer modified emulsion. Plate (3-3) demonstrate emulsified for acrylic polymer.

Table 3-4 Designation and Constituents of Binder

Binder Type	Constituents
Type 1	CMS* (control)
Type 2	CMS + 1.25% Acrylic
Type 3	CMS + 2.5% Acrylic
Type 4	CMS + 3.75% Acrylic
Type5	CMS + 5% Acrylic

*CMS=Cationic Medium- Setting emulsion

Table 3-5 Typical Property of AR Polymer at 25C°

Property	Test Method	Standard limits	Results of Test
Component	-	Single	Single
Form	-	Liquid	Liquid
Colour	-	Milky White	Milky White
Specific gravity	ASTM D1475	1.02 kg/Ltr +/-0.05	1.06 kg/Ltr.
Viscosity 25C°	-	100 ± 50 cps	125 cps
Percent of the solid	-	49.0 ±1.0%	49

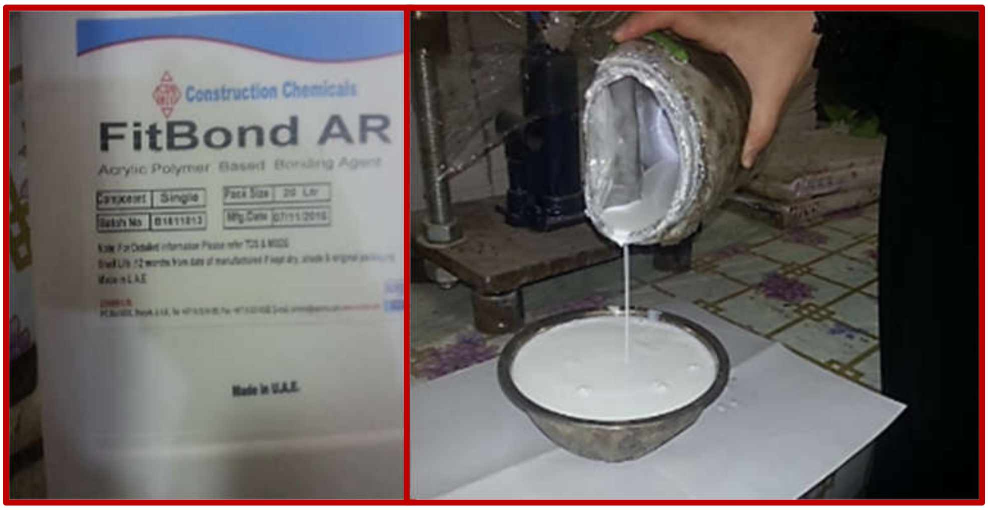


Plate 3-3 Acrylic Polymer

The advantages for this polymer comprised:

- Excellent the resistance for water action.
- Improved durability properties.
- Plasticizing effect and reduces shrinkage.
- Enhances protection from corrosion.
- Good the adhesion to mortar, concrete and plaster.
- Non-emission of toxic gases.
- As an additive enhance cohesion and workability.
- Enhances characteristics of flexural and tensile for permit to thin usage.

3.2.4 Asphalt Binders

Asphalt binders that utilized in this study included two types: the first type, grade asphalt cement with gradation 40-50, which was provided from Al-Nasseria factory for HMA with characteristics demonstrated in Table (3-6). Whereas the second, bitumen emulsion for CBEMs was manufactured by Henkel Company (under the trade name “POLYCOAT”) with characteristics are listed in Table (3-7). Results of the test of asphalt emulsion (CMS) demonstrated that this asphalt emulsion (CMS) was compatibility with the utilized aggregate because of different charges on their surfaces.

Table 3-6 Properties of Grade Asphalt Cement.

Property	**Test Values**	**ASTM Designation**	**SCRB,2003 Requirements**
Penetration,100 gm. ,25 °C,5sec (1/10 mm)	43	D5 (ASTM, 2015c)	40-50
Specific Gravity, 25 °C (gm./cm3)	1.02	D70 (ASTM, 2009a)	-
Ductility, 25 °C, 5 cm/min (cm)	130	D113 (ASTM, 2007)	>100
Flash Point, (°C)	318	D92 (ASTM, 2005)	>232
Softening Point (°C)	42	D36 (ASTM, 2000)	-
Solubility in Trichloroethylene, (%)	99.9	D2042 (ASTM, 2015f)	>99
After Thin Film Oven Test			
Penetration of Residue (%)	70.2	D 1754 (ASTM, 2014a)	>55
Ductility of Residue, (cm)	68.4		>25

Table 3-7 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)	> 57	58
Specific Gravity, gm./cm^3	D70(ASTM, 2009a)		1.02
Penetration, mm	D5(ASTM, 2015c)	100-250	230
Ductility, cm	D113(ASTM, 2007)	Min. 40	42
Viscosity, Rotational Paddle Viscometer 50 °C , mPa.s	D7226(ASTM, 2013b)	110-990	220
Freezing	D6929 (ASTM, 2010a)	Homogenous, broken	Homogenous
Solubility in Trichloroethylene, %	D2042(ASTM, 2015f)	Min. 97.5	97.7
Emulsified Asphalt/job Aggregate Coating Practice	D244 (ASTM, 2009b)	Good, fair, poor	Fair
Miscibility	D6999(ASTM, 2012)		Non-miscible
Evaluating Aggregate Coating	D6998(ASTM, 2011)		uniformly and thoroughly coated

3.3 Asphalt Mixtures Design

Three types of asphalt mixtures were prepared in this study work. The first was HMA, which used for comparison with other mixture types. The second type, which is known by CBEMs is used to measure the level of CBEM development. While, the third type was HWBEM. There are several considerations were adopted to prepare these three technologies.

- Compaction Methods

In this research work, two types of compaction method were adopted to achieve the laboratory tests, which are:

- Marshall compaction: This method was performed by applying 75 blows on each face of the specimen to simulate heavy traffic load. This method utilized in preparing specimens for Marshall test, indirect tensile strength, creep compliance (D) and durability test represented by water damage.
- Vibration compaction: This method was performed to prepare specimens of wheel track test (WTT) with dimension 300*165*50 to predict the rutting performance for asphalt mixture.

- Curing Systems for CBEMs and HWBEM

In this research work, two curing systems were utilized to accelerate strength rate of CBEMs and HWBEM for the laboratory tests, which comprised:

- Normal Curing system simulate strength after 7-14 days : This system was recommended by Jenkins (2000) in which specimens of CBEMs were placed in a mold for 24hr at laboratory temperature, then another 24hr in an oven at 40°C. This curing system was utilized to cure specimens of Marshall test, indirect tensile strength, creep compliance (D) and durability test represented by water damage.
- Curing system simulate full strength: This system was recommended by Thanaya (2003a) in which specimens of CBEMs were placed in mold for 24hr at laboratory temperature, then 14 days in oven at 40°C .This curing systems was utilized in cured specimens of wheel track test (WTT) to predict the rutting performance for CBEMs.

3.3.1 Hot Mix Asphalt (HMA)

Conventional Marshall design method was used for the preparation of HMA. The results for its mechanical, volumetric and durability properties with two type fillers; i.e., OPC and CMF will be shown in the next chapter, section 4.2.

3.3.2 Cold Bitumen Emulsion Mixture (CBEM)

In this research, CBEMs were prepared according to the design method which adopted by the Asphalt Institute, MS-14 as described in the following (Asphalt Institute, 1989):

- **Selection the Suitable Gradation of Mineral Aggregate**

In this research work, adopting the gradation for surface course type IIIA according to General Specification for Roads and Bridges (SCRB) (2003) section R9 as explicated in 3.2.1 .

- **Selection the initial Residual Asphalt Content (IRAC)**

MS-14 (Asphalt Institute, 1989) suggested two methods to find (IRAC); either the Centrifuge Kerosene Equivalent test or using empirical equation (3-1), which has been adopted here to determine the percent of asphalt emulsion for dense graded mixes, for simple as this value will corrected later as shown hereafter.

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

Where

P = a mount of asphalt emulsion based on weight of graded mineral aggregate, %.

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

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

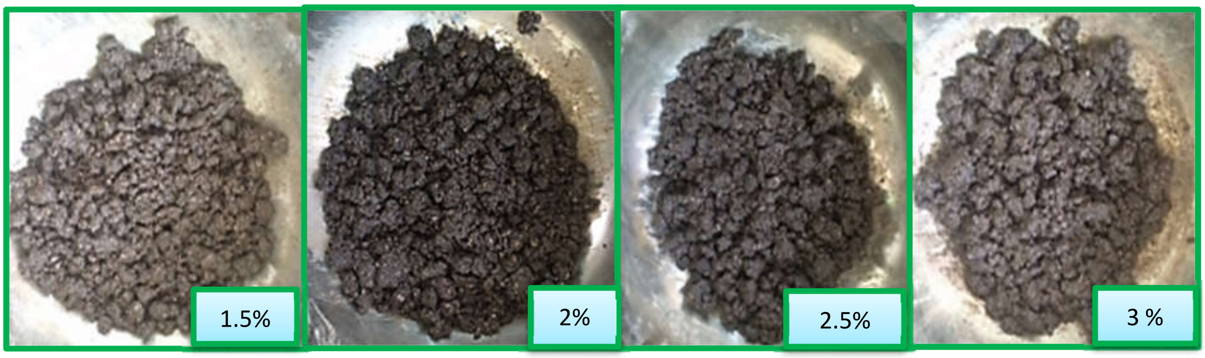
C = mineral aggregate mount passing (No.200).

With reference to the gradation that showed in Table (3-1) (A=57, B=36, and C=7), thus IRAC found to be equal to 6.965%. Also, the residual bitumen of asphalt emulsion was found to be 58 % ,which was selected according to ASTM D6934(ASTM, 2008). Therefore, Initial Emulsion Content (IEC) value can be obtained by dividing P by the percentage of the residual asphalt content in the bitumen emulsion.

$$\text{IEC} = \frac{P}{X} = \frac{6.965}{0.58} = 12.01 \approx 12\ \% \qquad \text{Equation 3-2}$$

- **Optimum Pre-Wetting Water Content** (OPWwc)

The OPWwc was determined for conventional CBEMs and modified CBEMs by OPC via visibility judgment as recommended by MS-14. The results are demonstrated in Plates (3-4a, b). However, OPWwc for CBEM-CMF was found to be 2.5%, while for CBEM-OPC was equal to 3.5%.



(a) Selected Pre-Wetting Water for CBEMs Comprising CMF

(b) Selected Pre-Wetting Water for CBEMs Comprising OPC

Plate 3-4 Different Water Content for CBEMs Comprising OPC or CMF

- **Optimum Asphalt Emulsion Content (OAEC)**

Marshall test was based to select the OAEC and with reference to filler type; i.e., CMF or OPC. Where, five different emulsion contents were nominated; two on each side of the calculated IRAC.

- **Determine Total Liquid Content (TLC)**

TLC is the summation of the (OPWwc) and (OAEC).

$$TLC = \mathrm{OPWwc} + \mathrm{OAEC}$$ Equation 3-3

Where

TLC: “Total Liquid Content”.

OPWwc: “Optimum Pre-wetting Water Content”.

OAEC: “Optimum Asphalt Emulsion Content”.

Through compaction, the OTLC is less than TLC. Either, because remain the mix for period or air van, which utilize to reduce TLC pre-compaction, in order to obtain the best performance represented by mechanical and volumetric properties for the mixture. Plate (3-5) demonstrates preparation process for CBEM.

Plate 3-5 Preparation of specimens of Marshall Stability

3.3.3 Half Warm Bitumen Emulsion Mixture (HWBEM)

In this research, HWBEM were prepared by applied heating energy to CBEMs pre-compacting process to decrease air voids content and increase the evaporation process of the trapped water. The domestic microwave mechanism was utilized, as can be seen in plate (3-6, b). After the mixing process of CBEMs which heated in the microwave, and then put the materials in mould and compact to show their mechanical properties represent by Marshall stability (MS), indirect tensile strength (ITS), creep compliance (D), wheel track test (WTT) and durability properties represent by water damage (WD). Plate (3-6, a) demonstrates process of the measurement of the external and internal temperature of asphalt mixture by two thermometers. The metal thermometers to measure the internal temperature of mixture and electronic thermometers to measure external temperature for the mixture. The curing system for this mixture is similar to CBEMs for each test, as can be seen in Plate (3-7).

(a) Measuring process for temperatures (b) Domestic microwave
Plate 3-6 Using the Microwave in This Work.

Plate 3-7 Curing Stages, (a) Specimens left in Mold for 24hr.@ 25℃, (b) Extracted from Mold (c) the Specimens in an oven for 24hr.@ 40℃.

3.4 The Laboratory Tests of Asphalt Mixtures

The properties of bituminous mixtures were determined by using various testing methods such as empirical tests included Marshall stability and the indirect tensile strength tests, fundamental tests included creep compliance, simulative tests included wheel track and durability tests included water damage, these tests were performed in the laboratory of Kerbala University. Routinely, researchers adopted tests that characterizing HMA for characterizing CBEMs. Nevertheless, some adjustments are required, mainly because of curing system of CBEMs. Table (3-8) shows a summary of the experimental tests, which used in this research to evaluate the performance of CBEMs.

Table 3-8 Test Methods Utilized for Analysis of Samples.

Property	Test Method	Standard	Function of Tests
Mechanical properties	• Marshall Stability and Flow	ASTM D6927 (ASTM, 2015a)	* select the optimum asphalt content for asphalt mixture. *assess water susceptibility (RMSR)
	• Indirect Tensile Strength	AASHTO D6931 (AASHTO, 2012)	*assess cracking potential of the asphalt mixture.
	• Creep Compliance	AASHTO T322 (AASHTO, 2003)	*indication of the crack progression for asphalt mixture and creep compliance values are the inverse of the stiffness properties.
	• Wheel Track	EN BS 12697-22 (BSI, 2003a)	* evaluate the rutting resistance of asphalt mixtures
Durability Tests	• Water Sensitivity (RMSR)	MS-14 (Asphalt Institute, 1989)	*resistance of mixture for water damage.
Volumetric Properties	• Bulk Density • Air Void • V.M.A, and V.F. B	MS-14 (Asphalt Institute, 1989)	*Bulk density *Air void *V.M. A, and V.F. B

3.4.1 Tests of Mechanical Properties

In this research, the mechanical properties of CBEMs were evaluated via several tests. Such test methods were adopted depends on the recommendations of the design method (such as Marshall method as recommended by (MS-14)). While others adopted as they offer clear details of the fundamental properties of the mixes performance under loadings (such as indirect tensile strength test, creep compliance test, and wheel track test).

3.4.1.1 Marshall Test

Unconfined compression test is used to measure the resistance to plastic flow due to load, which is applied in a perpendicular direction to the cylindrical axis of cylindrical specimens of asphalt paving mixture. There are two major indicators are provided by Marshall test these are stability-flow Marshall and density-voids. The Marshall stability (MS) represents the maximum capacity of the specimen to resist the applied load at a particular test temperature. Whereas, the Marshall flow (MF) represents the resistance of the specimen for deformation at maximum applied load (Dash, 2013). This test is based to select the optimum binder content for asphalt mixtures. In this test, several parameters such as maximum stability, unit weight, limited range of air voids, and flow were used to select the optimum binder content. The test was conducted in accordance to the ASTM D6927 (ASTM, 2015b), Plate (3-8) shows a system configuration of Marshall test, while Plate (3-9) shows computer screen of Marshall test with lab view program package. The major test conditions are tabulated in Table (3-9) and table (3-10) demonstrates the Iraqi specification requirements for asphalt mixture for the surface layer.

It is worth to mention that for CBEM, MS-14 recommends that Marshall stability should conducted at 25°C , while in this research work, 60 °C was selected to involve the environment condition of Iraq.

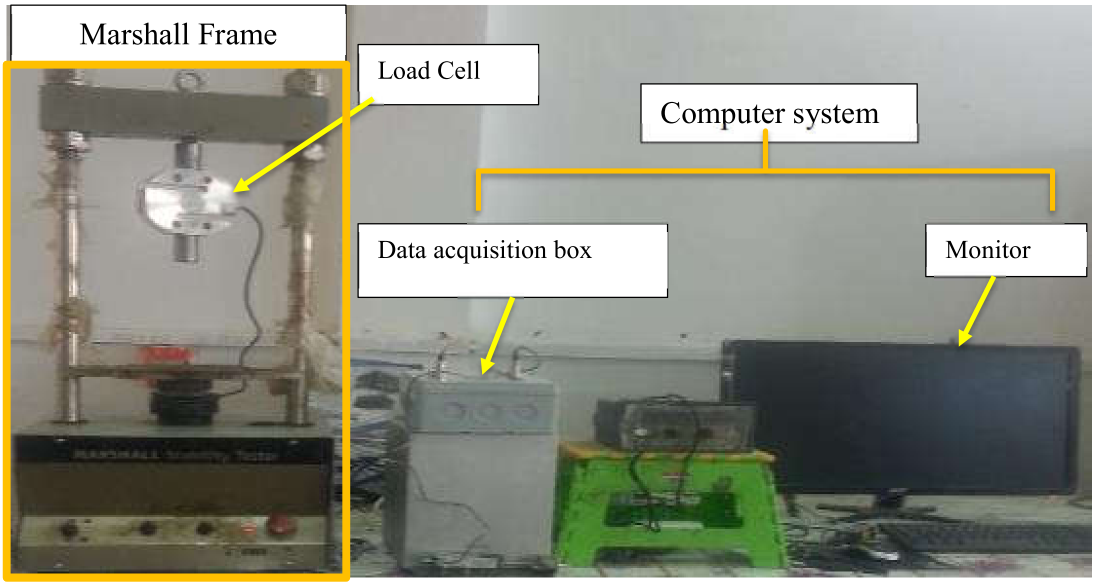


Plate 3-8 Configuration System for Marshall Test.

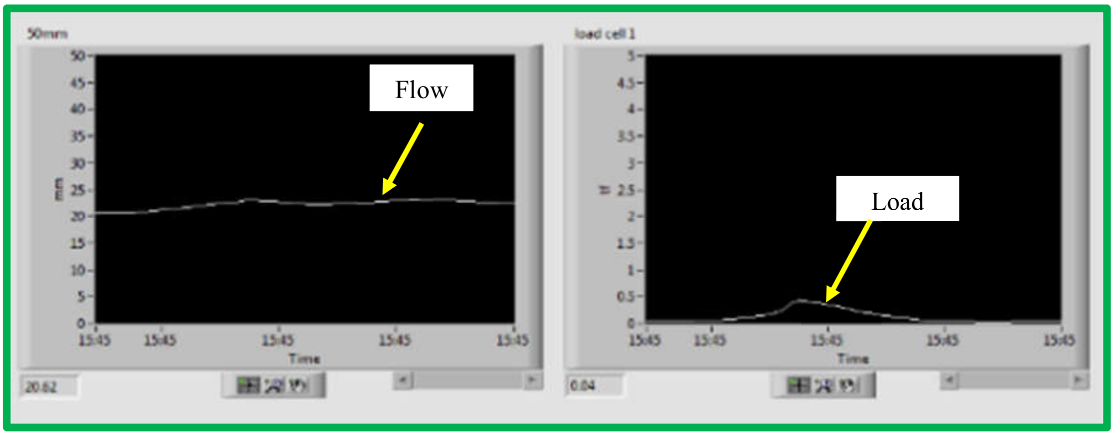


Plate 3-9 Computer Screen of Marshall Test with Lab View Program Package

Table 3-9 Marshall Test Condition for Asphalt Mixture According to ASTM D6927(ASTM, 2015b)

Parameter	Standard	Used Value for HMA	Used Value for CBEM	Used Value for HWBEM
Temperature of Asphalt (℃)	150−165	165	25	25
Temperature of Aggregate ºC	170	170	25	25
The Required Number of Specimens	3	3	3	3
The load Application Rate mm/min	50 ± 5	50	50	50
The Accuracy of Measuring Device	Min. 0.01 N	0.01 N	0.01 N	0.01 N
Temperature of Test ºC	60 ± 1	60	60	60
Diameters of Specimen mm	101.6-101.7	101.6	101.6	101.6
Thickness of Specimen mm	63.5 ± 2.5	63.5 ±2.5	63.5 ± 2.5	63.5 ± 2.5
Compaction, Marshall Hammer	75x 2	75x2	75x2	75x2
Specimen Conditioning Pre-Test in Water Bath (or an oven)	30-40 min. (120-130 min.)	30 min.	30 min.	30 min.
Curing		24hr.@25°C	24hr.@25°C in mold+24hr.@ 40°C	24hr. @25°C inmold+24hr .@ 40°C

Table 3-10 Indexes of Marshall Test of Surface Course according to GSRB

Index	SCRB limits (Surface Layer)
Stability Value kN	> 8
Flow Value, mm	2- 4
Air Void (%)	3- 5
Void in Mineral Aggregate (%)	>14

3.4.1.2 Indirect Tensile Strength Testing

The tensile characteristics of asphalt mixtures are acted by loading a cylindrical specimen through its vertical diametric level at a limited rate of deformation and test temperature. The maximum load at failure is registered and based to calculate the ITS of the specimen. This test provides two indications for bituminous mixture; the first indication is used for assess the cracking potential of a bituminous mixture. Tensile strain at failure is more beneficial for forecasting cracking potential. Mixtures that have to allow high strains before failure are more possible to resist cracking. While, the second indication is utilized to assess water susceptibility of bituminous mixtures. The test method was achieved according to ASTM D6931 (AASHTO, 2012) and the conditions of this test are listed in Table (3-11). Plate (3-10) demonstrates configuration of the testing ITS. Equation (3-4) is used for calculate ITS.

$$ITS = \frac{2P}{\pi.D.t} \qquad \text{Equation 3-4}$$

Where:

ITS = indirect tensile strength, kPa.

P = maximum load, N.

t = specimen height immediately before test, mm.

D = *specimen diameter*, mm.

Table 3-11 Test Conditions of ITS (AASHTO, 2012)

Parameter	**Standard**	**Used Value for HMA**	**Used Value for CBEM**	**Used Value for HWBEM**
Number of Required Specimens	3	3	3	3
Rate of the Applied Load mm/min	50 ± 5	50	50	50
Measuring Device accuracy	Min. 0.01 N	0.01 N	0.01 N	0.01 N
Temperature of the Test, °C	25 ± 2	23	23	23
Diameters of Specimen, mm	101.6, 150	101.6	101.6	101.6
Thickness of Specimen mm	50.8-65.5	63.5 ± 2.5	63.5 ± 2.5	63.5± 2.5
Compaction, Marshall Hammer	75x 2	75x2	75x2	75x2
Curing	unselected	24hr. @25°C	24hr.@25°C in mold+ 24hr.@ 40°C	24hr. @25°C in mold+ 24hr.@ 40°C
Specimen Conditioning before Test	2hr.@20°C	2hr.@20°C	2hr.@20°C	2hr.@20°C

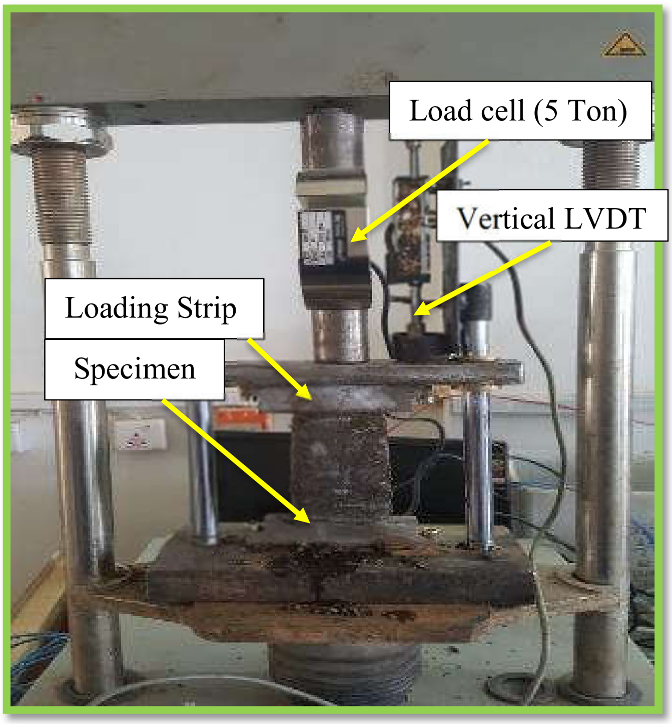


Plate 3-10 Configuration of ITS Testing Machine

3.4.1.3 Creep Compliance Test

Creep compliance is defined as the time-dependent strain per unit stress (AASHTO, 2003). This test is non-destructive, in which the applied load is controlled so that the upper linear-elastic boundary of the asphalt mixture is not exceeded. This test is an indication of the crack progression for asphalt mixture. Also, creep compliance values represent the inverse of the stiffness properties. The creep compliance values were calculated by Equations (3-5,6) according to AASHTO T322 (AASHTO, 2003), Table (3-12) lists the test conditions.

$$D(t) = \frac{\Delta X \times D_{avg} \times b_{avg}}{GL \times P_{avg}} \times C_{Cmpl} \qquad \textit{Equation 3-5}$$

Whereas:

ΔX = trimmed mean of the horizontal deformations, mm.

Davg = average specimen diameter, mm.

Bavg = average specimen thickness, mm.

Pavg = average force during the test.

GL = gage length, mm.

Ccmpl = creep compliance parameter at any given time, computed as:

$$C_{Cmpl} = 0.6345 \times \left(\frac{X}{Y}\right)^{-1} - 0.332 \qquad \text{Equation 3-6}$$

Whereas:

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

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

Table 3-12 Creep Compliance Test Condition of HMA According to AASHTO T322 (AASHTO, 2003)

Parameter	Standard	Used value for HMA	Used value for CBEM	Used value for HWBEM
Number of Required Specimens	3	3	3	3
The tolerance in load	± 2%	± 2%	± 2%	± 2%
Temperature of Test ºC	0, -10, -20°C	0°C	0°C	0°C
The test Time	100 ±2 Sec.	100 Sec.	100 Sec.	100 Sec.
The load Application Rate mm/min	12-75	12	12	12
Diameter of Specimen, mm	150 ± 9	101.6	101.6	101.6
Thickness of Specimen	38 to 50 mm	63.5 ± 2.5	63.5 ± 2.5	63.5 ± 2.5
Compaction, Marshall Hammer	unselected	75x2	75x2	75x2
Curing	unselected	24 @25°C	24@25°C in mold+ 24@ 40°C	24@25°C in mold+ 24@ 40°C
Horizontal Strain, mm	0.00125-0.019	0.00125-0.019	0.00125-0.019	0.00125-0.019
Conditioning of Specimen before Test	3±1hr., plate (3-11)	2 hr.	2 hr.	2 hr.

Plate 3-11 Condition of Marshall Specimens before Creep Compliance Test at 0°C Temperature in the Freezer.

There are many modifications that must be considered in this test such as:

- The specimen were prepared with a diameter of 101.6 mm instead of 150 mm that is recommended by AASHTO T322, because there is no suitable equipment to prepare the specimen with a diameter of 150 mm.
- Consequently, the specimen diameter was selected gauge length about 101.6 mm instead of 38 mm as can be seen in Plate (3-12).
- The applied load was provided by utilizing manual hydraulic jack and control on it by hand to generate load with tolerance ± 2%, as can be seen in Plate (3-12). This load must generate horizontal deformation between (0.00125 - 0.019 mm) to retain strain of specimens within linear viscoelastic limits as recommended by AASHTO T322.
- The test was very sensitive to noise that causes repeating of the test for various times to obtain the acceptable level of the applied load. Horizontal deformation indicates the acceptable level of the applied load, which was selected with three colors for this reason, as can be seen in plate (3-13). The black color is an indication of horizontal deformation less than the minimum limit of 0.00125 mm. Green color is an indication of horizontal deformation within acceptable limit 0.00125 to 0.019 mm. Whereas the red color is an indication of horizontal deformation higher than 0.019 mm. In case, the reading of horizontal deformation is unsatisfied to limits, the test should be repeated after exiting the specimen to rest for 5 min.

Lab view program was utilized for programming the computer system for this test, as can be seen in Plate (3-12). The program window demonstrates loading index in ton, the reading of vertical deformation, and the reading for two horizontal deformations at the top of the left side of the program window.

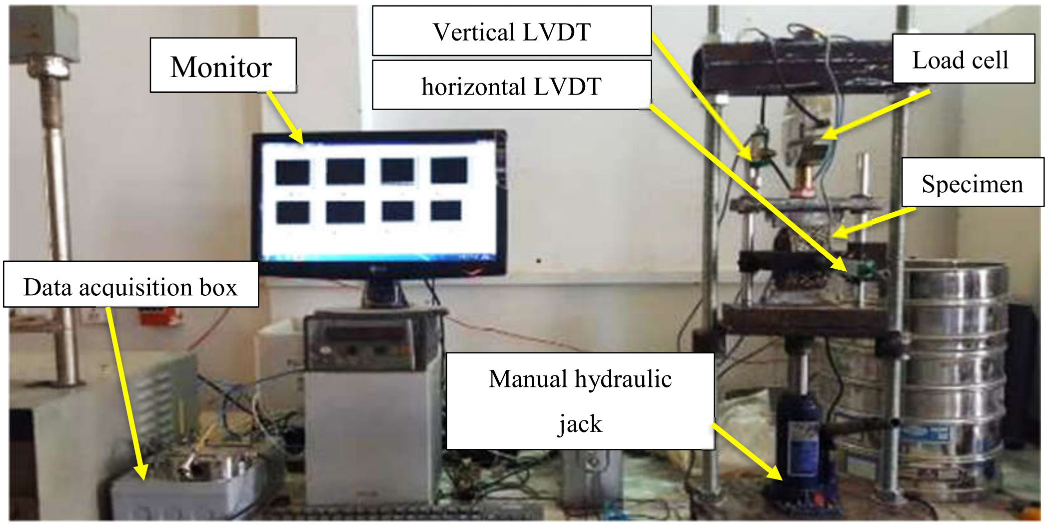
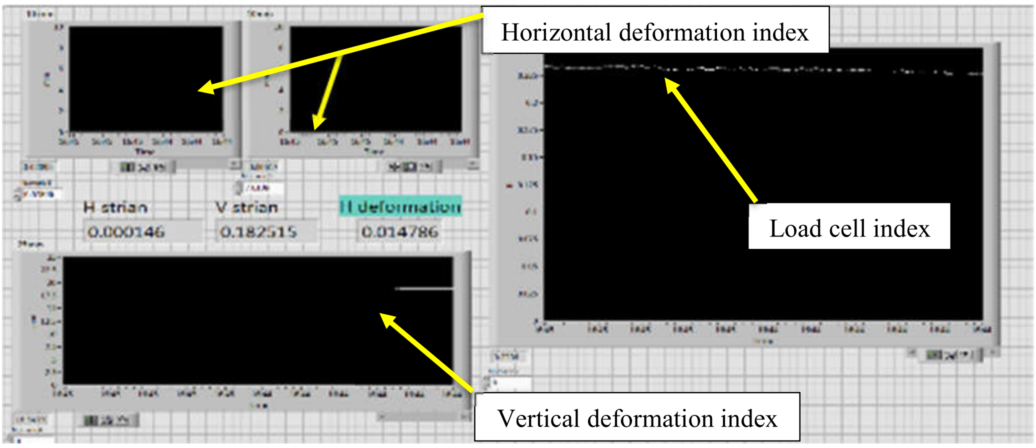


Plate 3-12 Apparatuses of Creep Compliance Testing



H strian 0.000146
V strian 0.182515
H deformation 0.014786

Plate 3-13 Computer Screen for Creep Compliance Test with Lab View Program Package

3.4.1.4 Wheel Track Test (WTT)

Permanent deformation (rutting) is one of the main damage distresses in flexible pavement, especially in high temperature during the summer seasons. It is the accumulation of permanent deformation in whole layers under the effect of traffic loading (Al-Khateeb et al., 2011). Rutting performance test is used to evaluate the rutting resistance of asphalt mixtures. In this study, slab samples were prepared with dimensions 300x165x50 mm according to BS EN 12697-22, (BSI, 2003a), which compacted in two layers by vibration compaction according to BS EN 12697-32 (BSI, 2003b) , as shown in plate (3-14). In this research work, air void was used equal to 7% as constructed pavement condition (Read and Whiteoak, 2015).

The test method for CBEMs is similar to HMA method with a difference in curing protocol. Normally, the rutting deformation happens during the lifecycle of pavement. Therefore, the full strength of CBEMs was adopted to simulate this condition. However, full strength for CBEMs represented by 1day @25ºC+14 day @40ºC which was suggested by Thanaya (2003b), was adopted here for both CBEM and HWBEM, as demonstrate in Plate (3-15).

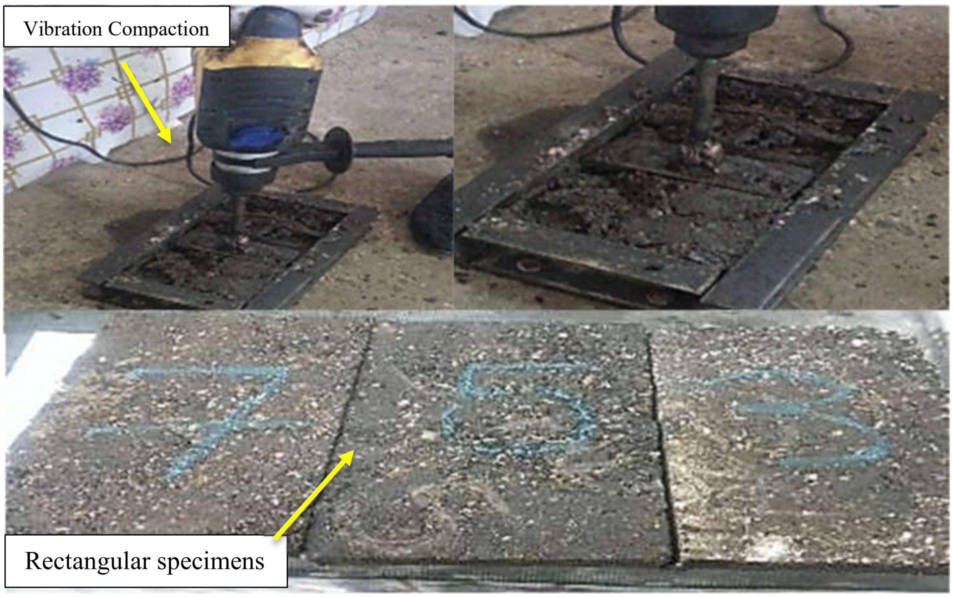


Plate 3-14 Preparation of Specimens of Wheel Track Test.

Plate 3-15 Curing of Specimens of Wheel Track Test.

In HMA, four trials were achieved to obtain the optimum compaction time that opposite to 7% air void. This percentage was obtained at 3 minutes, as shows in Figure (3-2).

In CBEMs, three trials were achieved to obtain the optimum compaction time that opposite to 7% air void. However, the result does not show any sensible change in air void, as can be seen in Figure (3-2). Therefore, the compaction time that opposite to 7% air void of HMA was adopted for CBEMs.

In HWBEMs, the specimen were prepared by heating CBEMs pre-compaction by microwave machine for 6 minutes. The results demonstrate that the optimum compaction time of HWBEM opposite to 7% air void was (4.35 minutes), as can be shown in Figure (3-2).

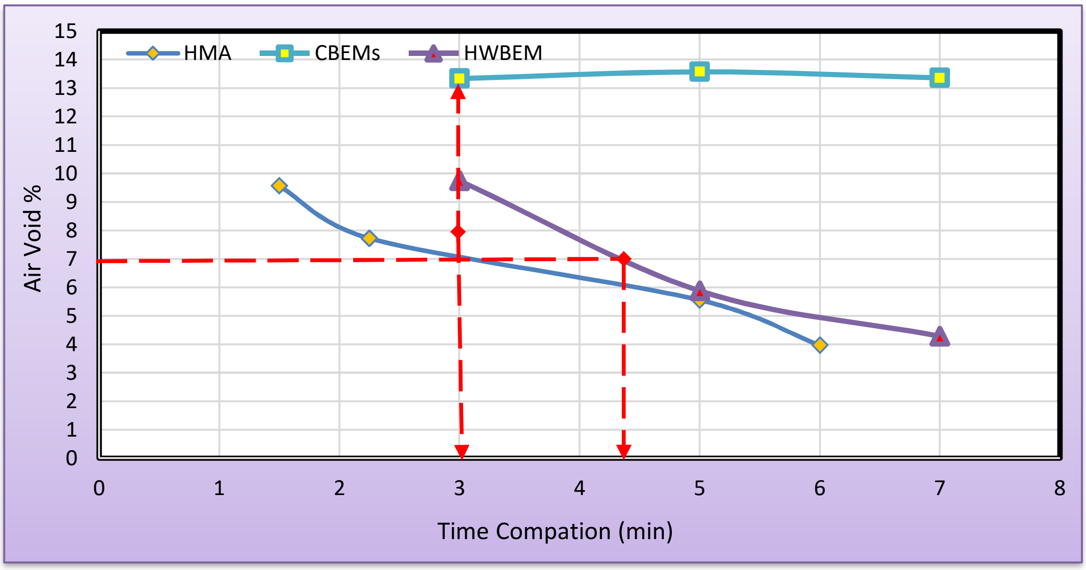


Figure 3-2 Optimum Time compaction of Wheel Track Specimens for HMA, CBEM and HWBEM

Also, wheel track test can be provided another indication for resistance the rutting deformation of asphalt mixtures, which is the dynamic stability (DS). Dynamic stability (DS) is represented by a number of wheel passes essentially to cause a deformation of 1 mm (Read and Whiteoak, 2015). DS values can be obtained by the following formula:

$$DS = \frac{N_{15}}{D_{60} - D_{45}} \qquad \text{Equation 3-7}$$

Whereas:

DS: Dynamic stability (passes/mm)
N_{15}: Number of wheel passes after the first 15 minutes of testing (mm).
D_{60}-D_{45}: The change in the rutting depth at the last 15 minutes of testing (passes).

In this research, WTT device was manufactured locally according to BS EN 12697-22 (BSI, 2003a) specification that recommended for small wheel track device. Conditions of this test are summarized in Table (3-13). Wheel track device and computer system as associated with wheel track device can be demonstrated in Plates (3-16, 17), respectively. Whereas, Plate (3-18) demonstrates the depth of the rutting of specimens after complete the test.

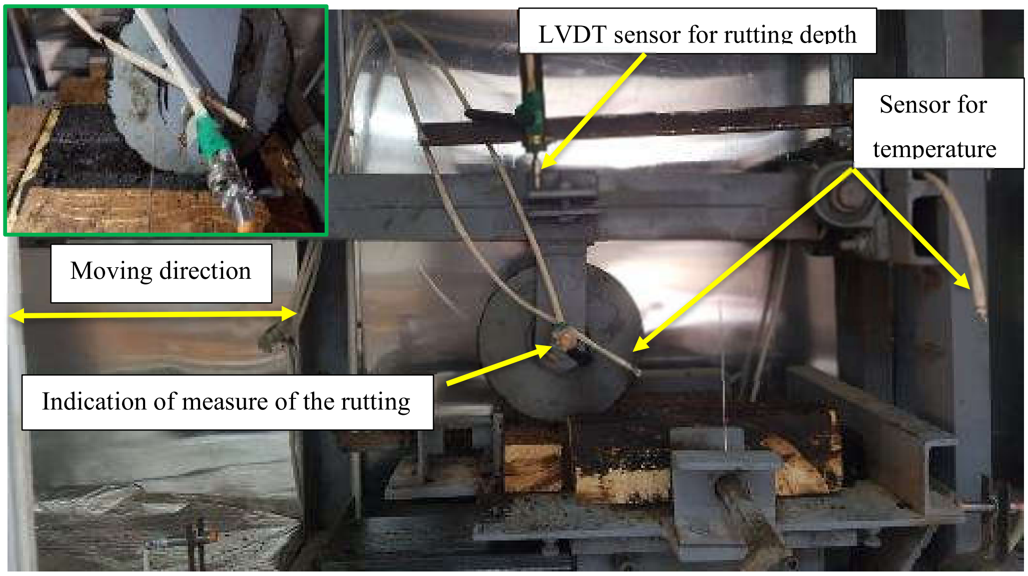


Plate 3-16 Apparatuses for Wheel Track Device

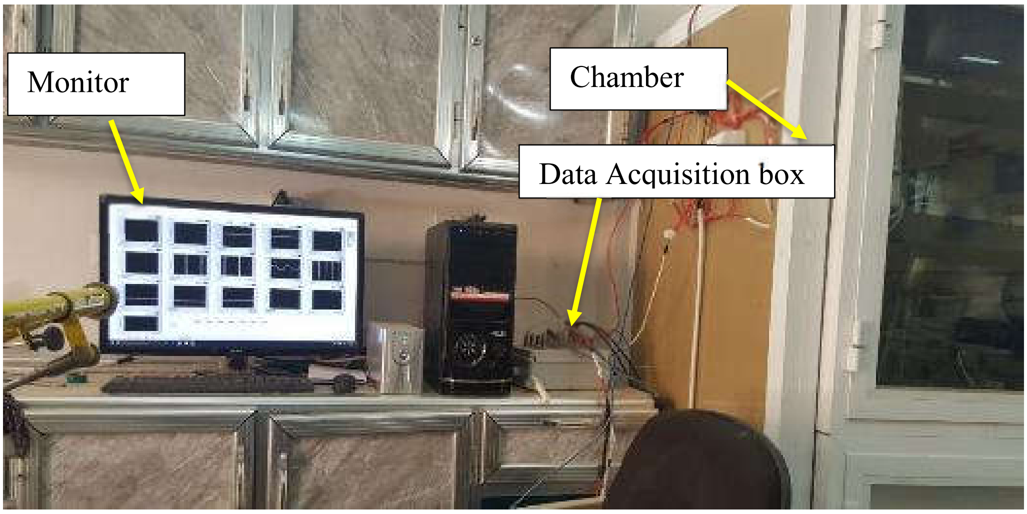


Plate 3-17 Computer System for Wheel Track Device

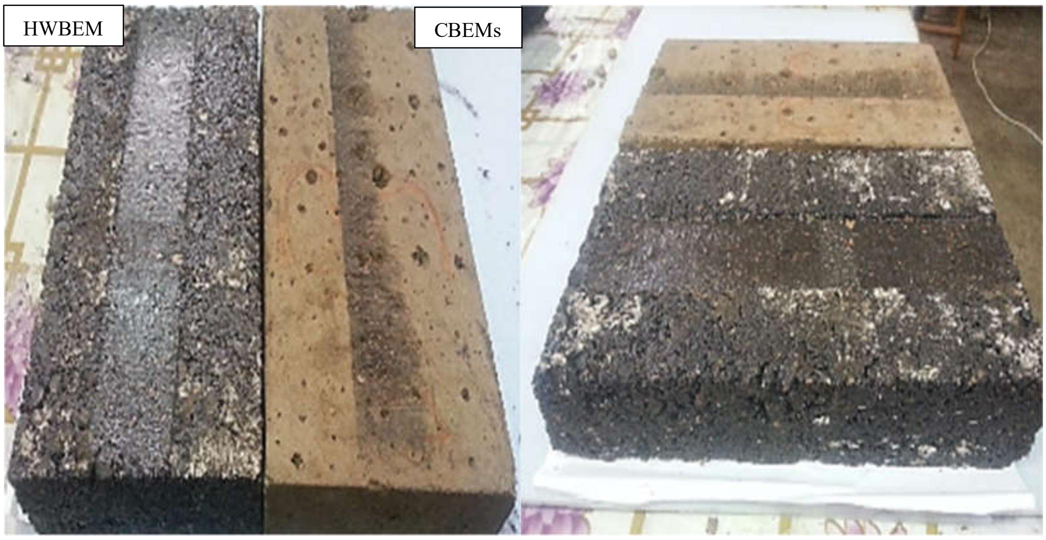


Plate 3-18 Depth the Rutting in Specimens the Wheel Track after the Test

Table 3-13 Test Conditions for Wheel Track Testing for Asphalt Mixtures (BSI, 2003a)

Parameter	Standard	Used Value for HMA	Used Value for CBEM	Used Value for HWBEM
No. of Required Specimens	2	1	1	1
Diameter of Rubber Wheel	200-205	200	200	200
Wide Rubber Wheel, mm	50 ∓5	50	50	50
No. Wheel Pass per min.	50 ∓5	50	50	50
Speed of Wheel, m/min	26.5	28	28	28
Load on the wheel	700 ±10 N	700	700	700
Specimen Thickness	38 -100 mm	50	50	50
Air Void Content Specimens	4 or 7 %	7 % as critical case	7 % as critical case	7 % as critical case
Test Temperature ºC	60 ± 2	60	60	60
No. of Conditioning Cycles pre-test	5	5	5	5
Specimens Type	Slab/beam or Cylinder	slab	slab	slab
Specimen Dimensions, mm	300 X 260	300x165	300x165	300x165
Compaction	Depended on the required air void 7% as critical case	3 min, Figure (3-2) *	3 min, Figure (3-3) *	4.15 min, Figure (3-4) *
Curing		24 @25°C	24@25°C in mold+ 14@ 40°C	24@25°C in mold+ 14@ 40°C

3.4.2 Durability Tests

Durability is defined as the resistance to weathering and the abrasive action of traffic (Epps et al., 2000). Weathering influence on asphalt mixture's properties can be found in terms of ageing and degradation or disintegration (Grenfell et al., 2009). Mostly, degradation of the aggregate results from the water influence to be then caused by traffic and freeze-thaw influences. Actually, water causes moisture damage resulting in a reduction in stiffness and stripping, whilst bitumen hardening affects the flexibility of the mixture and converts it to a brittle material.

In this study, water damage was investigated to identify the durability of the new CBEMs. While ageing was neglected as its effect is limited as reported by (Ahmed, 2017, Al-Busaltan, 2012). Moisture damage is known as the loss of the cohesion of binders and the adhesion between the aggregate and the bitumen (Terrel and Al-Swailmi, 1994). On the other side, cohesion loss take place as a result of binders deterioration. A number of test methods were utilized to assess the water action of asphalt mixture such as; retained Marshall Stability Ratio (RMSR), indirect tensile strength ratio (ITSR) and wheel track test.

In this study, retained Marshall stability ratio (RMSR) was carried out according to AASHTO (2008) for HMA to evaluate the resistance of the water damage as demonstrated in equation (3-8). SCRB (State Corporation for Roads and Bridges) is selected compressive testing for water damage characterization must be at least 70% (GSRB, 2003). Whereas, MS-14 (Asphalt Institute, 1989) selected the ratio of conditioned to unconditioned specimens to be not less than 50%.

$$\text{Retained Marshall Stability (RMS)} = \frac{\text{condition stability}}{\text{uncondition } stability} * 100 \qquad \textit{Equation 3-8}$$

Also, the same method was adopted to CBEMs and HWBEM according to MS-14 (Asphalt Institute, 1989), with one exception, which is difference in the curing protocol. Plate (3-19) demonstrates the curing specimens for 24 hours in a water bath at 60_o C.

Plate 3-19 Specimens of Water Damage in Water Bath

3.4.3 Volumetric Properties

volumetric properties are determined as demonstrate in plate (3-20) according to the MS-14, as follow (Asphalt Institute, 1989):

$$G = \frac{D}{F-E} \qquad \text{Equation 3-9}$$

$$G_d = G \times \frac{(100+A)}{(100+A+K)} \qquad \text{Equation 3-10}$$

$$K\,\% = \frac{mass\ of\ water, gm}{mass\ of\ dry\ mixture, gm} * (100 + A) \qquad \text{Equation 3-11}$$

$$V.M.A\,\% = \left[\left(\frac{100+A+K}{G} - \frac{100}{C}\right) \div \left(\frac{100+A+K}{G}\right)\right] \times 100 \qquad \text{Equation 3-12}$$

$$V.T.M\,\% = \left[\left(\frac{100+A+K}{G} - \frac{100}{C} - \frac{A}{B}\right) \div \left(\frac{100+A+K}{G}\right)\right] \times 100 \qquad \text{Equation 3-13}$$

$$Air\ Voids\,\% = V - \left[\left(\frac{K\times 100}{L}\right) \div \left(\frac{100+A+K}{G}\right)\right] \qquad \text{Equation 3-14}$$

$$V.F.B\,\% = \frac{V.M.A\,\% - V.T.M\,\%}{V.M.A\,\%} \qquad \text{Equation 3-15}$$

Where:

G = bulk specific gravity.

G_d = Dry 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.

Plate 3-20 Measurement of Volumetric Properties of Marshall Specimens.

3.5 Methodology

The methodology that is followed in this research to develop new CBEMs includes two stages as follows:

1. Using polymer modifier as additive for asphalt emulsion in CBEM with percentages 1.25,2.5,3.75 and 5 to improve the volumetric, mechanical and durability properties.
2. Using heating technique to improve volumetric properties without any effect on the other properties.

Abbreviations of the designation names of the various mixes of the two stages are explicated in Table (3-14). Figure (3-3) shows a schematic diagram of the proposed research methodology.

Table 3-14 Abbreviations of the designation Names for Used Asphalt Mixtures Used in the research

Mix No.	**Mixtures Types**	**Abbreviation**
1.	**Hot mix asphalt with Conventional Mineral Filler**	HMA- CMF
2.	**Hot Mix Asphalt with Ordinary Portland Cement**	HMA- OPC
3.	**Cold Bitumen Emulsion Mixtures with Conventional Mineral Filler**	CBEMs - CMF
4.	**Cold Bitumen Emulsion Mixtures with Ordinary Portland Cement and Acrylic Polymer**	CBEMs – OPC- AR
5.	**Cold Bitumen Emulsion Mixtures with Conventional Mineral Filler and Acrylic Polymer**	CBEMs -CMF - AR
6.	**Half Warm Bitumen Emulsion Mixture with Ordinary Portland Cement**	HWBEM- OPC
7.	**Half Warm Bitumen Emulsion Mixture with Conventional Mineral Filler**	HWBEM- CMF
8.	**Half Warm Bitumen Emulsion Mixture with Ordinary Portland Cement and Acrylic Polymer**	HWBEM-OPC-AR
9.	**Half Warm Bitumen Emulsion Mixture with Conventional Mineral Filler and Acrylic Polymer**	HWBEM- CMF -AR

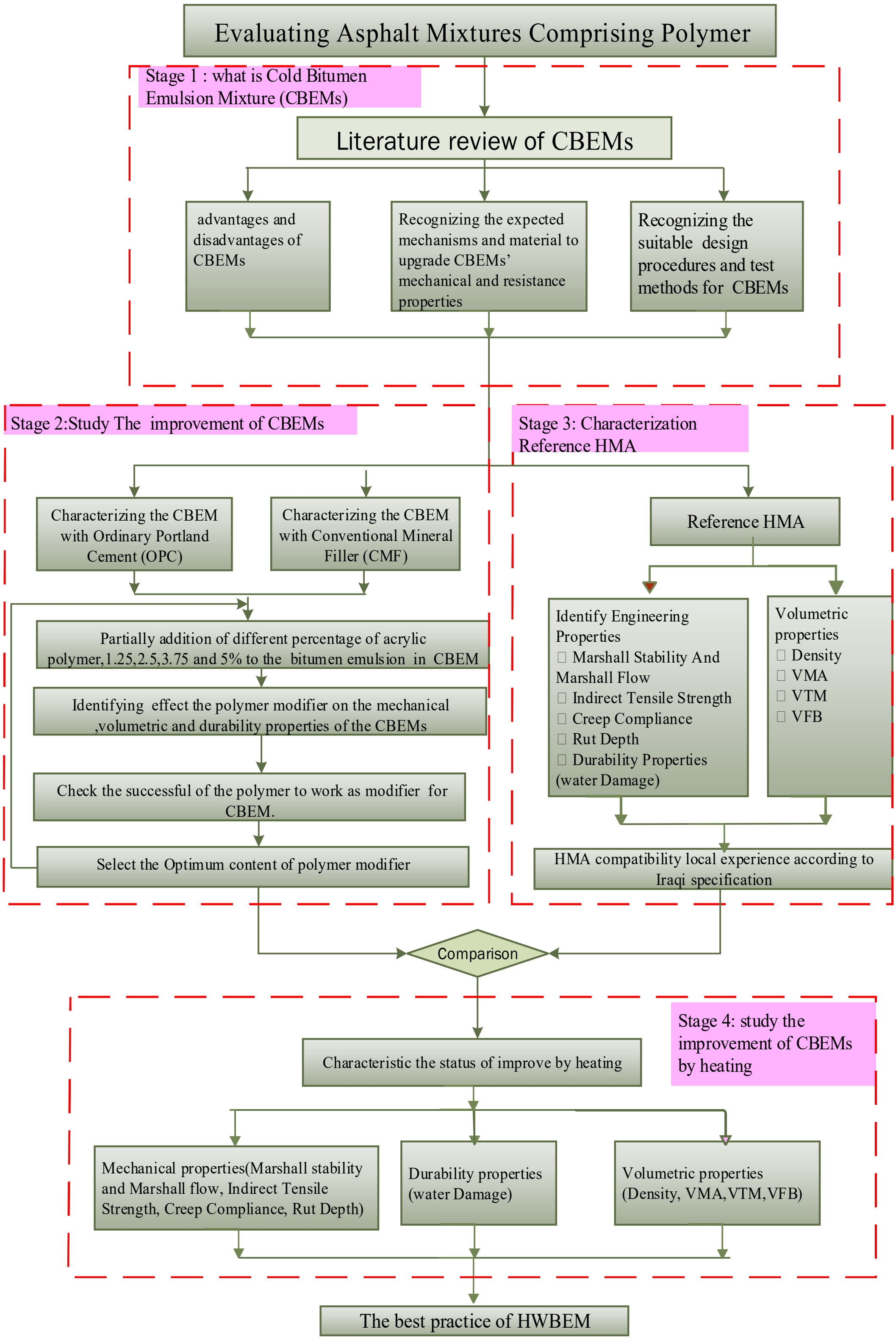


Figure 3-3 Research Methodology

3.6 Summary

This chapter included a brief description of the characterization of the used materials, test methods, and the research methodology. The materials were selected from local source. At the same time, tests such as mechanical properties include Marshall Stability, indirect tensile strength, creep compliance and wheel track test, and durability as a water damage test were adopted to evaluating the performance of CBEM. To date, CBEMs have no globally acceptable design method or tests techniques. Therefore, this research study was based on Asphalt Institute design method for CMA, and SCRB standards that specialized for HMA, to suit local applications. In addition, most of the tests, which are routinely applied to evaluate the HMA are used for CBEMs.

The methodology in this work research included two stages to modify CBEMs; the first stage was the addition of AR polymer in various dosages to CBEMs comprising CMF and OPC to improve their mechanical properties. While the second stage included utilizing heating technique to improve the volumetric properties.

Chapter Four

Results and Discussions of Polymer Modified CBEM

4.1 Introduction

This chapter presents the results and discussions of lab test findings. These tests are performed to evaluate the effect of polymer introducing on the performance of CBEMs. However, additional results of the performance of traditional HMA and CBEM are also presented for comparison purpose.

4.2 Hot Mix Asphalt (HMA) Characteristics

Out of sustainable and cost characteristics, to date HMA represents the best performance asphalt mixtures technology worldwide in terms of mechanistic, volumetric and durability performance. WMA and CMA technologies are recently gained more interesting for their environmental and cost characteristics effectiveness. However, for comparison purpose, HMA was prepared with two types of fillers, which were OPC and CMF. Generally, HMA characteristics and results are as follows:

4.2.1 HMA Preparation

HMA preparation included the following:

- The aggregate gradation was achieved to requirements of (GSRB, 2003), as mentioned previously in Figure (3-1).
- Various properties were adopted to select the optimum content of asphalt binder as density, air void, void in mineral aggregate (V.M.A), voids filled with binder (V.F.B), stability and flow, as can be shown in Figures (4-1, 2, 3, 4, 5, and 6), respectively. Asphalt content was utilized a range of (4.5 % - 6.5 %) with increment of 0.5%. The optimum asphalt content was found to be 5.5 % according to Marshall test method.

4.2.2 Volumetric Properties of HMA

The results shown that an increase in the asphalt content leads to an increase in the density of HMA comprising OPC or CMF until certain limit, as can be seen in Figure (4-1). This is because continuously increase in asphalt content causes an increase in weight with a constant volume of mixture to a certain limit, as asphalt facilitates the backing of mixture constitutes, and rest in void of the minerals. Then, any further increase in the asphalt content leads to a density decrease because over increasing of asphalt content increasing the volume of asphalt instead of aggregates; as a result of less specific gravity of asphalt when compared to aggregates. It is worth to mention that the densities of HMA comprising OPC are bit higher then these comprising CMF, which is a result of the higher specific gravity and fineness of OPC in contrast to CMF. Accordingly, air void contents of HMA comprising OPC or CMF reduce with increasing asphalt content, as can be seen in Figure (4-2), for the same reasons of the above.

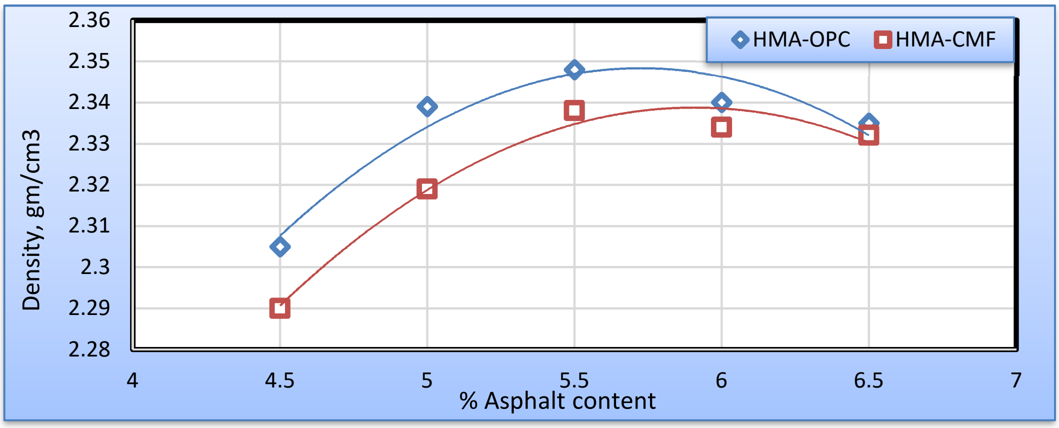


Figure 4-1 Density versus % Asphalt Content for HMA -OPC or CMF

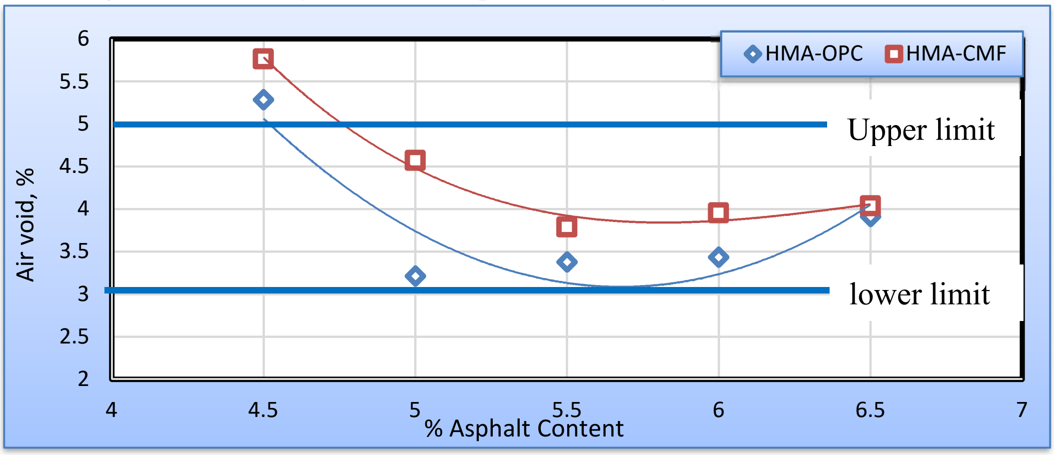


Figure 4-2 Air Void Content versus % Asphalt Content for HMA - OPC or CMF

VMA is the void spaces between the aggregate particles, which include both air voids and the effective binder film thickness. VMA varies slightly with increased asphalt content as demonstrated in Figure (4-3). It has to say that HMA with CMF showed higher VMA in contrast to HMA with OPC, which is mainly because of the particle size distribution of the two fillers. At the same time, VFB can be defined as void spaces that occupied with a binder in the compacted asphalt mixture. These VFB found to be increased relatively with an increase of asphalt content to a specific limit, to be then nearly constant, as can be seen in Figure (4-4). This is a result of filling the air void with extra asphalt content.

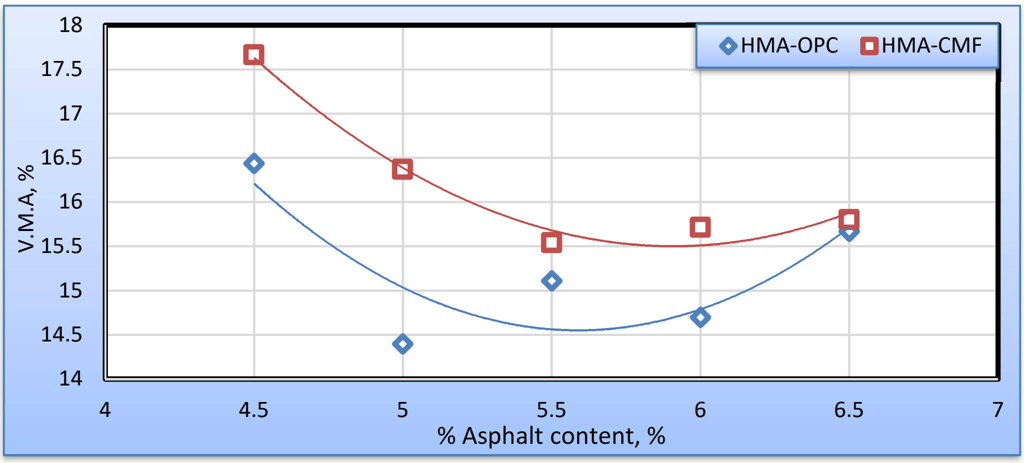


Figure 4-3 V.M.A % versus % Asphalt Content for HMA - OPC or CMF

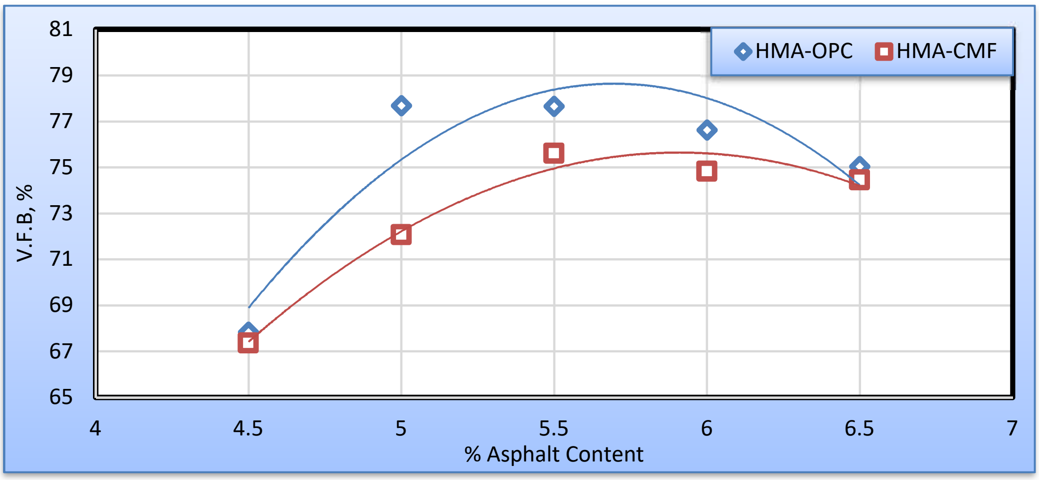


Figure 4-4 V.F.B% versus % Asphalt Content for HMA - OPC or CMF

4.2.3 Mechanical Properties of HMA

4.2.3.1 Marshall Test

This test reflects the strength of the bituminous mixture. This test provides two parameters, namely, stability (maximum shear strength) and flow (deformation) at peak strength. The results initially demonstrate that the stability increases with increasing asphalt content to a certain as can be shown in Figure (4-5). This could be a result of increase connecting between materials and exist limit internal friction between aggregates due to backing of materials. Furthermore, continues increase in asphalt content cause separation aggregates by asphalt film and caused weakness in interlocking connection and of course less friction between them. It worth to say that

OPC develops better stability than CMF, which could be a result of particle morphology as can be seen in Plate (3-2).

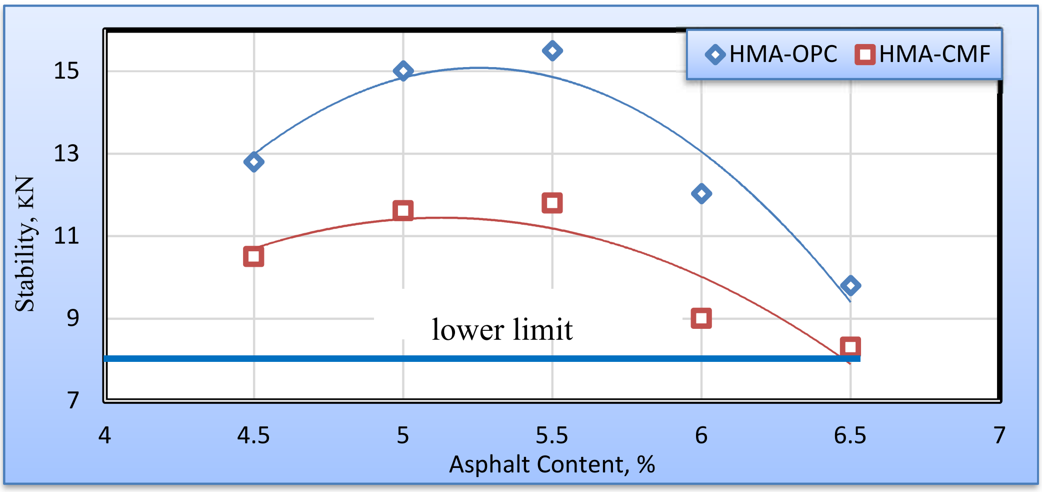


Figure 4-5 Stability versus Asphalt Content for HMA with Two Filler Types

Ordinarily, the flow increases with asphalt content increase; as a result of the asphalt nature to flow, further to loss of internal friction between the aggregate particles as can be shown in Figure (4-6). Generally, OPC showed a bit better flow characteristic in contrast to CMF, which could be a result of particle size destitution and surface area of the two fillers.

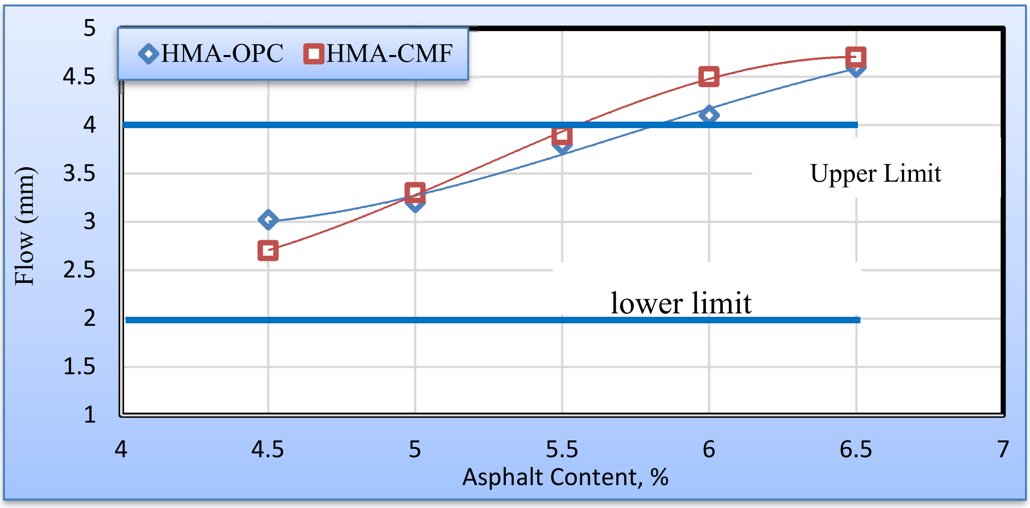


Figure 4-6 Flow versus Asphalt Content for HMA comprising OPC or CMF

4.2.3.2 Indirect Tensile Strength (ITS)

In this test, the specimens for HMA were prepared only with optimum asphalt content value. The results show in Figure (4-7), obviously proven that the values of ITS for HMA with OPC is about 18% higher than HMA with CMF, which might be related to the physical characteristics of OPC (particle size shape, surface area, and filler morphology). Such characteristics are facilitated better reinforcement to the asphalt mastic that gather bigger aggregate particles and reflects better tensile strength resistance.

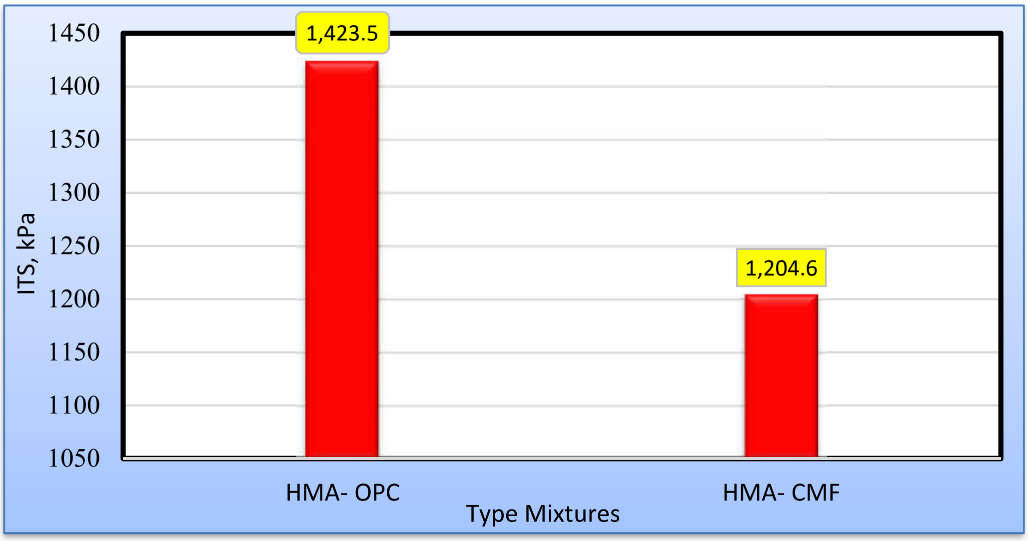


Figure 4-7 Indirect Tensile Strength (ITS) for HMA - OPC or CMF

4.2.3.3 Creep Compliance

Figure (4-8) demonstrates the creep compliance values for HMA comprising OPC and CMF. The results show that the creep compliance for HMA-OPC is less than HMA–CMF, might be for the same reasons mentioned for explaining the ITS. However, this result is an indication of increase the stiffness and primary the resistance of the mix to the progression of cracking. Also, Figure (4-8) demonstrates the creep stiffness values for HMA comprising OPC and CMF

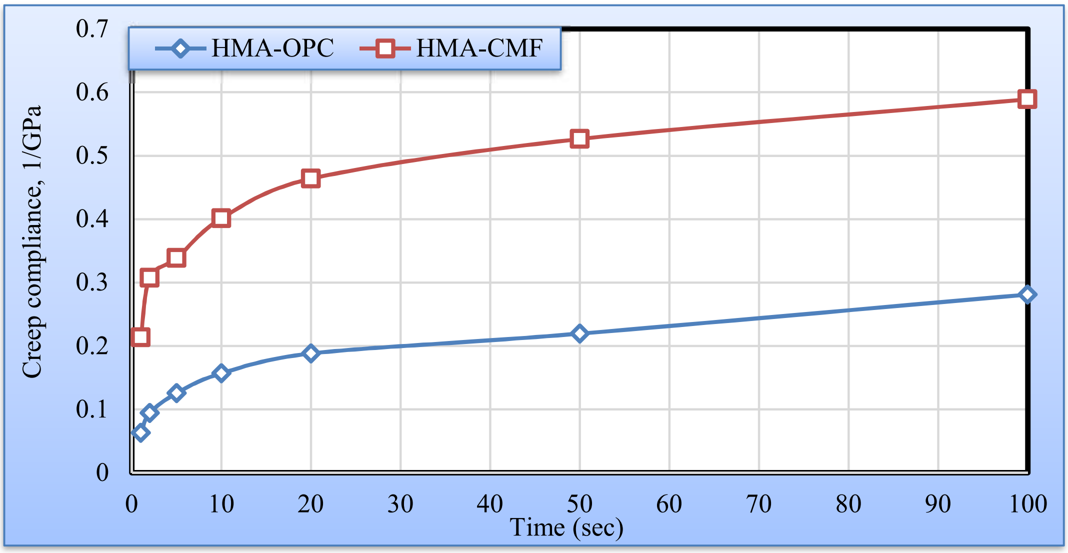


Figure 4-8 Creep Compliance versus Time for HMA comprising OPC or CMF

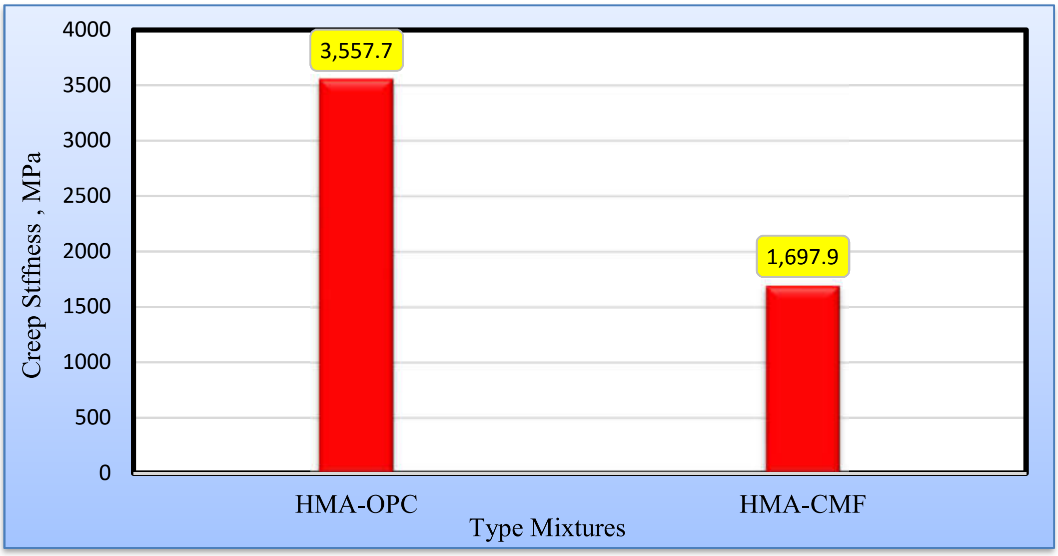


Figure 4-9 Creep Stiffness for HMA comprising OPC or CMF

4.2.3.4 Wheel Track Test (WTT)

Rutting is one of the main distresses that happening in HMA pavements; normally demonstrating itself as longitudinal depressions in the wheel tracks and it is mostly caused through shear deformation in the upper HMA layers under traffic loading. The rutting depth increases with the increase in the No. of cycles of wheel track load. Results showed that HMA - OPC is more resistance to rutting than HMA-CMF, as can be seen in Figure (4-10). Additionally, the same is true for dynamic stability value of HMA comprising OPC and CMF, as can be seen in Figure (4-11). However, both can be a result of the better mastic characteristics that facilitated by OPC as explained previously.

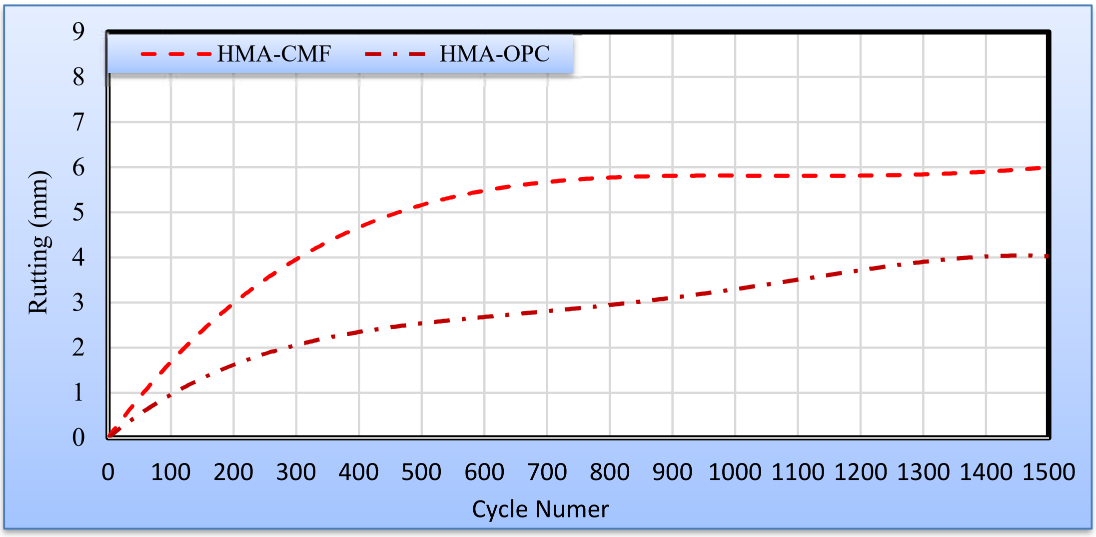


Figure 4-10 Rutting versus Number of Cycle for HMA comprising OPC or CMF

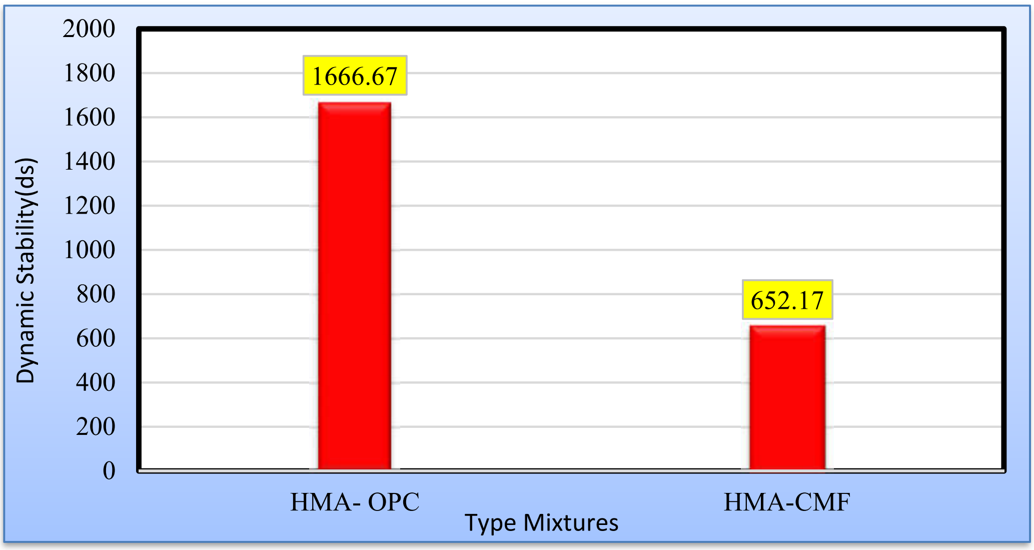


Figure 4-11 Dynamic Stability for HMA comprising OPC or CMF

4.2.4 Durability Tests

Marshall test used to determine the water damage (represented by RMSR) of the asphalt mixtures. Marshall specimens were prepared for both conditioned and unconditioned to obtain the retaining Marshall stability ratio (RMSR). The retaining Marshall stability ratio (RMSR) represent a good indicator of water damage, as explicate in Figure (4-12). The results appeared that the specimens including OPC were low sensitive to water damage than these with CMF, which is a result of interaction of the cement with exist water between aggregate and binder film causing increase relatively bonding, while CMF with exist water disintegration the mixture constituent without withstanding as occurred in OPC.

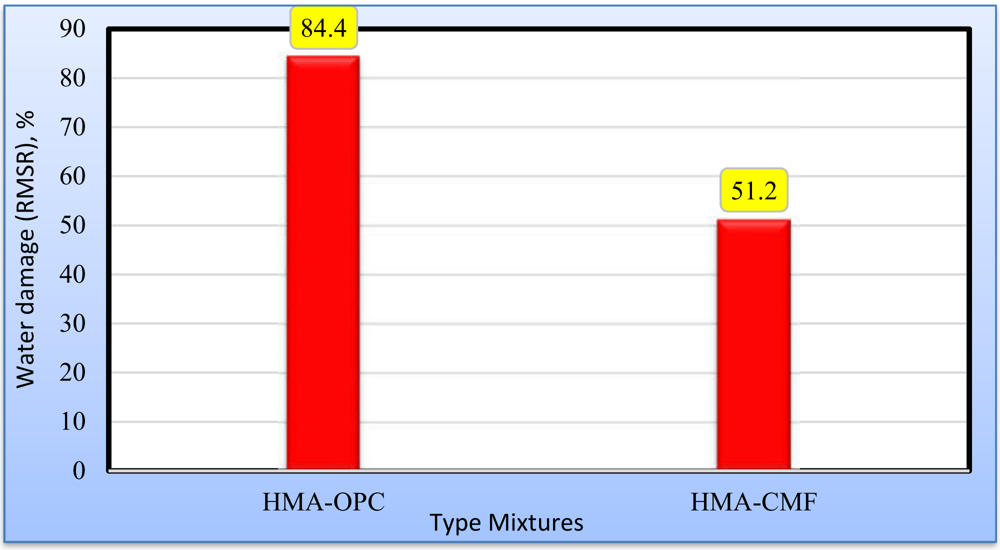


Figure 4-12 RMSR for HMA comprising OPC or CMF

4.3 Characteristics of Unmodified and Modified CBEMs by OPC

This section shows the volumetric, mechanical, and durability properties of conventional CBEM-CMF and CBEM- OPC. Mainly, OPC was used as a replacement to CMF; it is an attempt to enhance the performance of CBEMs. CMF and OPC properties described clearly in section 3.2.1., however Table (4-1) is demonstrated the results of the values of the OPWwc and OAEC for CBEMs with the two types of fillers. The results obviously showed that the pre-wetting water content required for CBEMs comprising OPC is higher in contrast to that for CBEMs comprising CMF. The same is true for optimum emulsion content as well. Accordingly, total liquid content at compaction for the modified CBEMs with OPC is higher, which might be a result of the hydraulic characteristics of the OPC itself. OPC needs water for the hydration process, especially in early time of the presence of water.

Table 4-1 Illustrated Values OPWwc and OAEC for CBEM-CMF and CBEM-OPC

Type of Mixture	W.C Used	AEC Used	OPWwc	OAEC	TLC
CBEMs- CMF	1.5-2-2.5 and 3%	11-11.5-12-12.5 and 13 %	2.5%	11.5%	14 %
CBEMs - OPC	3-3.5 and 4%	11-11.5-12-12.5 and 13 %	3.5%	12 %	15.5%

* OPWwc: “Optimum Pre-Wetting Water Content”

* OAEC: “Optimum Asphalt Emulsion Content”

* TLC: “Total Liquid Content”

4.3.1 Volumetric Properties

These properties can be gained from applying equations that recommended by MS-14 as stated in section 3.4.3. The results in Figure (4-13) demonstrate that the density of CBEMs-CMF is increased with increasing asphalt residue until certain limit, then decrease with continuance increase of asphalt residue. This is mainly because the water of asphalt emulsion in the beginning is facilitating the backing, but when its content increase lefts the mixture after curing with extra void, and this reduces the density. On the other side, the results show that the density of mixture with OPC decreases continuously with increasing asphalt residue, as CBEMs -OPC have higher water from both OPWwc and from the emulsion itself, whereas after curing left the mix with higher air voids, of course this is further to the reduction in workability due to OPC presence. Moreover, the above behavior is reflected on the air void characteristics for CBEMs with OPC or CMF, as can be shown in Figure (4-14).

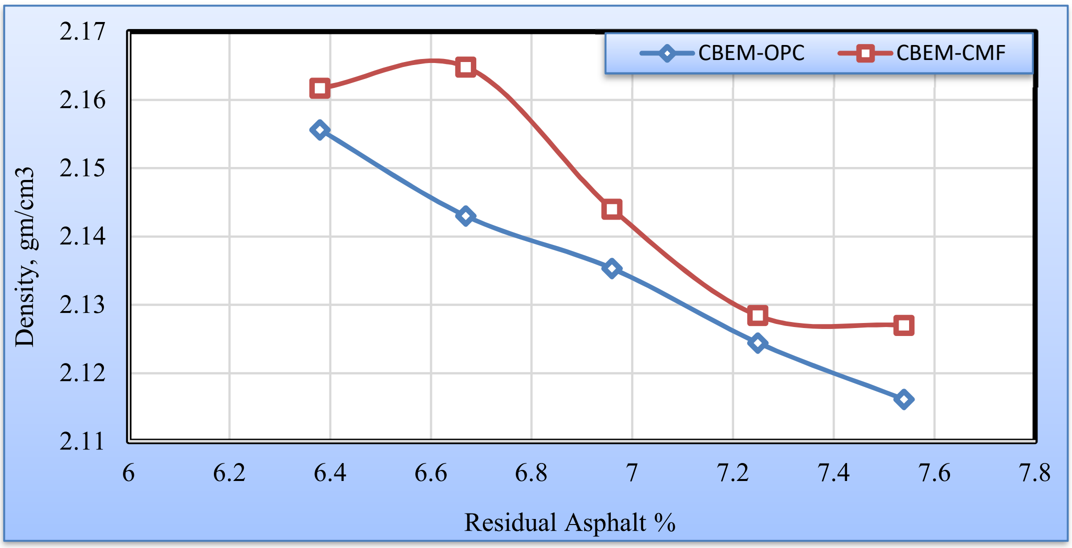


Figure 4-13 Density versus Residual Asphalt for CBEMs Comprising CMF or OPC

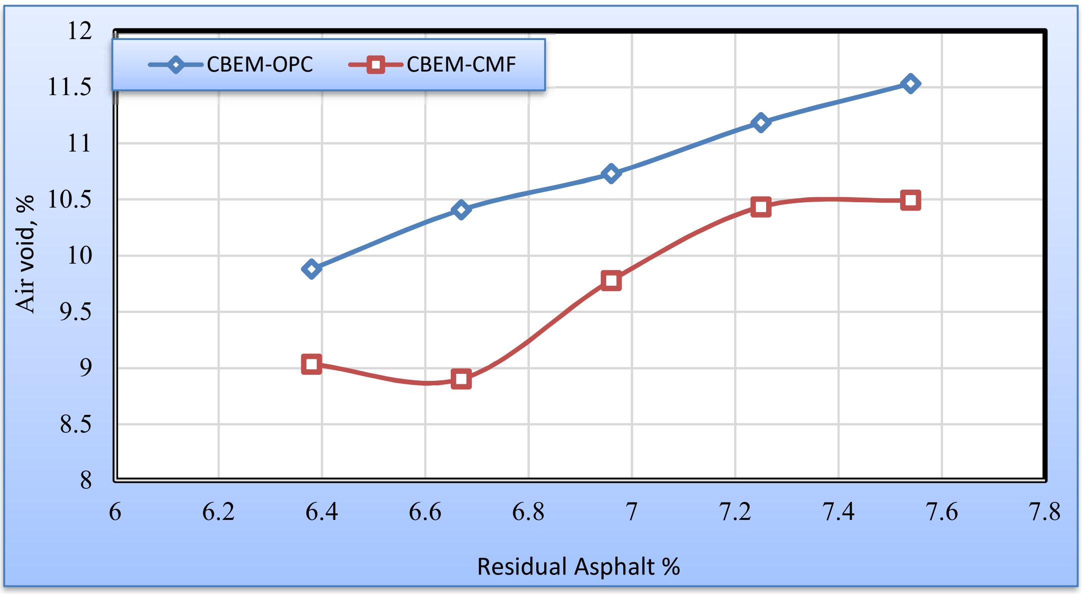


Figure 4-14 Air Void versus Residual Asphalt for CBEMs Comprising CMF or OPC

In the same trend as can be seen in Figure (4-15), the V.M.A of CBEM with OPC or CMF shows somehow a continuing increase, which might be due to the continuing increasing of water that left the mix after curing and of course the increase of the amount of volume of net binder. While for V.F.B character the effect of increase water in the mix control the continuing decrease in void filled with asphalt, as can be seen in Figure (4-16). Another prove for these explanation is the variation of the results of CBEM comprising OPC from those comprising CMF, where less water needed.

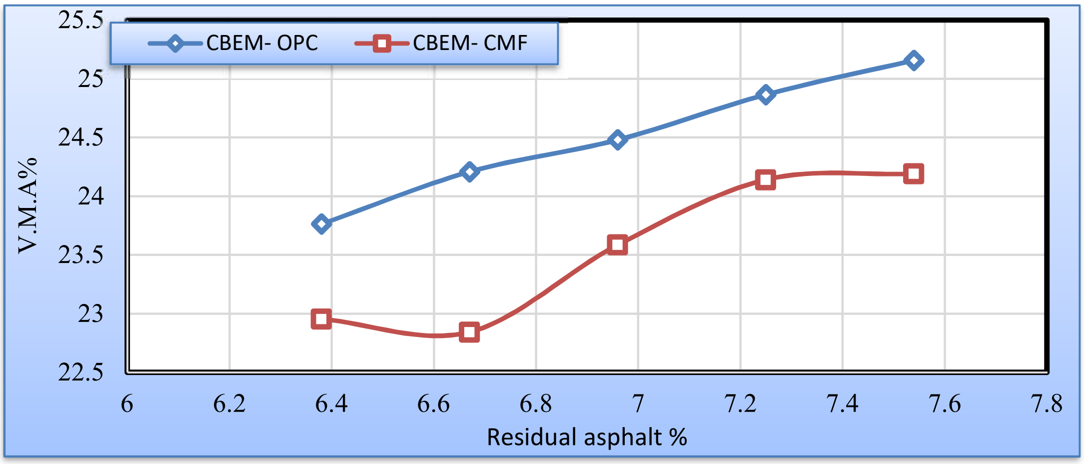


Figure 4-15 V.M.A versus Residual Asphalt for CBEMs Comprising CMF or OPC

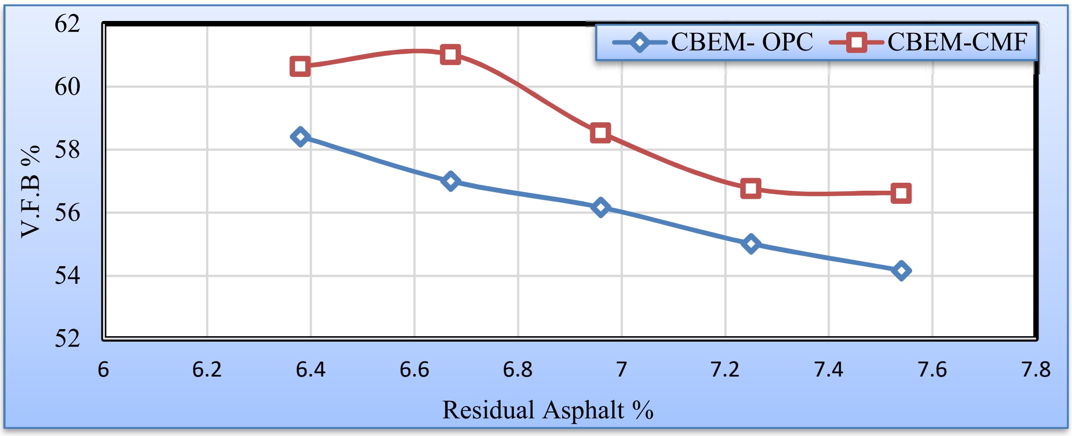


Figure 4-16 V.F.B versus Residual Asphalt for CBEMs Comprising CMF or OPC

4.3.1 Mechanical Properties

4.3.1.1 Marshall Test

The obtained result of Marshall stability (MS) values demonstrate that CBEM-CMF or CBEM-OPC is started low with low residue asphalt, as can be seen in Figure (4-17), then increase with high bitumen content to specific limits. Whereas introduce emulsion helps in increase the workability of the mix and facilitates the backing of materials and also initiation of binding, which both reflect better resistance to plastic deformation. After that, when binder increase the stability descends again, as a results of increase water that left the mix after curing and associate higher air void and lower aggregate interlock. It is worth to mention that OPC facilitate a significant improvement on Marshall stability, mainly because the initiation of the secondary binder that result from hydration process of the OPC, of course as a supplementary to the primary bitumen binder. However, the secondary binder needs water to continue the hydration process. Therefore, it is quite clear that there is a shift in the optimum residue asphalt than that for CBEM-CMF. In other words, extra emulsion provides extra water, which is facilitate in its turn extra hydration products.

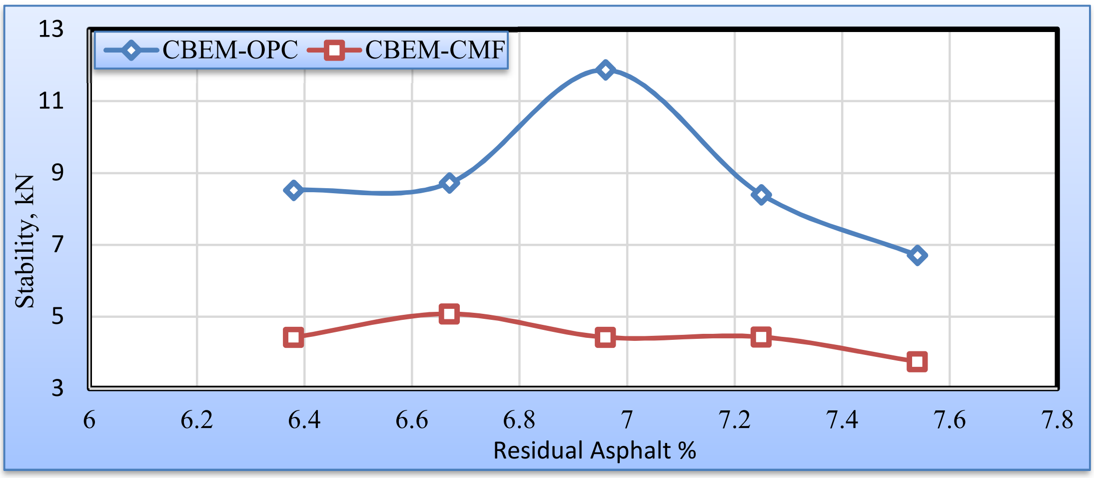


Figure 4-17 Stability versus Asphalt Content for CBEMs comprising CMF or OPC

Marshall flow results for CBEM-CMF and CBEM -OPC are demonstrated gradually increased with the increase in emulsion content, as can be seen in Figure (4-18). The results reflect the visco-plastic characteristics of the increment in bitumen binder. Nevertheless, OPC offers a significant reduction in the flow in contrast to CMF. This is might be a result of what called secondary binder effect, which has brittle characteristics, as explained in the last paragraph.

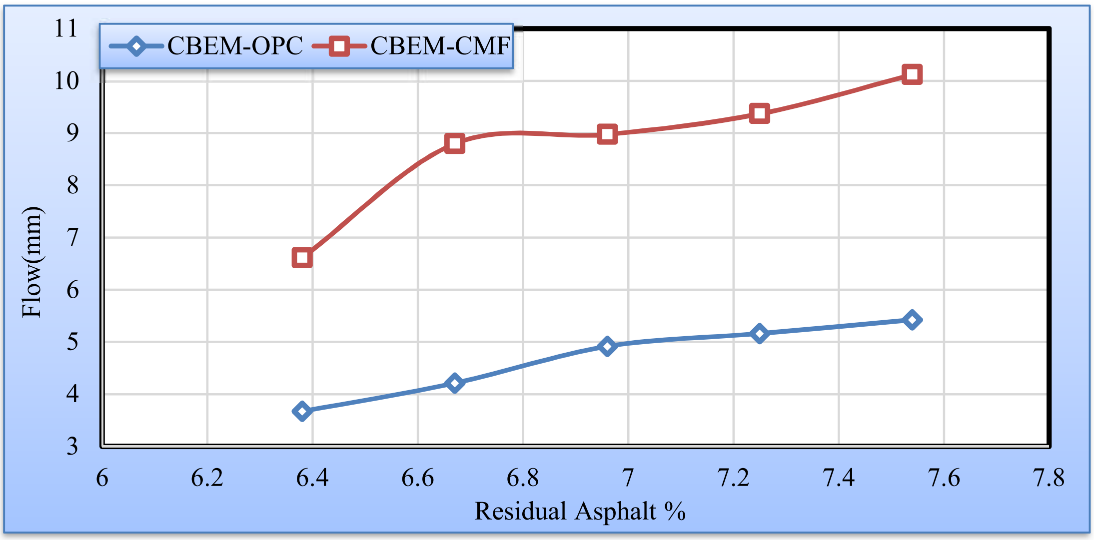


Figure 4-18 Flow versus Asphalt Content for CBEMs comprising CMF or OPC

4.3.1.2 Indirect Tensile Strength Test

For the shortage of time and resources, specimens were prepared only for optimum asphalt emulsion content for ITS characterizing. ITS for CBEM-OPC is high than ITS for CBEM-CMF, as can be seen in Figure (4-19), which is mainly because inclusion the OPC provides high secondary bonding for the mastic between coarse aggregate particles, further to the primary binding as explained previously. Nevertheless, this development is still un comparable to that gained by conventional HMA.

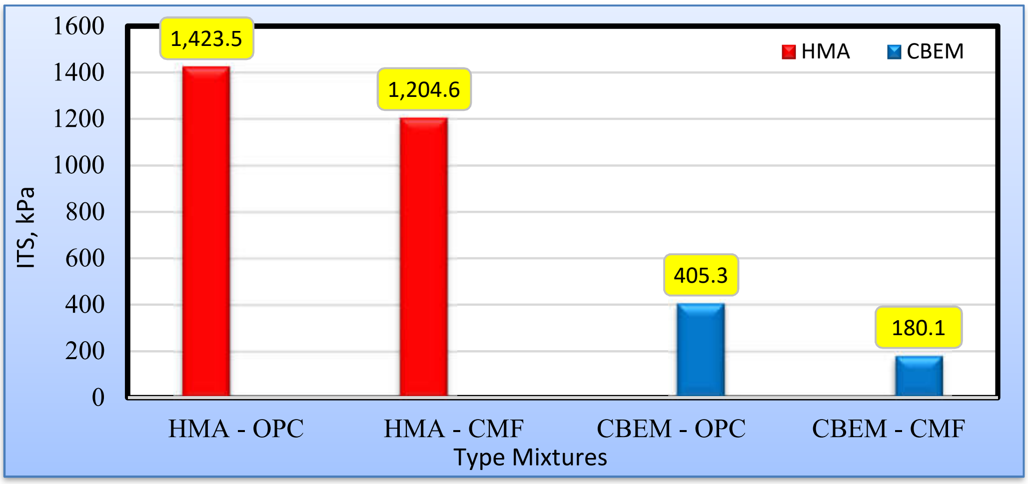


Figure 4-19 ITS for CBEMs comprising CMF or OPC

4.3.1.3 Creep Compliance Test

The creep compliance test for CBEM-CMF and CBEM-OPC was achieved for OAEC. The results showed that creep compliance for CBEM **-** OPC is less than that for CBEMs – CMF, as can be seen in Figure (4-20). The addition of OPC leads to increase the stiffness and tensile strength of CBEM as a result of the evaporation of the water from the mix and creation the cementitious bonds beside bitumen bonds. Also, Figure (4-21) demonstrate results of the creep stiffness CBEM**-**CMF and CBEM**-**OPC.

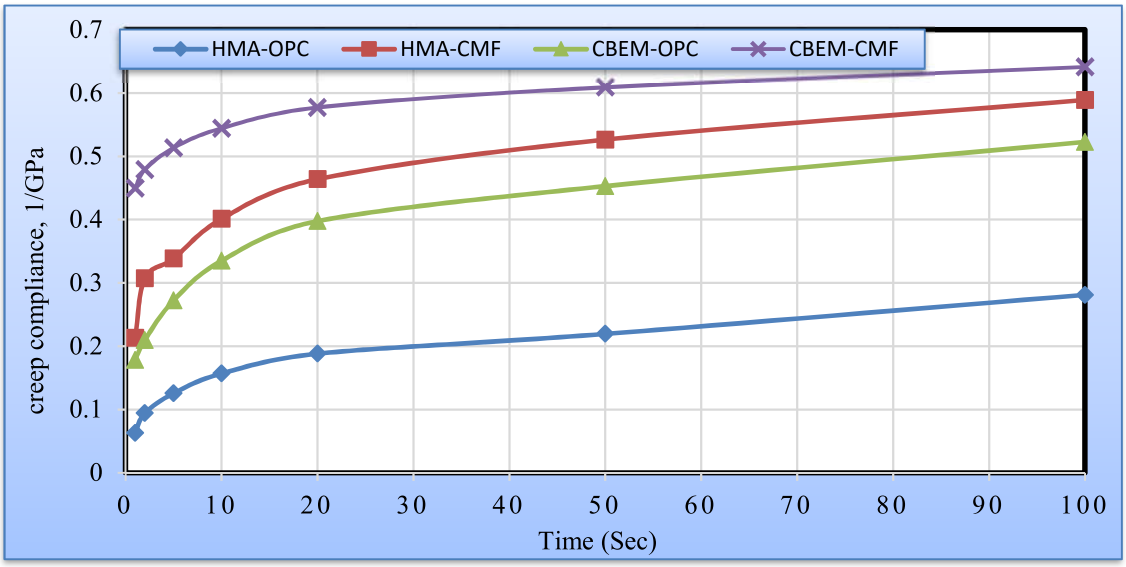


Figure 4-20 Creep Compliance versus Time for CBEMs comprising CMF or OPC

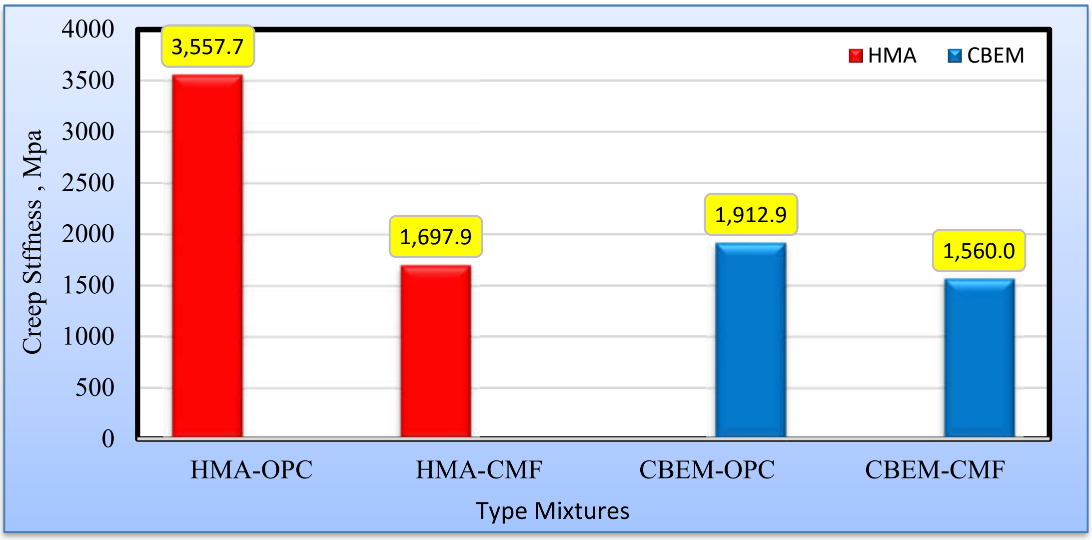


Figure 4-21 Creep Stiffness for CBEMs comprising CMF or OPC

4.3.1.4 Wheel Track Test

The wheel track test (WTT) was utilized to evaluate the permanent deformation characteristics of the CBEMs. The results demonstrate that the CBEM-OPC has less rutting comparison with HMA -CMF and HMA- OPC, as can be seen in Figure (4-22). The addition of OPC to CBEM leads to reinforce the viscous component in the mix by the hydration products. Dynamic stability for CBEMs comprising OPC have large values by about 31% and 50% in contrast to conventional HMA and CBEMs-CMF, respectively, as demonstrated in Figure (4-23). At the same time, CBEMs-CMF showed the most inferior permanent deformation resistance in contrast to other mixes, which reflects the inherent weakness of mix itself as explained previously.

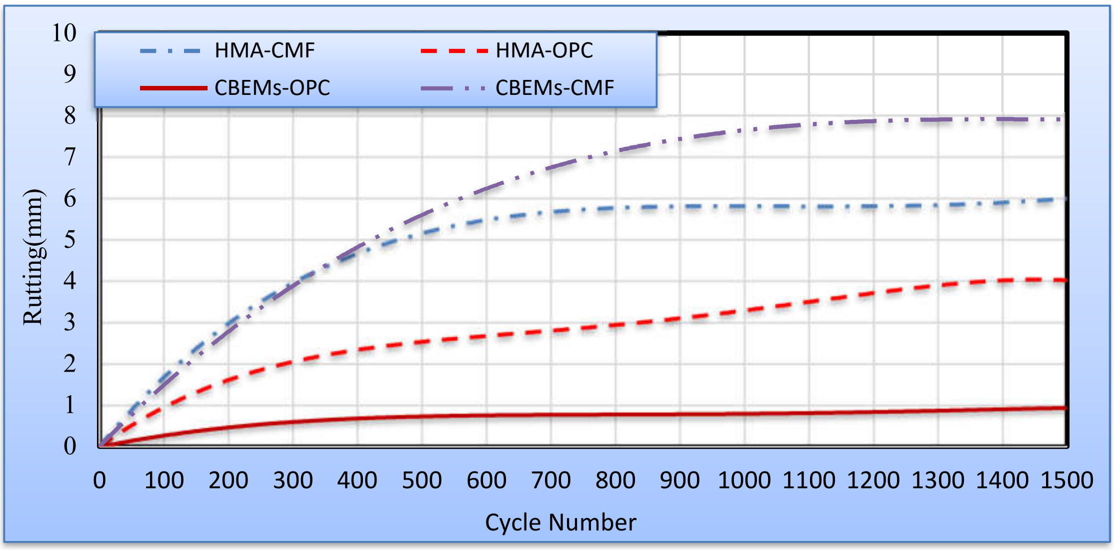


Figure 4-22 Rutting versus Cycle Number for CBEMs comprising CMF or OPC

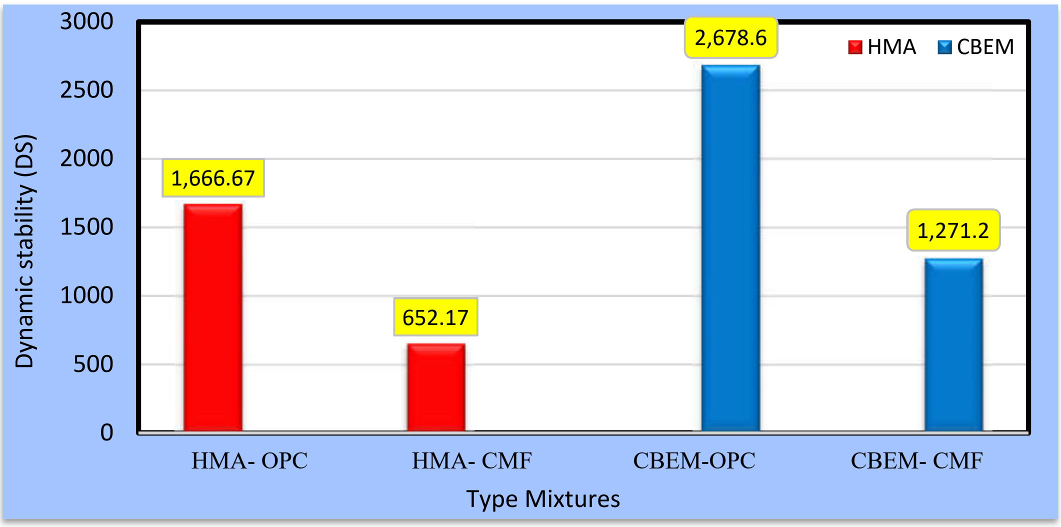


Figure 4-23 Dynamic Stability for CBEMs comprising CMF or OPC

4.3.2 Durability Tests

Water damage test (represented by RMSR) for CBEM - CMF and CBEM - OPC was achieved to identify the ability of CBEMs to resist stripping. OAEC was selected for these mixtures, as demonstrated in Figure (4-24). The results showed that CBEM - OPC are more resistance to water damage than CBEM – CMF. This is could be a result of OPC action against stripping as explained previously. It is worth to mention that the retaining Marshall strength ratio (RMSR) values of CBEM-OPC exceeded the other mixtures, which is significant marks of the validity of OPC in cold mix, such results have been proved by many other researchers (Oruc et al., 2006, Schmidt et al., 1973, Ahmed, 2017).

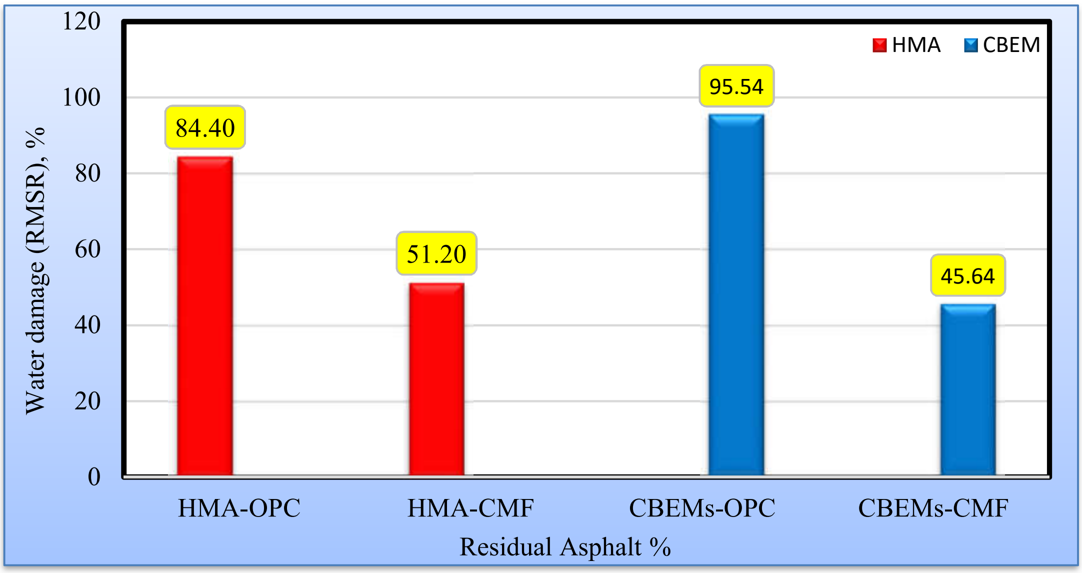


Figure 4-24 RMSR for CBEMs comprising CMF or OPC

4.4 Characteristics of Modified Conventional CBEMs and CBEMs Comprising OPC by Polymer

This section presents the volumetric, mechanical, and durability properties of modified CBEMs by acrylic (AR) polymer after selection of the (OPWwc) and (OAEC) of CBEMs-CMF and CBEMs–OPC. The addition of polymer is an advance step to obtain further improvements for CBEM. AR polymer was added to asphalt emulsion at percentages of 1.25, 2.5, 3.75, and 5% of residual asphalt to achieve one of the objectives of this research work.

4.4.1 Volumetric Properties

Figure (4-25) demonstrates that the density of CBEMs-CMF and CBEMs-OPC decreases dramatically with the increase in AR polymer. This is could be a result of adding AR polymer, which leads to increase the water in total mix (the water that form the continuous phase of AR polymer, the pre-wetting water, and the water from the emulsion itself). Such water left the mix later on and causes a noticeable reduction in density. The densities of CBEM-CMF are more than CBEM-OPC because of the occurrences of the hydration process which minimizing the workability. Also, the pre-wetting water content of the CBEM-OPC is higher than the one of CBEM-CMF, and this facilitate more water in total mix which minimizes the density. Along this, the above behavior is reflected on the air void characteristics identical, as can be seen in Figure (4-26).

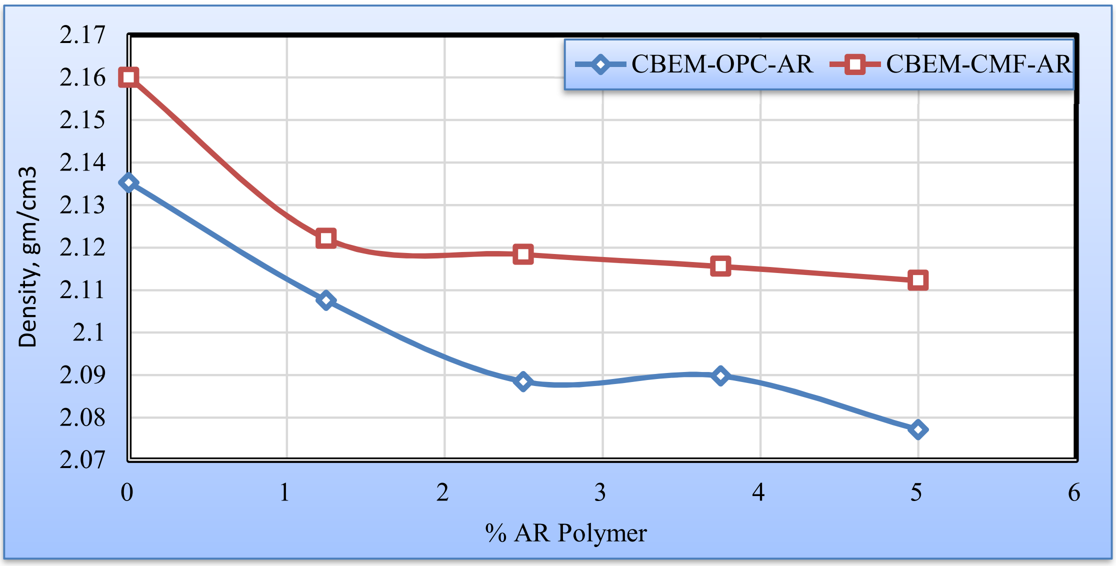


Figure 4-25 Density versus % AR for CBEMs Comprising AR Polymer and CMF or OPC

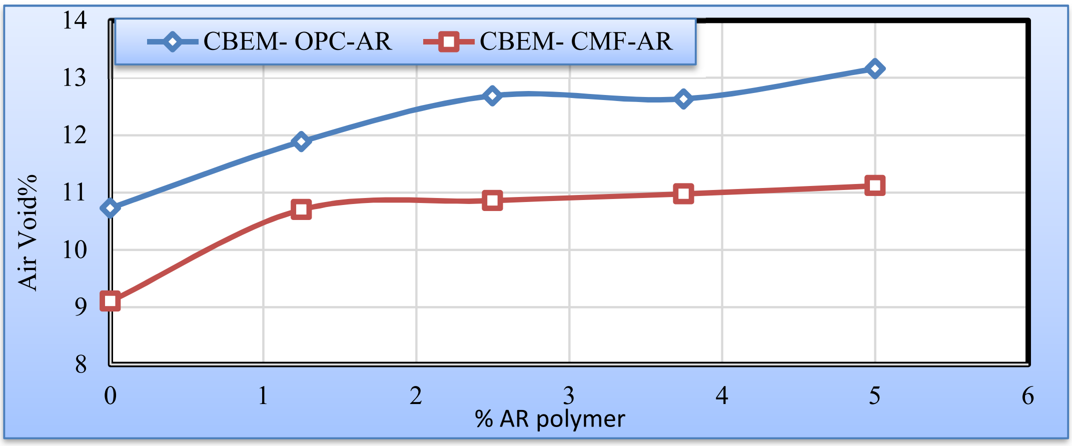


Figure 4-26 Air Void versus % AR for CBEMs Comprising AR Polymer and CMF or OPC

In the same trend as can be seen in Figure (4-27), the V.M.A of CBEMs-CMF and CBEMs- OPC demonstrate a continuing increase, might be due the increase in air void content. While for V.F.B, the increase in AR polymer content leads to the continuing decrease in void filled with asphalt, as can be seen in Figure (4-28). This is could be a result of increasing the AR polymer at the expense of bitumen.

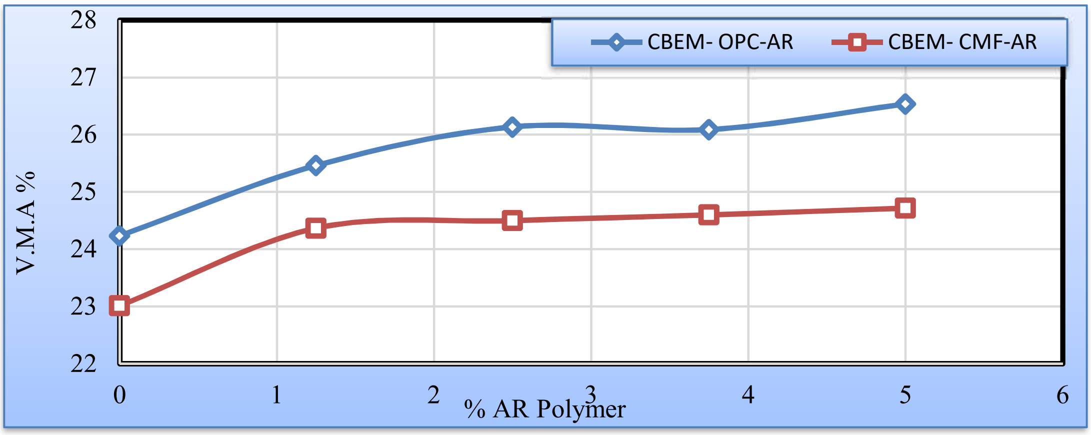


Figure 4-27 VMA versus % AR for CBEMs Comprising AR Polymer and CMF or OPC

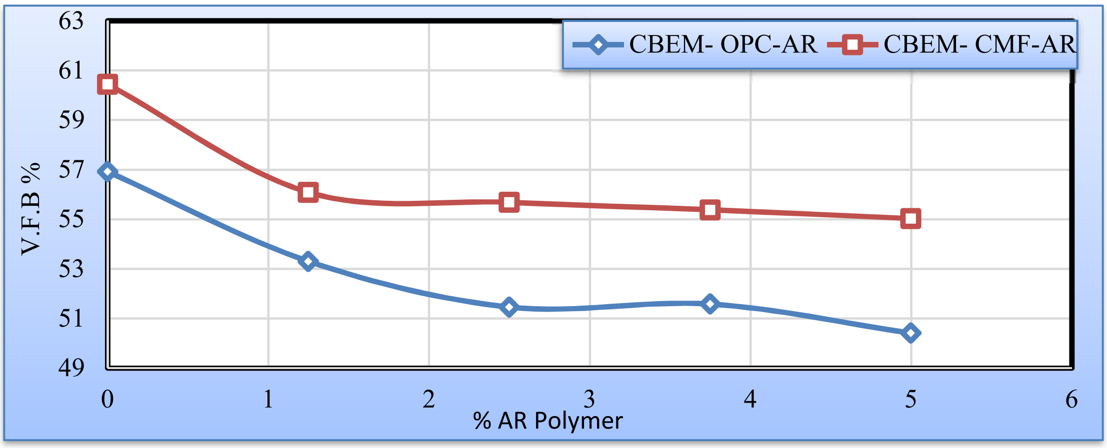


Figure 4-28 VFB versus % AR for CBEMs Comprising AR Polymer and CMF or OPC

4.4.2 Mechanical Properties

4.4.2.1 Marshall Test

The polymer could improve Marshall stability, where CBEMs comprising 1.25 % AR polymer showed better characteristics than non-polymer mix, but extra polymer could affect stability inversely, as can be seen in Figure (4-29). This incremental in stability could be a result of cross-linking characteristics of the polymer and improve both primary and secondary binding characteristics. Whereby, maximum stability values of modified CBEMs with OPC and 1.25% AR polymer is high than conventional HMA, CBEM with CMF and CBEM with OPC by about 5%, 344% and 15 %, respectively, as it explicates in Table (4-2). On the other hand, stability values of CBEMs with CMF and 1.25% AR is less than conventional HMA, but it is higher than CBEM with CMF by about 71% and 22% respectively, as it explicates in Table (4-3). However, the same table shows that polymer could be very critical, especially when the extra polymer is comprised.

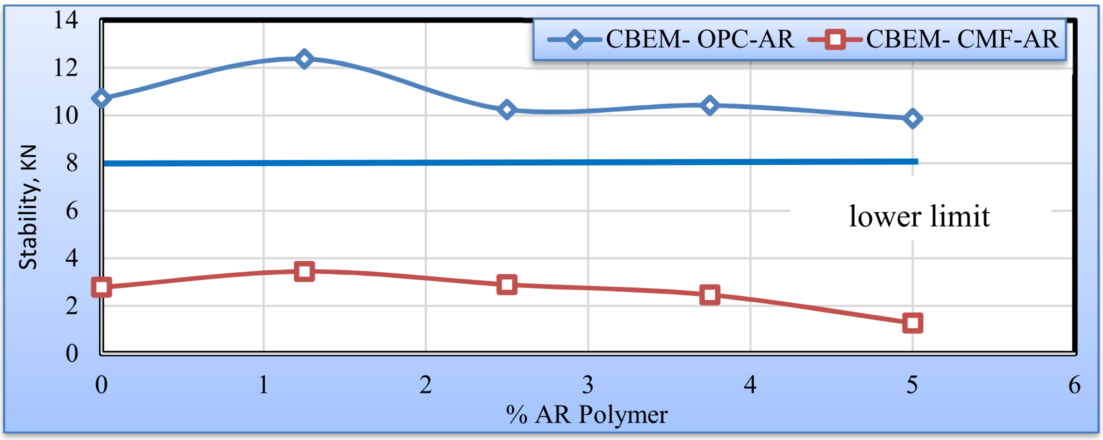


Figure 4-29 Marshall Stability versus % AR for CBEMs Comprising AR Polymer and CMF or OPC

The Marshall flow values for CBEMs with OPC and AR polymer, as demonstrated in Figure (4-30), are improved and catch the specification limits (i.e.,2-4 mm) in several percentages especially with high AR content. This reduction could be a result of cross-linking and polymer elastic characteristics, which reflected on the binder. It made CBEMs more flexibility, which can be stretched without noticeable breaking and return immediately to its initial form after non-loading. Whereas, the flow values of CBEMs with OPC and 1.25% AR are less than conventional HMA, CBEMs with CMF and CBEMs with OPC by 6 %,60% and 25%, respectively, as explicate in Table (4-2). However, this improvement in flow is limited for CBEMs-CMF.

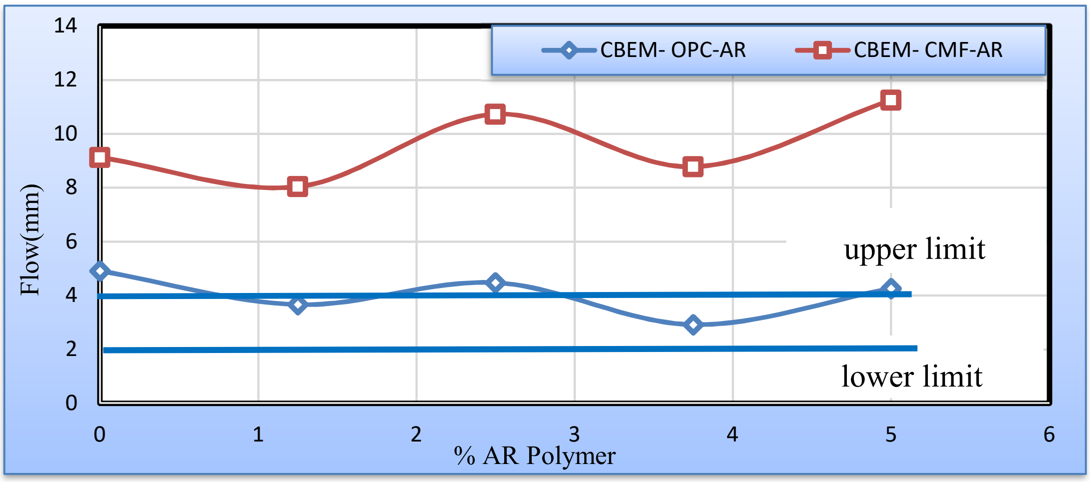


Figure 4-30 Flow versus % AR for CBEMs Comprising AR Polymer and CMF or OPC

Table 4-2 Percentages Change in Marshall Stability (ΔMS) and Marshall Flow (ΔMF) Relative to Reference Mixture

Reference Mixture	**CBEM – OPC -0.00% AR**		**CBEM – OPC -1.25% AR**		**CBEM– OPC -2.50 % AR**		**CBEM – OPC -3.75 % AR**		**CBEM – OPC -5.00 % AR**	
	ΔMS	**ΔMF**	**ΔMS**	**ΔMF**	**ΔMS**	**ΔMF**	**ΔMS**	**ΔMF**	**ΔMS**	**ΔMF**
HMA	-9.15	26.03	4.9	-6.03	-13.2	14.74	-11.6	-25.13	-16.3	9.23
CBEM-CMF	285.0	-46.1	344.3	-59.8	267.9	-51.0	274.4	-68.0	254.6	-53.3
CBEM-OPC	0	0	15.4	-25.4	-4.4	-50.9	-2.8	-68	-7.9	-53.3
Reference Mixture	**CBEM– CMF -0.00% AR**		**CBEM – CMF -1.25% AR**		**CBEM– CMF -2.50 % AR**		**CBEM– CMF -3.75 % AR**		**CBEM– CMF -5.00 % AR**	
	ΔMS	**ΔMF**	**ΔMS**	**ΔMF**	**ΔMS**	**ΔMF**	**ΔMS**	**ΔMF**	**ΔMS**	**ΔMF**
HMA	-76.4	133.9	-70.8	106.1	-75.4	175.1	-79.1	125.1	-89.1	188.5
CBEM-CMF	0	0	22.2	-11.9	7.3	17.6	-14.8	-3.8	29.3	23.3

4.4.2.2 Indirect Tensile Strength

Significant improvement in ITS of CBEM due to polymer introduction, whereas its value for CBEMs with OPC and 2.5% AR is achieved the optimum value, as can be seen in Figure (4-31). This indicates that the mixtures containing AR have higher tensile and crack resistance at failure, which could be the reflection of improvement due to cross-linking of the polymer to the binder. However, this percentage of AR is less than conventional HMA and high than CBEMs with CMF and control CBEMs by about 4 %, 597% and 210%, respectively, as explicate in Table (4-3). Whereas, ITS values of CBEM with CMF and 2.5% AR is less than conventional HMA conventional but high than CBEMs with CMF by about 56 %, and 192 %, respectively, as explicate in Table

(4-3). Also, the features of the cracks showed less dispersion when AR polymer increase, as can be seen in Plate (4-1).

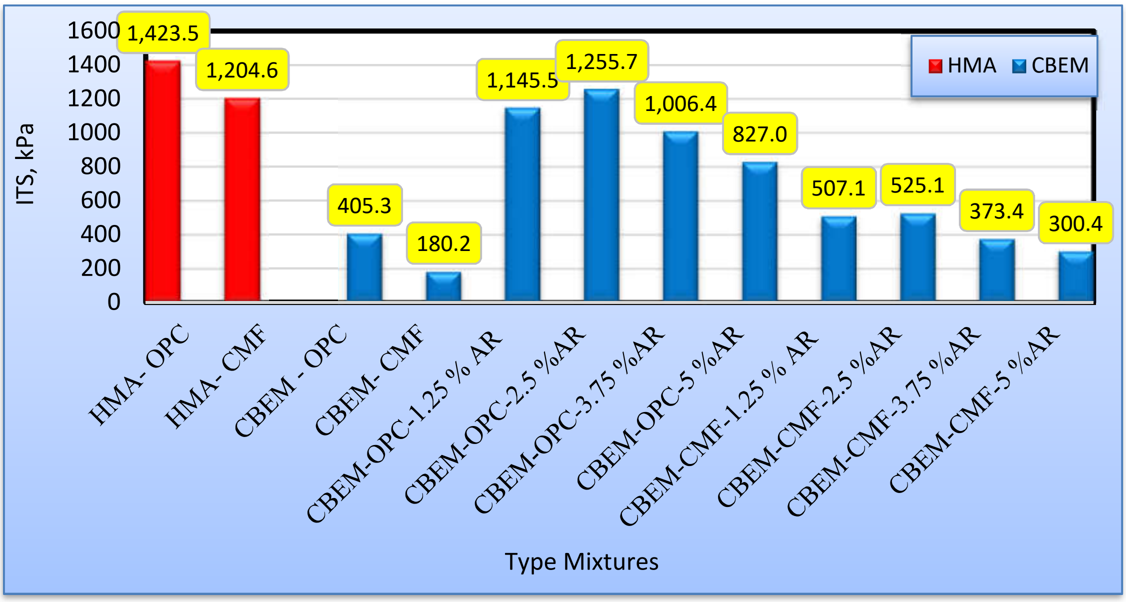
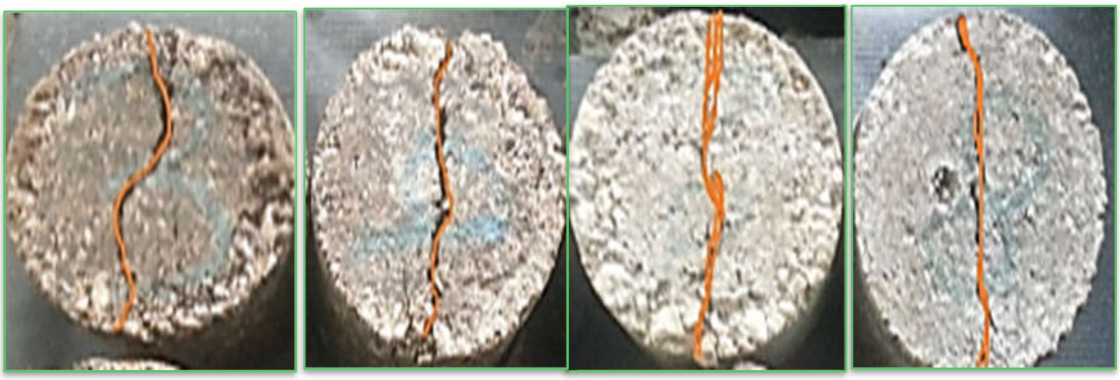
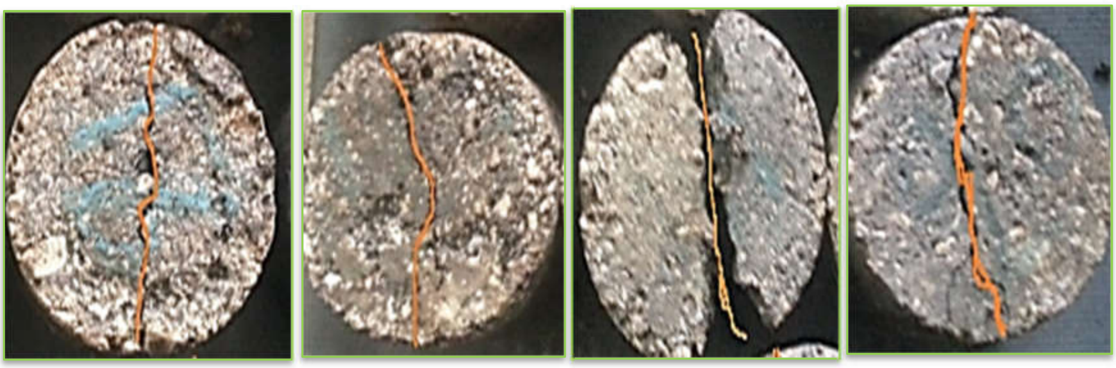


Figure 4-31 ITS versus % AR for CBEMs Comprising AR Polymer and CMF or OPC



(a): CBEM s - OPC – AR polymer from 1.25% to 5% in step 1.25% respectively



(b): CBEMs Acrylic CMF – AR polymer from 1.25% to 5% in step 1.25% respectively

Plate 4-1 Cracking pattern of CBEMs Comprising AR Polymer and CMF or OPC

Table 4-3 Percentages Change in Indirect Tensile Strength (ΔITS) relative to Reference Mixture

Reference Mixture	**CBEM– OPC -0% AR**	**CBEM– OPC -1.25% AR**	**CBEM– OPC -2.5 % AR**	**CBEM – OPC -3.75 % AR**	**CBEM– OPC- 5 % AR**
	ΔITS				
HMA	-66.4	-4.9	4.2	-16.5	-31.3
CBEM-CMF	125.0	535.9	597.0	458.6	359.0
CBEM-OPC	0	182.6	209.8	148.3	104.0
Reference Mixture	**CBEM– CMF -0% AR**	**CBEM– CMF -1.25% AR**	**CBEM– CMF -2.5 % AR**	**CBEM– CMF -3.75 % AR**	**CBEM– CMF -5 % AR**
	ΔITS				
HMA	-85.0	-57.9	-56.4	-69.0	-75.1
CBEM-CMF	0	181.5	191.5	107.3	66.8

4.4.2.3 Creep Compliance

The results for creep compliance demonstrate that the addition of AR polymer for CBEMs leads to a decrease the creep compliance. In other words, increase the stiffness, which could be because of the improving in binder characteristics due to cross-linking that offers by the polymer. The change percentages in stiffness for modified CBEMs comparison with conventional each of HMA and CBEMs and control CBEMs are explicated in Table (4-4). Creep compliance values for modified CBEMs explicate in Figure (4-32, 33). It worth to mention that the improvement in creep compliance for CBEMs-OPC is much better than these for mixes comprising CMF, which is mainly due to the reasons that were mentioned for an explanation of the mechanics of cross-linking.

Creep stiffness results are demonstrated in Figure (4-34), which clears that CBEM comprised OPC and 1.25% AR has Creep stiffness higher than CBEM-CMF, and comparable to conventional HMA.

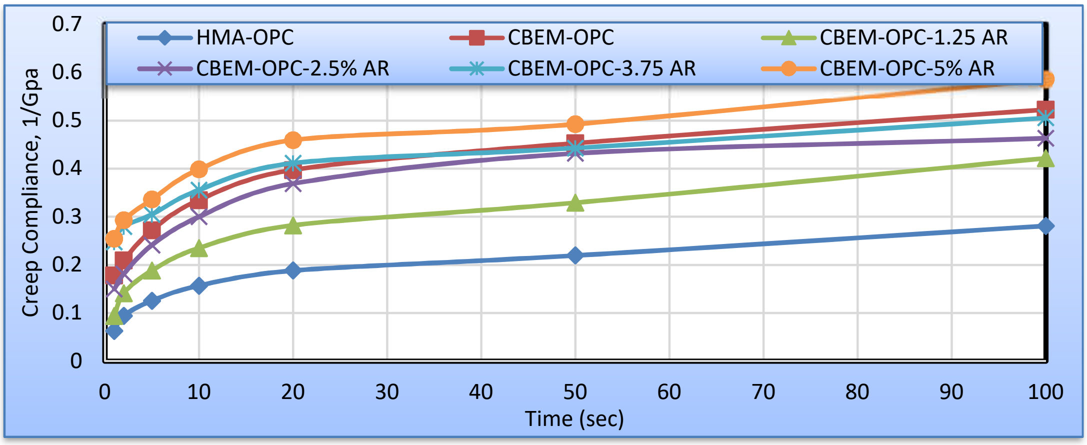


Figure 4-32 Creep Compliance for CBEMs comprising OPC and AR at 0°C

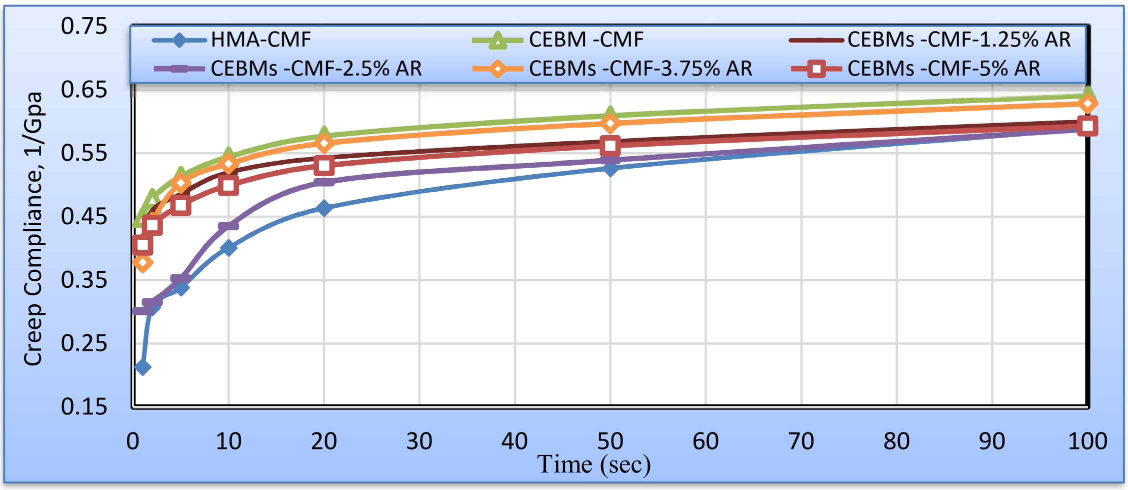


Figure 4-33 Creep Compliance for CBEMs comprising CMF and AR at 0° C

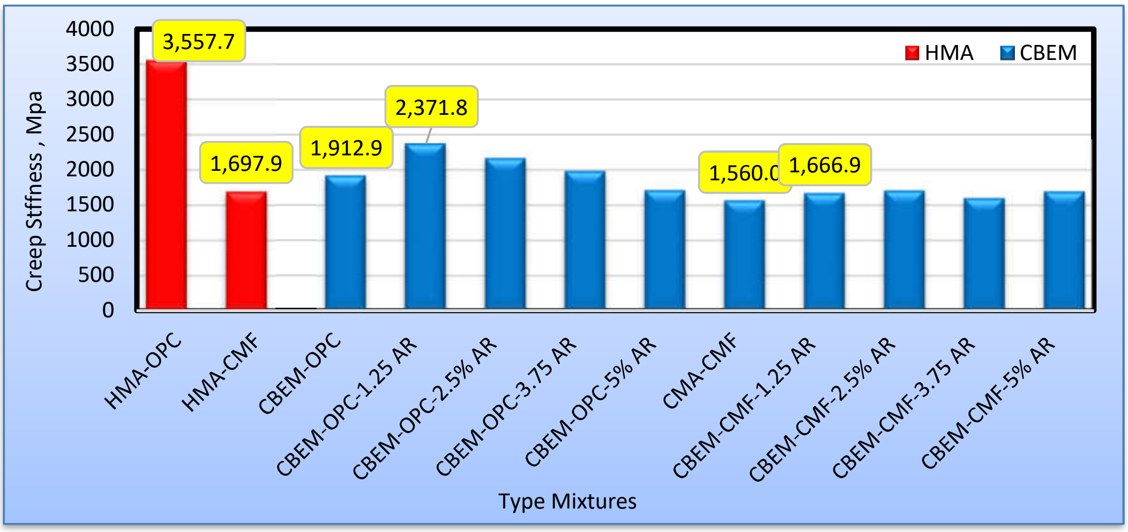


Figure 4-34 Creep Stiffness for CBEMs comprising CMF and AR at100 sec for 0°C

Table 4-4 Percentages Change in Creep Compliance (ΔD) and Creep Stiffness (ΔC) Relative to Reference Mixture

Reference Mixture	**CBEM– OPC -0.00% AR**		**CBEM – OPC-1.25% AR**		**CBEM– OPC -2.50 % AR**		**CBEM– OPC -3.75 % AR**		**CBEM– OPC-5.00 % AR**	
	ΔD	**ΔC**	**ΔD**	**ΔC**	**ΔD**	**ΔC**	**ΔD**	**ΔC**	**ΔD**	**ΔC**
HMA	-11.2	12.7	-28.4	39.7	-21.4	27.2	-14.2	16.5	-0.4	0.4
CBEM-CMF	-18.4	22.6	-34.2	52.0	-27.8	38.5	-21.2	26.8	-8.5	9.3
CBEM-OPC	0	0	-19.4	24.0	-11.4	12.9	-3.3	3.4	12.2	-10.9
Reference Mixture	**CBEM– CMF -0.00% AR**		**CBEM– CMF -1.25% AR**		**CBEM– CMF -2.50 % AR**		**CBEM – CMF -3.75 % AR**		**CBEM– CMF - 5.00 % AR**	
	ΔD	**ΔC**	**ΔD**	**ΔC**	**ΔD**	**ΔC**	**ΔD**	**ΔC**	**ΔD**	**ΔC**
HMA	8.8	-8.1	1.9	-1.8	-0.2	0.2	6.7	-6.3	0.7	-0.7
CBEM-CMF	0	0	-6.4	6.9	-8.3	9.1	-2.0	2.0	-7.5	8.1

4.4.2.4 Wheel Track Test

Almost, polymer added further improvements to CBEMs with OPC or CMF in terms of resistance to permanent deformation, as can be seen in Figures (4-35, and 36). The optimum value of the rutting resistance of CBEM - OPC - 1.25% AR is recognized to be higher than other percentages. The rutting resistance of CBEM - OPC - 1.25% AR increase by about 90 %, 93% and 40% in contrast to conventional HMA, CBEMs comprising CMF and CBEMs comprising OPC, respectively as explicate in Table (4-5). This is could be because of the high flexibility of elastomer polymers as AR polymer that made the mixture more resistance to the rutting or permanent deformation by stretch and returns immediately to its initial form after non-loading. Also, addition of OPC to CBEMs formed a secondary binder. Furthermore, the rutting resistance of CBEM - CMF - 1.25% AR increase by about 58 % and 69% in contrast to conventional HMA, CBEMs comprising CMF, respectively as explicate in Table (4-5).

Dynamic stability of CBEMs comprising OPC and 1.25% AR is higher than conventional HMA, CBEMs with CMF and CBEMs with OPC by about 1300%, 1080% and 460%, respectively, as can be seen in Figure (4-37). Whereas, dynamic stability of CBEMs comprising CMF and 1.25% AR is higher than conventional HMA, and CBEMs with CMF by 133 % and 97 %, respectively.

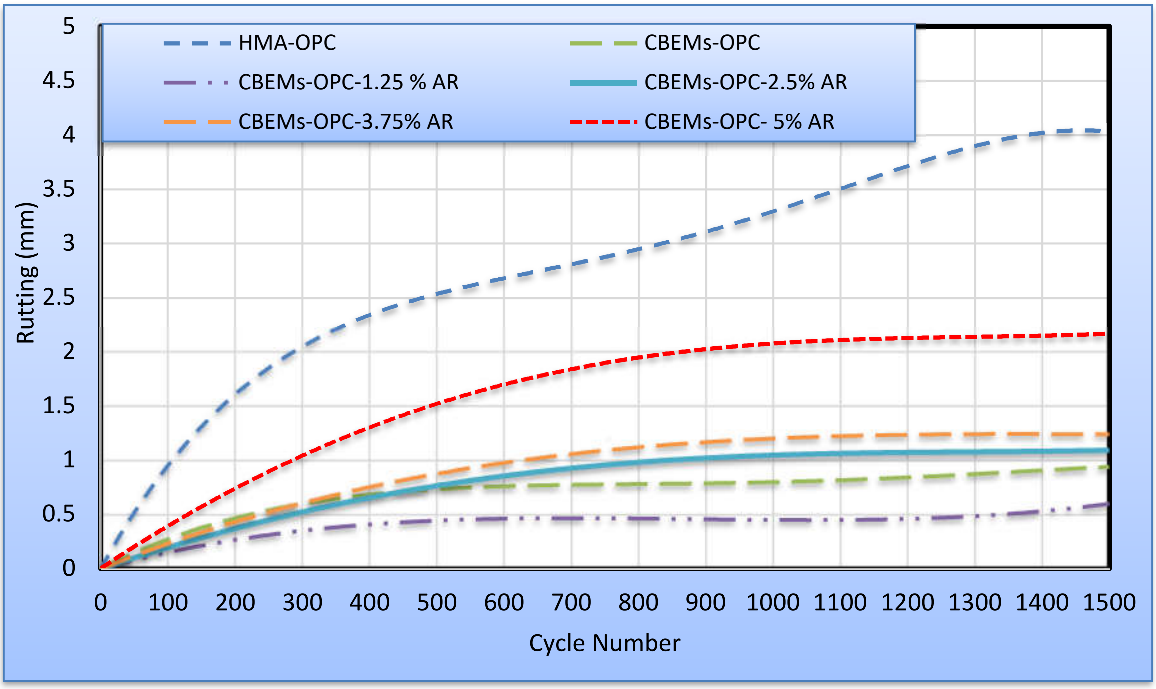


Figure 4-35 Rutting versus Cycle Number for CBEMs comprising AR Polymer and OPC

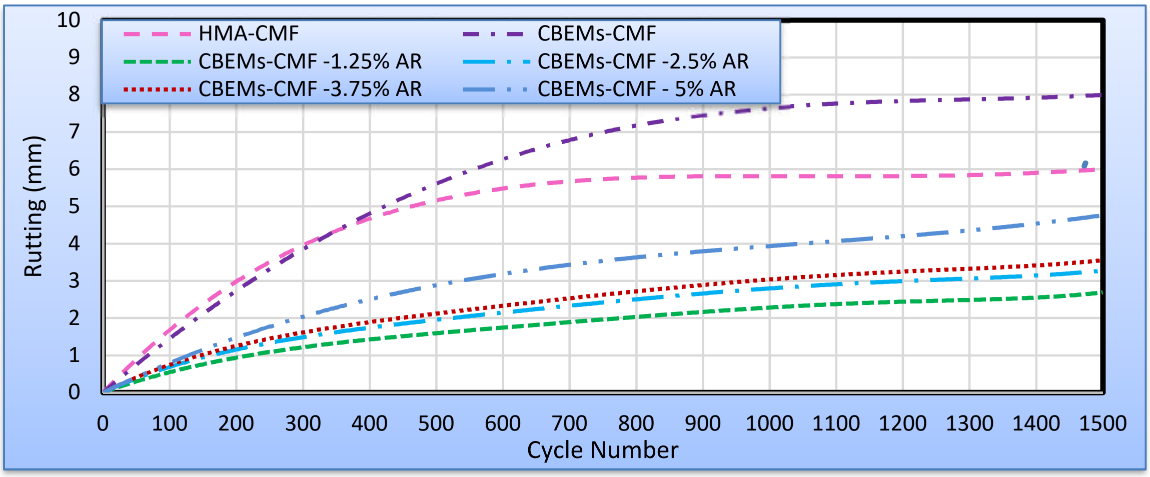


Figure 4-36 Rutting versus Cycle Number for CBEMs comprising AR Polymer and CMF

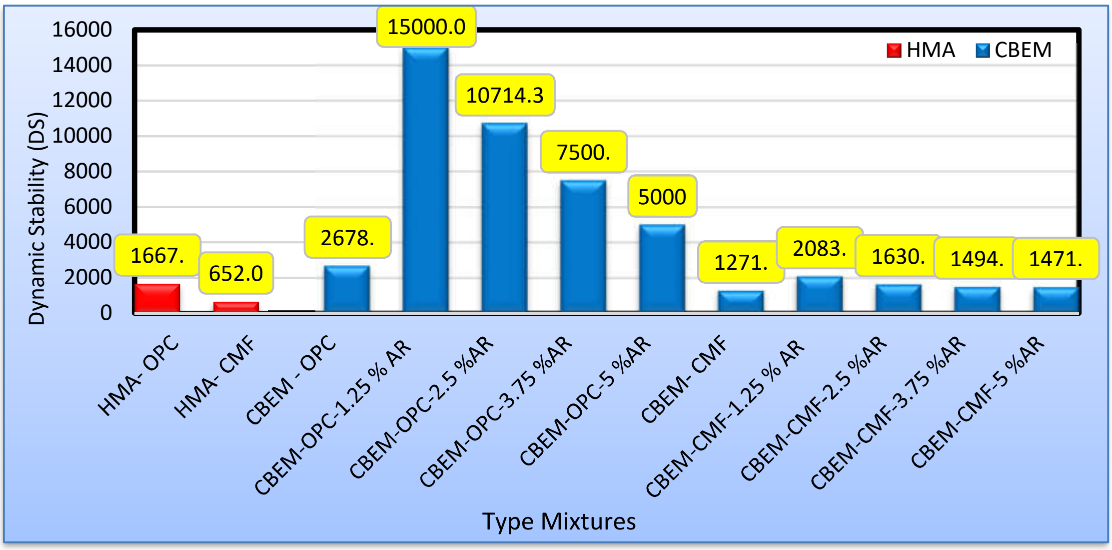


Figure 4-37 Dynamic Stability for CBEMs comprising AR Polymer and OPC or CMF

Table 4-5 Percentages Change in Rutting Depth (ΔRD) and Dynamic Stability (ΔDS) Relative to Reference Mixture

Reference Mixture	**CBEM– OPC -0.00% AR**		**CBEM – OPC-1.25% AR**		**CBEM– OPC -2.50 % AR**		**CBEM– OPC -3.75 % AR**		**CBEM– OPC-5.00 % AR**	
	ΔRD	**ΔDS**	**ΔRD**	**ΔDS**	**ΔRD**	**ΔDS**	**ΔRD**	**ΔDS**	**ΔRD**	**ΔDS**
HMA	-83.3	150.0	-90.0	1300.0	-81.7	1066.7	-79.2	900.0	-61.7	600.0
CBEM-CMF	-87.5	110.7	-92.5	1080.0	-86.3	883.3	-84.4	742.8	-71.3	490.0
CBEM-OPC	0	0	-40.0	460.0	10.0	366.7	25.0	300.0	130.0	180.0
Reference Mixture	**CBEM– CMF -0.00% AR**		**CBEM– CMF -1.25% AR**		**CBEM– CMF -2.50 % AR**		**CBEM – CMF -3.75 % AR**		**CBEM– CMF -5.00 % AR**	
	ΔRD	**ΔDS**	**ΔRD**	**ΔDS**	**ΔRD**	**ΔDS**	**ΔRD**	**ΔDS**	**ΔRD**	**ΔDS**
HMA	33.3	18.6	-58.3	133.3	-46.7	125.8	-40.0	75.0	6.7	0.0
CBEM-CMF	0	0	-68.8	96.6	-60.0	90.3	-55.0	47.5	-20.0	-15.7

4.4.3 Durability Tests

The results for water damage (represented by RMSR) demonstrate that the inclusion of AR polymer into CBEM **-** OPC made the mixture more resistance to water damage whereas it has adverse effect on CBEM – CMF, as can be seen in Figure (4-38). The optimum value of this resistance is of CBEM with OPC and 1.25% AR, which reach to about 109%, 55% and 12% comparison with conventional HMA, CBEMs and control CBEMs, respectively as explicate in Table (4-6). Whereas, addition AR polymer into CBEM - CMF is led to decrease the resistance of the water damage compared with conventional HMA and CBEMs with different percentages as explicate in Table (4-6). This behavior of the polymer was based on filler type in CBEM, CBEM comprising OPC show more resistance than CBEM comprising CMF, which is mainly because water sensitivity is a reflection of the mechanical and volumetric characteristics of the mix. Also, improving the stability or tensile resistance improves the water sensitivity as well.

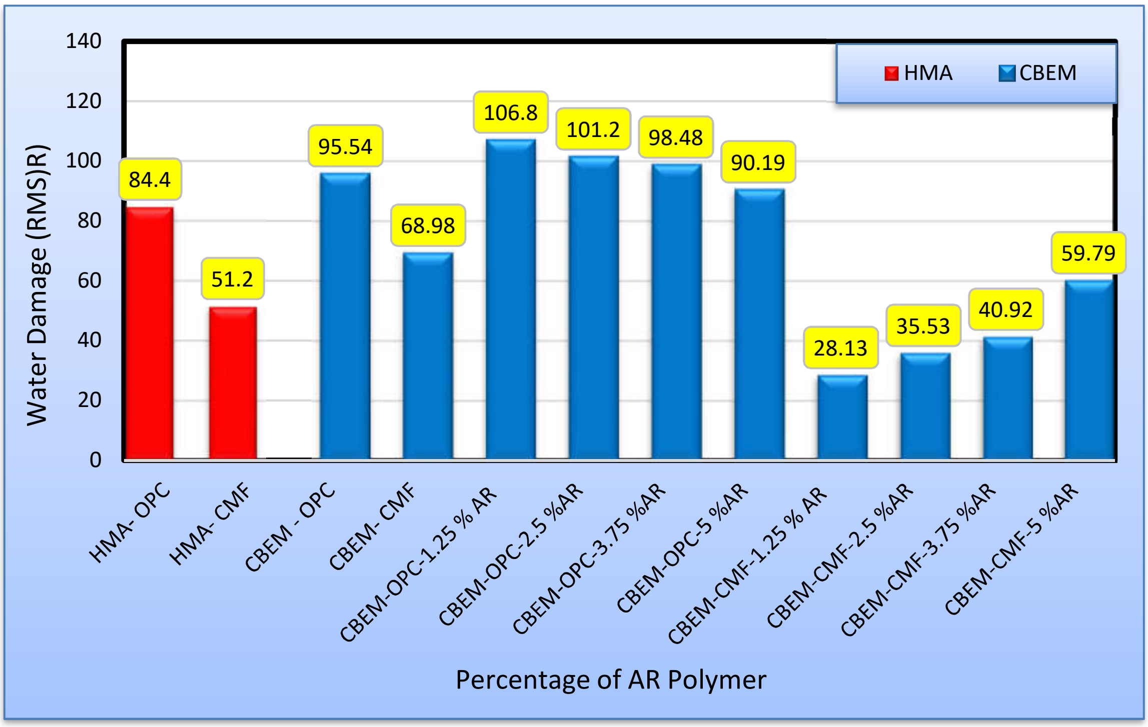


Figure 4-38 RMSR for CBEMs Comprising AR Polymer and CMF or OPC

Table 4-6 Percentages Change in Water Damage (Δ WD) relative to Reference Mixture

Reference Mixture	**CBEMs – OPC -0.00% AR**	**CBEM – OPC -1.25% AR**	**CBEM– OPC -2.50% AR**	**CBEM– OPC -3.75 % AR**	**CBEM– OPC-5.00 % AR**
	Δ WD				
HMA	86.6	108.5	97.8	92.3	76.1
CBEM-CMF	38.5	54.8	46.8	42.8	30.8
CBEM-OPC	0	11.8	6.0	3.1	-5.6
Reference Mixture	**CBEM – CMF -0.00% AR**	**CBEMs– CMF -1.25% AR**	**CBEM – CMF -2.50 % AR**	**CBEM – CMF -3.75 % AR**	**CBEM– CMF -5.00 % AR**
	Δ WD				
HMA	34.7	-45.05	-30.9	-20.1	17
CBEM-CMF	0	-59.2	-48.7	-40.7	-13.1

4.5 Summary for the Modified CBEMs by AR Polymer

This chapter included the testing results of modified CBEM by OPC alone and OPC and AR polymer. The results indicated the importance role of AR polymer in enhance the mechanical properties of CBEM comprising OPC at 1.25%. This percentage demonstrate improve in Marshall stability, creep compliance, rutting resistance, and durability properties (represented by RMSR) comparable with conventional HMA by 5, 28,90 and 109%, respectively. But, also this percentage reduce indirect tensile strength by 5 %. In addition, the results demonstrate that high level of air void content consequently this improvement have proven that the high air void content for the new CBEM has not influenced on its durability in terms of water damage. The next chapter present one solution to decrease the air void content of the new CBEM with conserve the improvement in mechanical and durability properties.

Chapter Five

Characterization of Half Warm Bitumen Emulsion Mixtures

5.1 Introduction

The previous chapter of this research described the results of the trails for overcoming the shortages in volumetric, mechanical and durability properties of CBEMs by addition AR polymer to CBEMs comprising OPC or CMF. Unfortunately, the developed CBEMs still have high air void content and low density in contrast to HMA or to a phase where it is not acceptable by pavement engineers for road surfacing layers as they still believe that volumetric properties play the vital role in other mix characteristics. Consequently, this chapter describes the utilization of low energy heating to improve the volumetric properties without effect to the obtained mechanical and durability properties. Thus, microwave heating was selected to achieve this job, as it was proven as one of the best low energy heating for asphalt mixture in lab scale attempts (Al-Busaltan, 2012, AL-HDABI, 2014).

5.2 Selection the Optimum Heating Time of Unmodified and Modified CBEMs by AR Polymer

The obtained results in previous chapter demonstrated that the best value of volumetric, mechanical, and durability properties of modified CBEMs was achieved by adding AR polymer of 1.25 % as a percentage from the residual asphalt, compared with other percentages for two type fillers, i.e., OPC and CMF. Therefore, this percentage of AR polymer was adopted for a mixture that utilizes in pre-compaction heating treatment by microwave energy. These new mixtures hereafter will call as Half Warm Bitumen Emulsion Mixture (HWBEM). This is because the mix preparation temperature still under 100°C, as can be seen later on.

5.2.1 Preparation of Half Warm Bitumen Emulsion Mixture (HWBEM)

HWBEM and HWBEM with AR polymer at 1.25 % of residual asphalt were prepared by heating the pre-compaction mixes by microwave technology. Heating times were ranged from (1.5 to 7.5 min) with an interval of 1.5 min. accordingly, mixes temperature was raised nearly from 85 to 95 °C, as can be seen in Figure (5-1). Unmodified and modified HWBEM by AR polymer were prepared at the same steps for CBEM, except the steps that followed the mixing. Whereas, the mixes were subjected to microwave heating (pre–compaction) with different heating times, as mentioned before. However, after heating the mixtures were subjected again to the same further steps for preparing CBEMs.

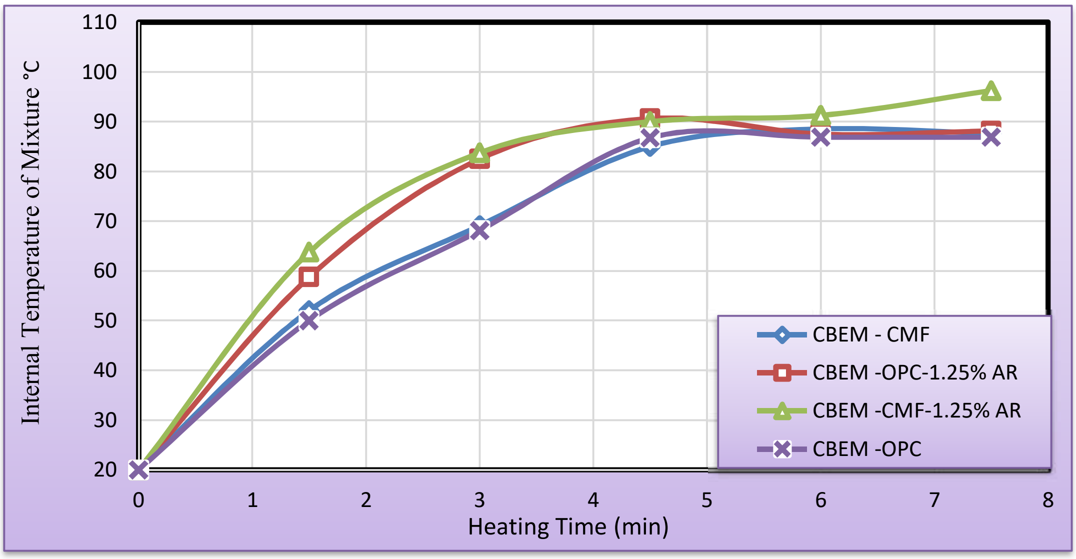


Figure 5-1 Internal Temperature versus Heating Time for Unmodified and Modified CBEMs

5.2.2 Volumetric Properties

Volumetric properties were the first parameters to select an optimum heating time for unmodified and modified HWBEM. The results in Figure (5-2) demonstrate that the density is increased with the increasing in the heating time until a certain limit, then it decreases with the continuance increase of heating time. This is mainly because continue heating process lead to decrease binder viscosity and reduce water content by evaporation. Consequently, it increases the breaking rate of asphalt emulsion, and increase mix workability. Nevertheless, extra heating removes almost all water and reduce the workability of the mix, then in its turn result in reduce in the density. Moreover, the above behavior is reflected on the air void characteristics for unmodified and modified HWBEMs with the two type fillers (OPC or CMF), as can be shown in Figure (5-3).

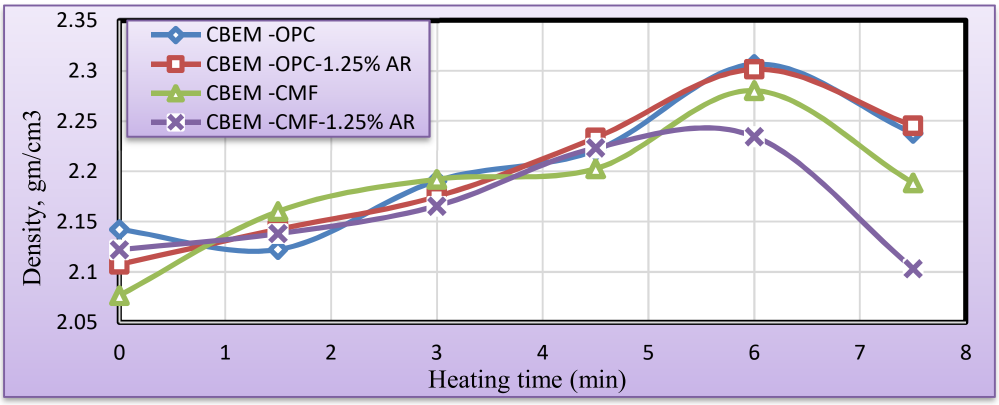


Figure 5-2 Density versus Heating Time for Unmodified and Modified CBEMs

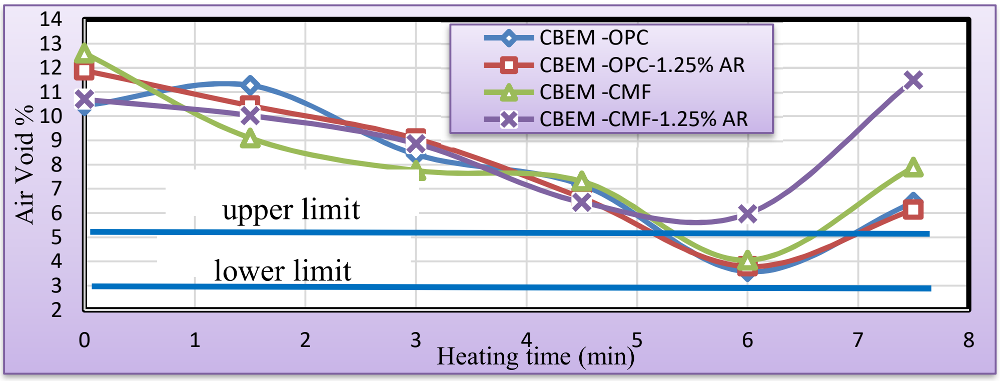


Figure 5-3 Air void versus Heating Time for Unmodified and Modified CBEMs

In the same trend, as can be seen in Figure (5-4), the V.M.A of unmodified and modified HWBEMs demonstrate a continuing decrease, which might be due to continuing reduction in water content and decrease of the viscosity. While for V.F.B character, the effect of increase heating time for these mixtures lead to the continuing increase in voids filled with asphalt, as can be seen in Figure (5-5). It is worth to mention that the volumetric characteristics of the HWBEM catch the specification levels, which could not be achieved before for any other treatment techniques.

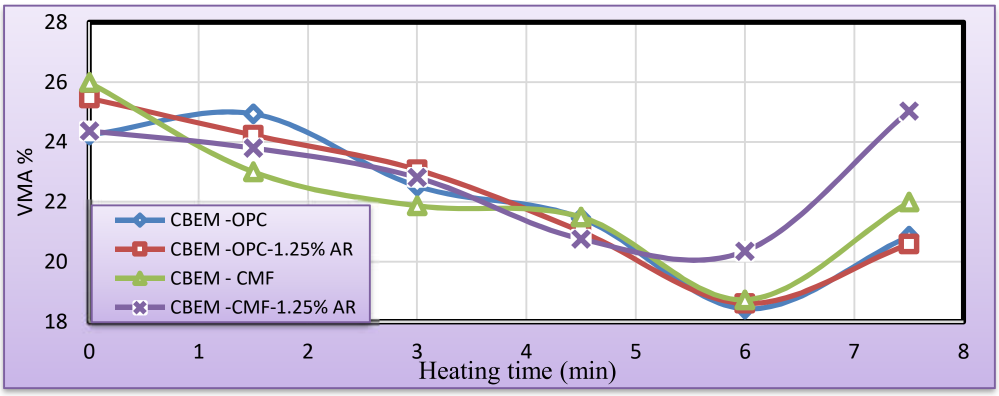


Figure 5-4 VMA versus Heating Time for Unmodified and Modified CBEMs

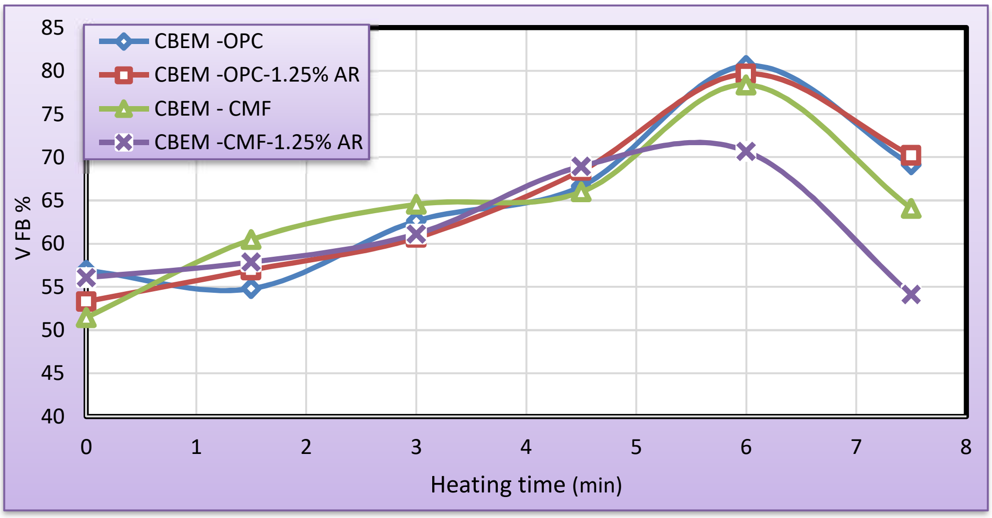


Figure 5-5 VFB versus Heating Time for Unmodified and Modified CBEMs

5.2.3 Mechanical properties

Mechanical properties were the second parameter to select optimum heating time.

- **Marshall Test**

Marshall stability for unmodified or modified HWBEM were showed low improvement with low temperature, as can be seen in Figure (5-6). Then, it increased with the increase in temperature of the mix before compaction to specific limits; introduce temperature helps in increase the workability of the mix, the backing of materials and the interlocking between aggregate particles, which reflect better resistance to plastic deformation. After that, when temperature increases, the stability descends again, as a result of extra decreasing the water content that leaves the mix after curing and associates higher air void and decreases the viscosity of the bitumen. Marshall flow results for unmodified or modified CBEMs demonstrated gradually decreased with the increase in the heating time, as can be seen in Figure (5-7). This is might be a result of the continues reduction in asphalt film thicknesses that have been reduced continually due to lowering the viscosity of the bitumen as a result of further heating. It is worth to mention that heating process facilitates better mechanical properties to significant levels in contrast to a specification limit, even with a conventional mix.

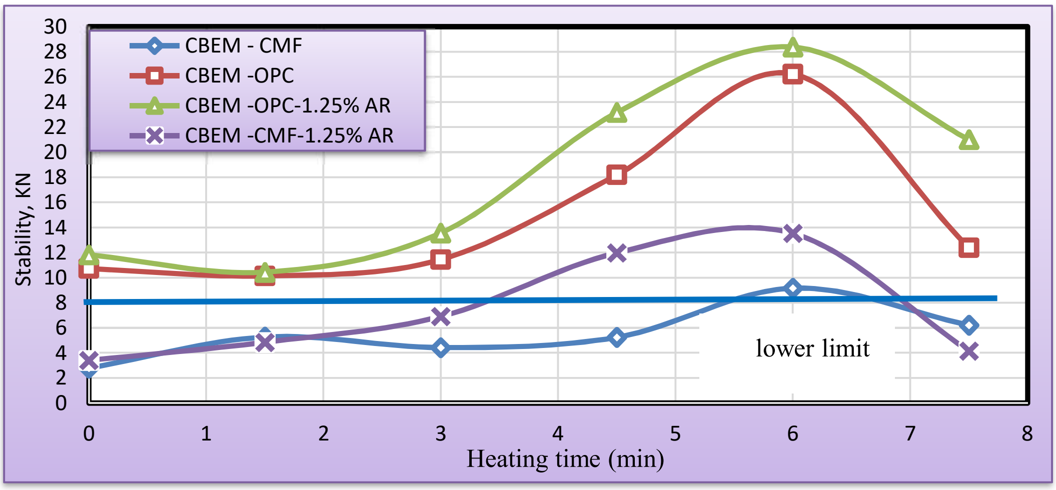


Figure 5-6 Stability versus Heating Time for Unmodified and Modified CBEMs

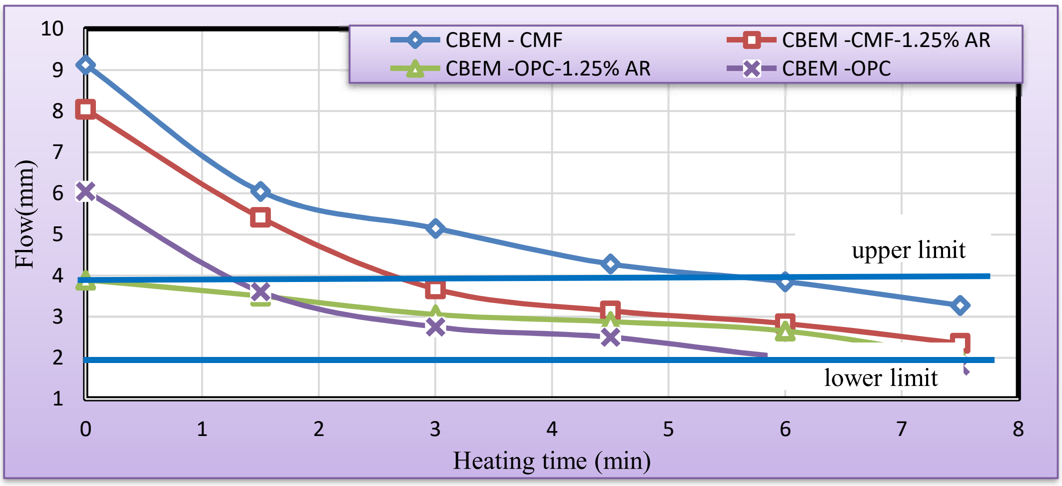


Figure 5-7 Flow versus Heating Time for Unmodified and Modified CBEMs

5.3 Selection the Optimum Percentage of AR Polymer

The mechanical and volumetric properties in the previous section 5.2 showed that the optimum heating temperature is about 90°C, which is associated with heating time of 6 mins. Therefore, it shall be adopted as a constant heating time for modified and unmodified HWBEM.

5.3.1 Half Warm Bitumen Emulsion Mixture (HWBEM) Preparation

The same preparation process was adopted as explained in section 5.2.1, whereas the specimens were prepared in different percentages of AR polymer; i.e., 1.25, 2.5, 3.75 and 5% with constant heating time of 6 mins. Also, extra characterization has been achieved for unmodified HWBEM for comparison purpose.

5.3.2 Volumetric Properties

The results in Figure (5-8) demonstrate that the density is decreased with increasing AR polymer content, because continuous increase leads to increase the water in total mix (the water that form the continuous phase of AR polymer). Such water left the mix later on and causes a noticeable reduction in density if no heat is use. Moreover, the above behavior is reflected on the air void characteristics, as can be shown in Figure (5-9).

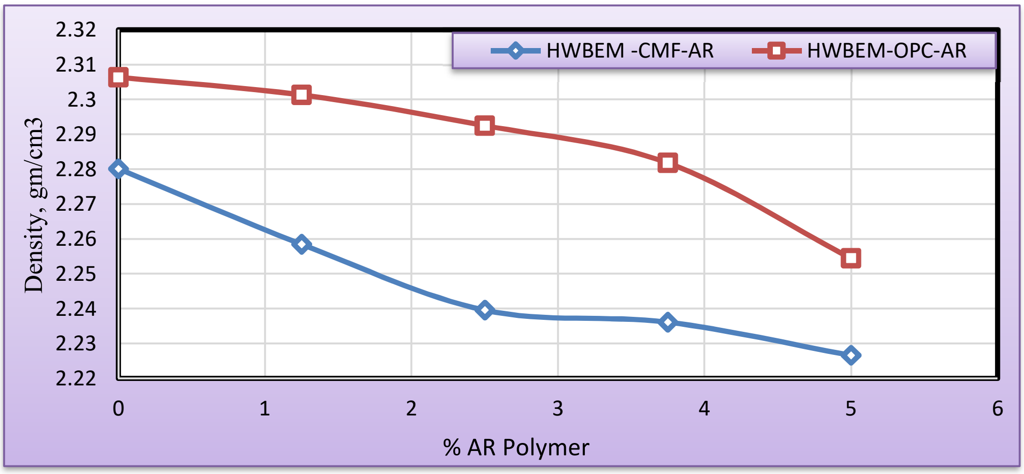


Figure 5-8 Bulk Density of HWBEM versus AR Polymer Content

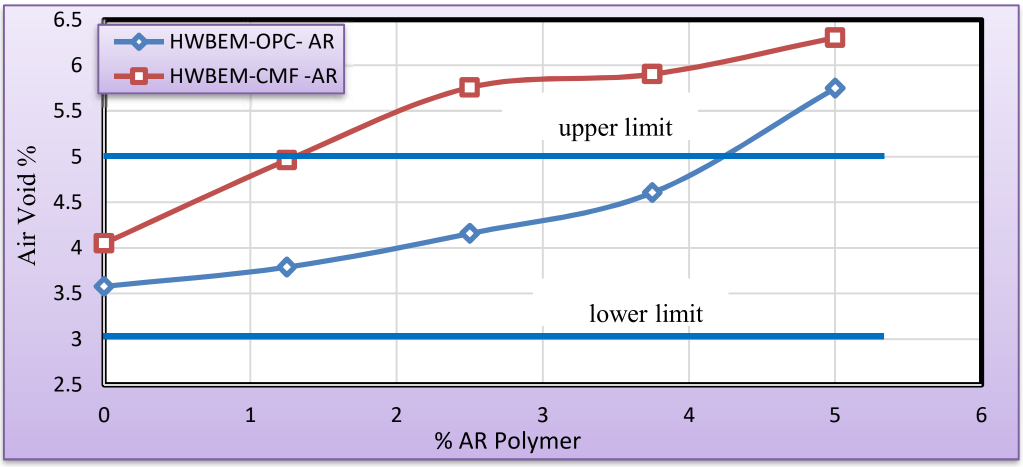


Figure 5-9 Air void of HWBEM versus AR Polymer Content

In the same trend as can be seen in Figure (5-10), the V.M.A of unmodified and modified HWBEM demonstrate a continuing increase, which might be due to continuing the increase in air void content. While for V.F.B, the increase in AR polymer content leads to the continuing decrease in void filled with asphalt, as can be seen in Figure (5-11). This is could be a result of increasing the AR polymer at the expense of bitumen.

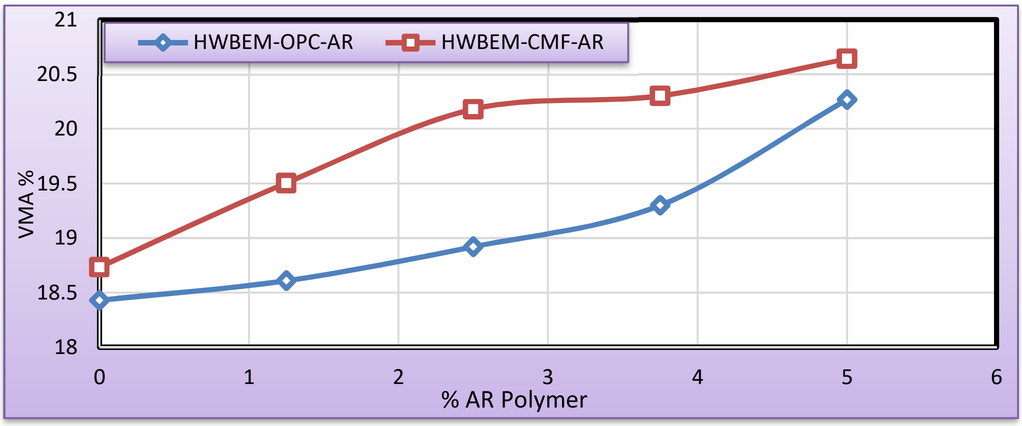


Figure 5-10 V.M.A of HWBEM versus AR Polymer Content

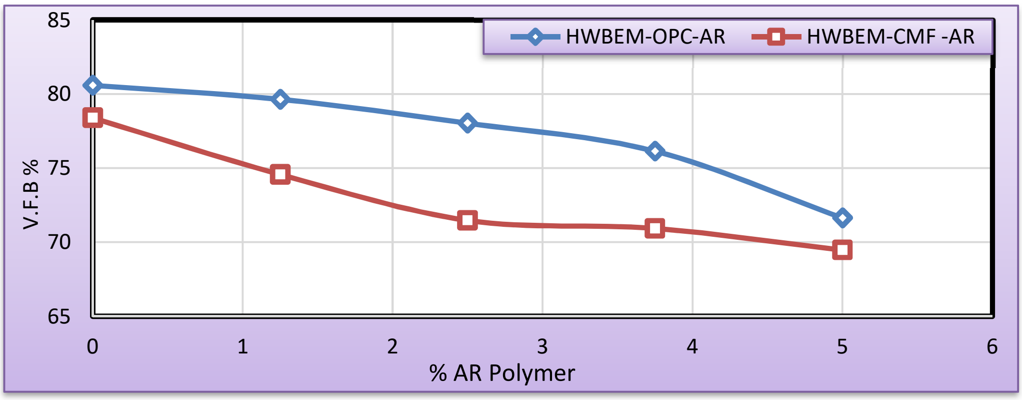


Figure 5-11 V.F.B of HWBEM versus AR Polymer Content

5.3.3 Mechanical properties

The same tests were utilized to characterize the mechanical properties of unmodified or modified HWBEM by AR polymer.

5.3.3.1 Marshall Test

The polymer could improve Marshall stability, where HWBEMs comprising 1.25 % AR polymer showed better characteristics than a non-polymer mix, but extra polymer could affect stability, or increase the viscous phase of the binder, as can be seen in Figure (5-12). This incremental in stability could be a result of cross-linking characteristics of the polymer and it improves both primary and secondary binding characteristics. Whereby, maximum stability values of modified HWBEM with OPC and AR polymer is at 1.25% AR that is high than each of conventional HMA and HWBEM, and control HWBEM by about 140 %, 210% and 8%, respectively, as it explicates in Table (5-1). However, the stability values of HWBEM with CMF and 1.25% AR is higher than each of conventional HMA and

HWBEM is by about 15% and 48%, respectively, as it explicates in Table (5-2). The same table shows that polymer could be very critical, especially when extra polymer is comprised.

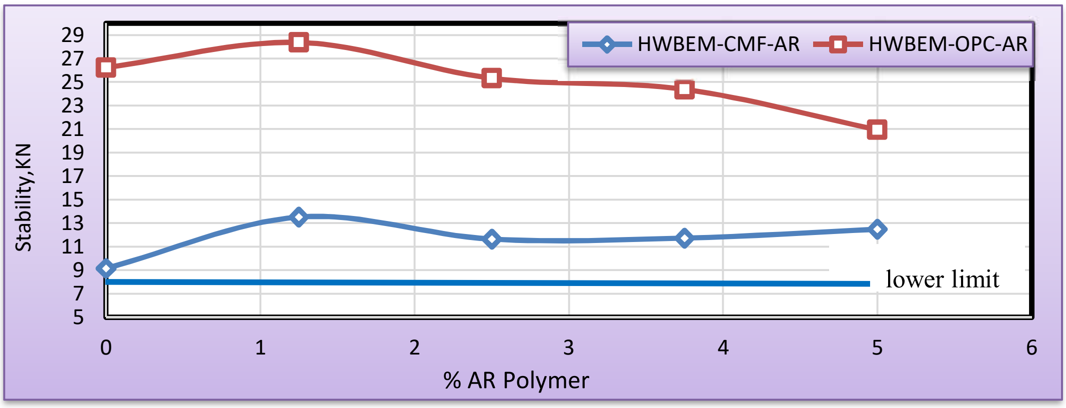


Figure 5-12 Stability of HWBEM versus AR Polymer Content

Marshall flow results for HWBEM with CMF demonstrated increased gradually with the increase in AR polymer content, as can be seen in Figure (5-13). The results reflected the effect of heating on visco-plastic characteristics of the increment in AR polymer because the high elasticity of this polymer that results from physical and crosslink of the molecules into a three dimensional network. For HWBEM – OPC, the flow initially increases with the increase in AR polymer, as the polymer adds more elastic characteristics, then it decreased as a modification of cross linking, after that increase as a result of a further increase of elastic material. As an expansion of effect, modifiers as OPC and AR on conventional HWBEM improve the level of MS and MF in comparison with conventional HMA, as can be shown in Table (5-1).

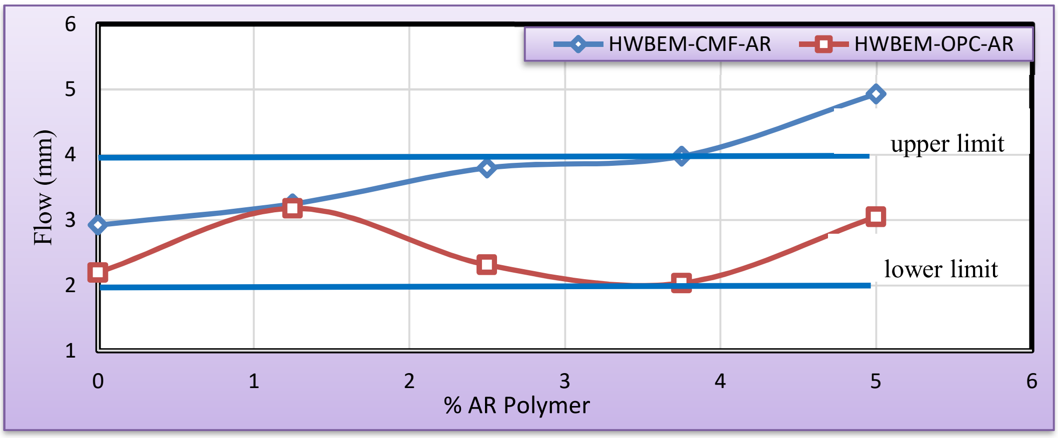


Figure 5-13 Flow of HWBEM versus AR Polymer Content

Table 5-1 Percentages Change in Marshall Stability (ΔMS) and Marshall Flow (ΔMF) Relative to Reference Mixture

Reference Mixture	**HWBEM -OPC -0.00% AR**		**HWBEM -OPC -1.25% AR**		**HWBEM -OPC -2.50 % AR**		**HWBEM -OPC -3.75 % AR**		**HWBEM -OPC -5.00 % AR**	
	Δ MS	**Δ MF**	**Δ MS**	**Δ MF**	**Δ MS**	**Δ MF**	**Δ MS**	**Δ MF**	**Δ MS**	**Δ MF**
HMA	122.3	-25.0	140.4	-18.4	114.6	-40.6	106.6	-47.8	77.4	-21.7
HWBEM -CMF	186.4	33.0	209.8	44.5	176.5	5.2	166.2	-7.5	128.6	38.6
HWBEM -OPC	0	0	-8.2	8.7	3.5	-20.9	7.1	-30.4	20.2	4.3
Reference Mixture	**HWBEM -CMF -0.00% AR**		**HWBEM –CMF -1.25% AR**		**HWBEM –CMF -2.50 % AR**		**HWBEM –CMF -3.75 % AR**		**HWBEM– CMF -5.00 % AR**	
	Δ MS	**Δ MF**	**Δ MS**	**Δ MF**	**Δ MS**	**Δ MF**	**Δ MS**	**Δ MF**	**Δ MS**	**Δ MF**
HMA	-22.4	-43.5	14.6	-16.7	-1.3	-2.6	-0.6	1.9	5.79	26.3
HWBEM -CMF	0	0	47.6	47.6	27.2	72.6	28.1	80.7	36.3	124.0

5.3.3.2 Indirect Tensile Strength

Indirect tensile strength values for HWBEM–OPC or HWBEM– CMF are increased with addition AR polymer, as can be seen in Figure (5-14). While continuous increasing lead to the decrease the indirect tensile strength. This is result of addition AR at first increase interlock between aggregate particles. Continuous increase leads to decrease the binder effect of the bitumen at the aggregate binder interface connection. As an expansion of this effect, modifiers as OPC and AR on conventional HWBEM and the improvement level in ITS comparison with conventional HMA, as explicates in Table (5-2). Also, the feature of the cracks showed less dispersion when AR polymer increase, as can be seen in Plate (5-1).

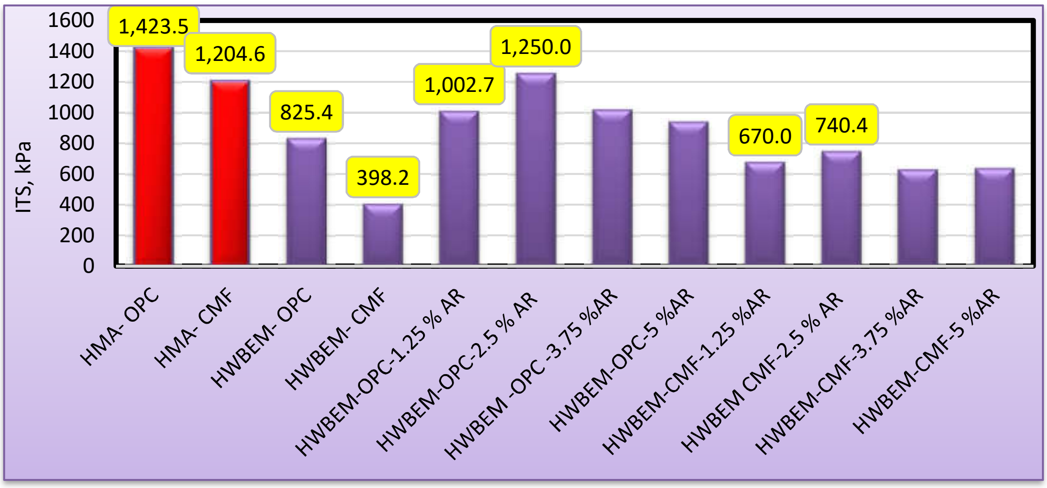


Figure 5-14 ITS of HWBEM versus AR Polymer Content

(a) HWEBM comprising OPC – AR polymer

(b) HWEBM comprising CMF – AR polymer

Plate 5-1 Cracking pattern of specimens for modified CBEM s by acrylic polymer

Table 5-2 Percentages Change in Indirect Tensile Strength (∆ITS) Relative to Reference Mixture

Reference Mixture	**HWBEM – OPC-0.00% AR**	**HWBEM – OPC-1.25% AR**	**HWBEM – OPC-2.50 % AR**	**HWBEM – OPC-3.75 % AR**	**HWBEM – OPC-5.00 % AR**
	∆ ITS				
HMA	-31.5	-16.8	3.8	-16.1	-22.8
HWBEM -CMF	107.3	151.8	213.9	153.7	133.5
HWBEM -OPC	0	21.5	51.4	22.4	12.7
Reference Mixture	**HWBEM – CMF -0.00% AR**	**HWBEM – CMF -1.25% AR**	**HWBEM – CMF – 2.5 % AR**	**HWBEM – CMF – 3.75 % AR**	**HWBEM – CMF – 5 % AR**
	∆ ITS				
HMA	-66.9	-44.4	-38.5	-48.5	-47.6
HWBEM -CMF	0	68.3	85.9	55.9	58.4

5.3.3.3 Creep Compliance Test

The creep compliance values for HWBEM with OPC or HWBEM with CMF at 0°C reached an optimum value at 1.25% AR, as can be seen in Figures (5-15, and 5-16). However, the continuous increase of AR polymer causes an increase in creep compliance. This could be because addition optimum AR polymer facilitates the best cross-linking, while further increase leads to decrease the bitumen binder in the interface as explained previously. Figure (5-17) demonstrates the creep stiffness for 100 sec at 0°C. As an expansion of effect, modifiers as OPC and AR on conventional HWBEM reach significant characteristics in contrast with conventional HMA, as explicates in Table (5-3).

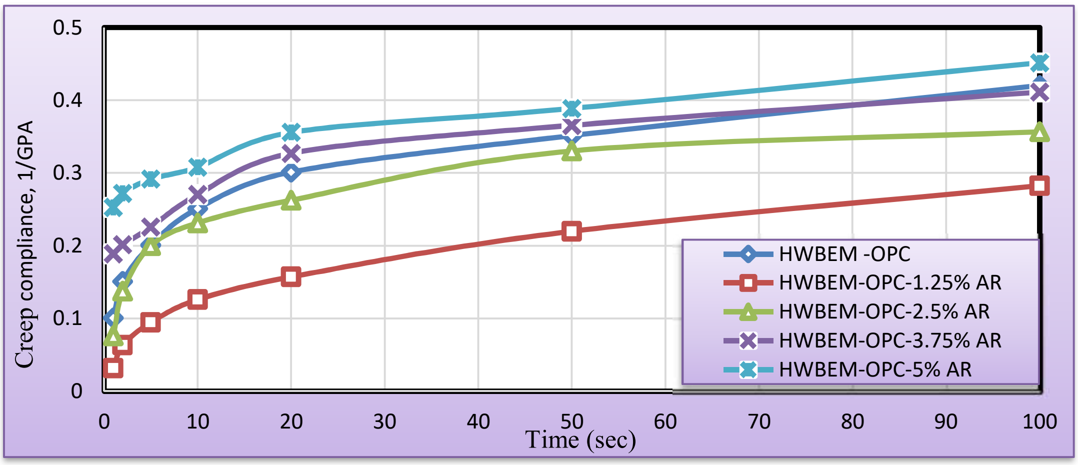


Figure 5-15 Creep Compliance for HWBEM-OPC-AR at 0°C

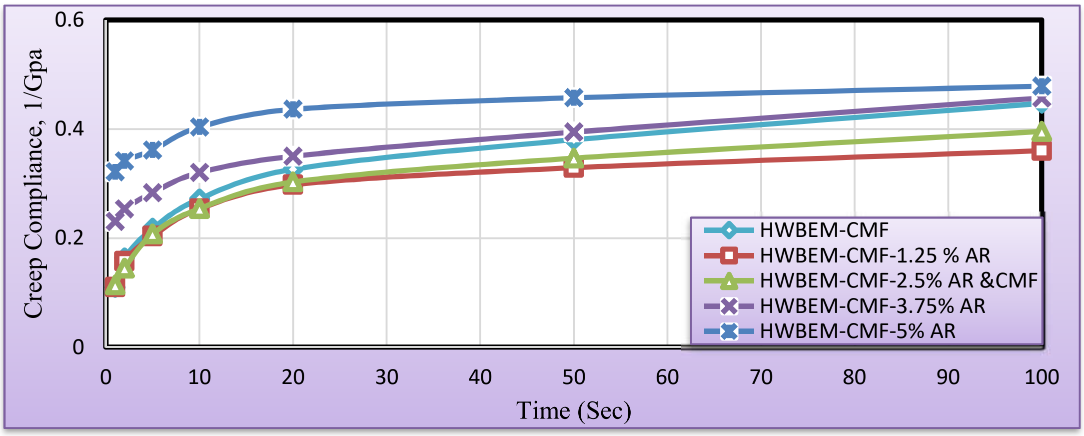


Figure 5-16 Creep Compliance for HWBEM – CMF-AR at 0°C

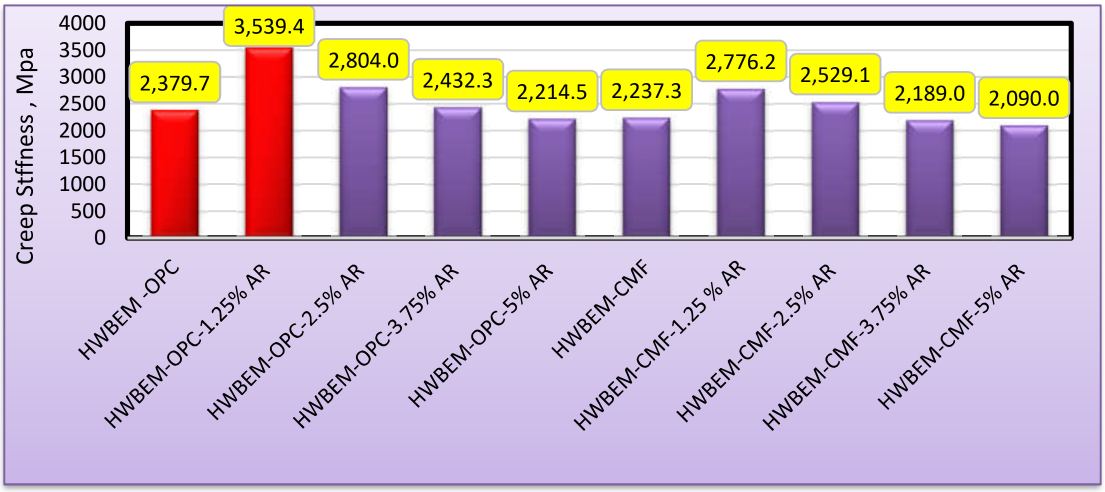


Figure 5-17 Creep Stiffness of Modified HWBEM for 0°C at 100 sec

Table 5-3 Percentages Change in Creep Compliance (ΔD) and Creep Stiffness (ΔC) Relative to Reference Mixture

Reference Mixture	**HWBEM–OPC -0.00% AR**		**HWBEM –OPC-1.25% AR**		**HWBEM–OPC -2.50 % AR**		**HWBEM–OPC -3.75 % AR**		**HWBEM–OPC-5.00 % AR**	
	ΔD	**ΔC**	**ΔD**	**ΔC**	**ΔD**	**ΔC**	**ΔD**	**ΔC**	**ΔD**	**ΔC**
HMA	-28.7	40.2	-52.0	108.5	-39.4	65.1	-30.2	43.3	-23.3	30.4
HWBEM-CMF	-6.0	6.4	-36.8	58.2	-20.2	25.3	-8.0	8.7	1.0	-1.0
HWBEM-OPC	0	0	-32.8	48.7	-15.1	17.8	-2.2	2.2	7.5	-6.9
Reference Mixture	**HWBEM–CMF -0.00% AR**		**HWBEM–CMF -1.25% AR**		**HWBEM–CMF -2.50 % AR**		**HWBEM –CMF -3.75 % AR**		**HWBEM–CMF -5.00 % AR**	
	ΔD	**ΔC**	**ΔD**	**ΔC**	**ΔD**	**ΔC**	**ΔD**	**ΔC**	**ΔD**	**ΔC**
HMA	-24.1	31.8	-38.8	63.5	-32.9	49.0	-22.4	28.9	-18.8	23.1
HWBEM-CMF	0	0	-19.4	24.1	-11.5	13.0	2.2	-2.2	7.0	-6.6

5.3.3.4 Wheel Track Test

The results demonstrated that the optimum value of the rutting resistance for modified HWBEM with OPC and HWBEM with CMF by AR polymer at 1.25% too, as can be seen in Figure (5-18, 19). The same interoperation for creep compliance can be adopted here for the improvement in resistance of permanent deformation. As an effect, modifiers as OPC and AR on conventional HWBEM catch an improvement level in WTT significantly comparative to conventional HMA, as can be explicated in Table (5-4). Dynamic stability of HWBEM with OPC and 1.25% AR is high than each of conventional HMA and HWBEM and control HWBEM by about 2233%, 1233 and 300 %, as demonstrate in Figure (5-20).

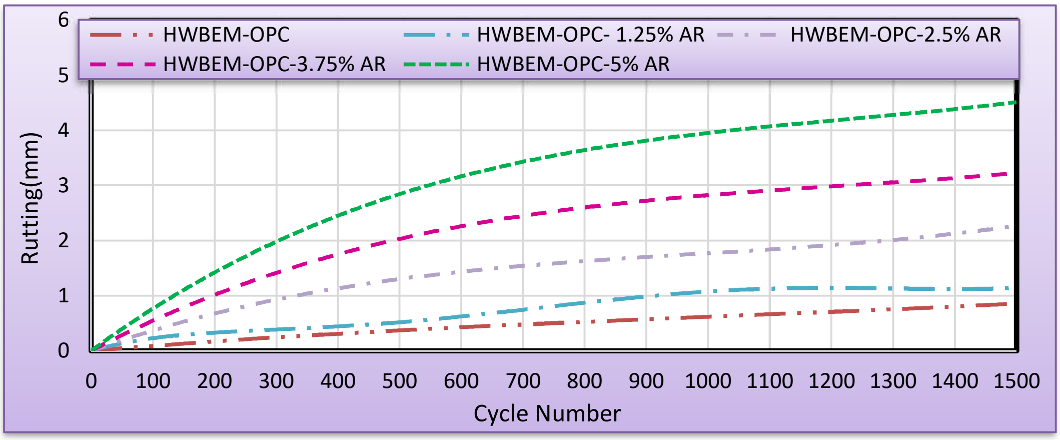


Figure 5-18 Rutting versus Cycle Number for HWBEM-OPC-AR

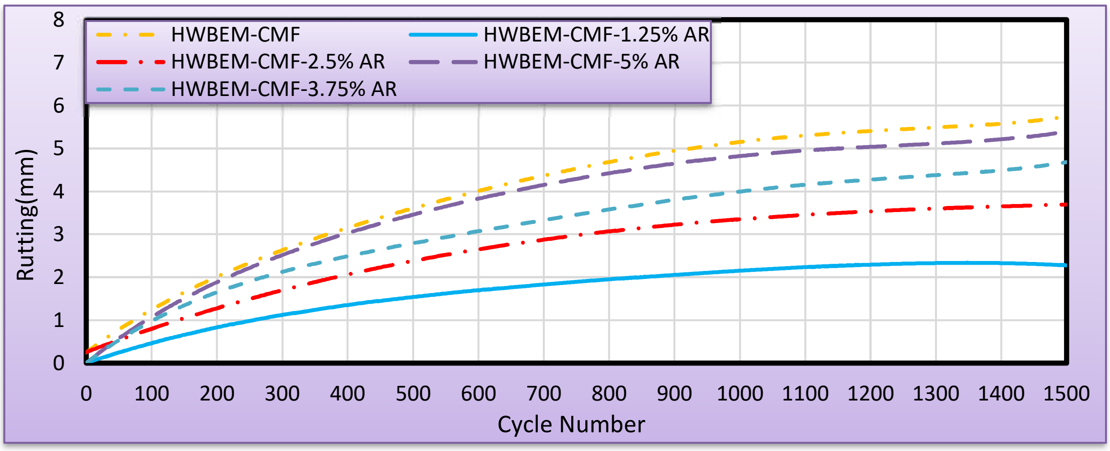


Figure 5-19 Rutting versus Cycle Number for HWBEM-CMF –AR

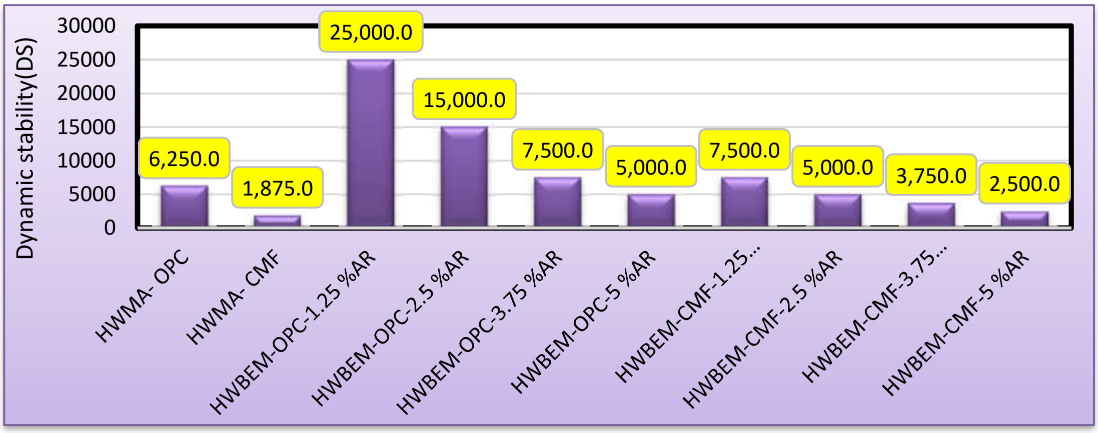


Figure 5-20 Creep Stiffness for HWBEM Comprising AR Polymer

Table 5-4 Percentages Change in Rutting Depth (ΔRD) and Dynamic Stability (ΔDS) Relative to Reference Mixture

Reference Mixture	**HWBEM – OPC-0.00% AR**		**HWBEM – OPC-1.25% AR**		**HWBEM – OPC-2.50 % AR**		**HWBEM – OPC-3.75 % AR**		**HWBEM – OPC-5.00 % AR**	
	Δ RD	**Δ DS**	**Δ RD**	**Δ DS**	**Δ RD**	**Δ DS**	**Δ RD**	**Δ DS**	**Δ RD**	**Δ DS**
HMA	-83.7	483.3	-80.8	2233.4	-62.5	1300.0	-45.8	600.0	-25.0	366.7
HWBEM -CMF	-83.1	233.3	-80.2	1233.3	-61.2	700.0	-44.0	300.0	-22.4	166.7
HWBEM -OPC	0	0	17.3	300.0	129.6	140.0	231.6	20.0	359.2	-20.0
Reference Mixture	**HWBEM - CMF-0.00 % AR**		**HWBEM – CMF -1.25% AR**		**HWBEM – CMF -2.5 % AR**		**HWBEM – CMF -3.75 % AR**		**HWBEM – CMF -5 % AR**	
	ΔRD	**Δ DS**	**ΔRD**	**Δ DS**	**ΔRD**	**Δ DS**	**ΔRD**	**Δ DS**	**Δ RD**	**Δ DS**
HMA	-3.3	75.0	-61.7	600.0	-36.7	366.7	-25.0	250.0	-13.3	133.3
HWBEM -CMF	0	0	-60.3	300.0	-34.5	166.7	-22.4	100.0	-10.3	33.3

5.3.4 Durability

Water damage test (represented by RMSR) for HWBEM with CMF and HWBEM with OPC was achieved to identify the ability of HWBEM to resist the water damage. The results demonstrated that the optimum percentage of addition AR polymer for HWBEM was 1.25% for the two type of fillers, as demonstrates in Figure (5-21). Whereas, the water damage resistance for HWBEM with OPC was more than HWBEM with CMF because addition OPC acts as a secondary binder as mentioned previouslly. On the other hand, water damage resistance for HWBEM with OPC and AR was higher than HWBEM with CMF because the addition of AR polymer facilitates cross-linking to the binder and prevents stripping or better water damage resistance. However, characteristics of modified HWBEM with OPC and HWBEM with CMF by AR polymer compared with each of conventional HMA and HWBEM and control HWBEM is explicated in Table (5-5). It is worth to mention that the RMSR values of HWBEM with OPC exceeded the level of 100%, which is significant marks of the validity of OPC, AR polymer, and heating all together in improving CBEMs.

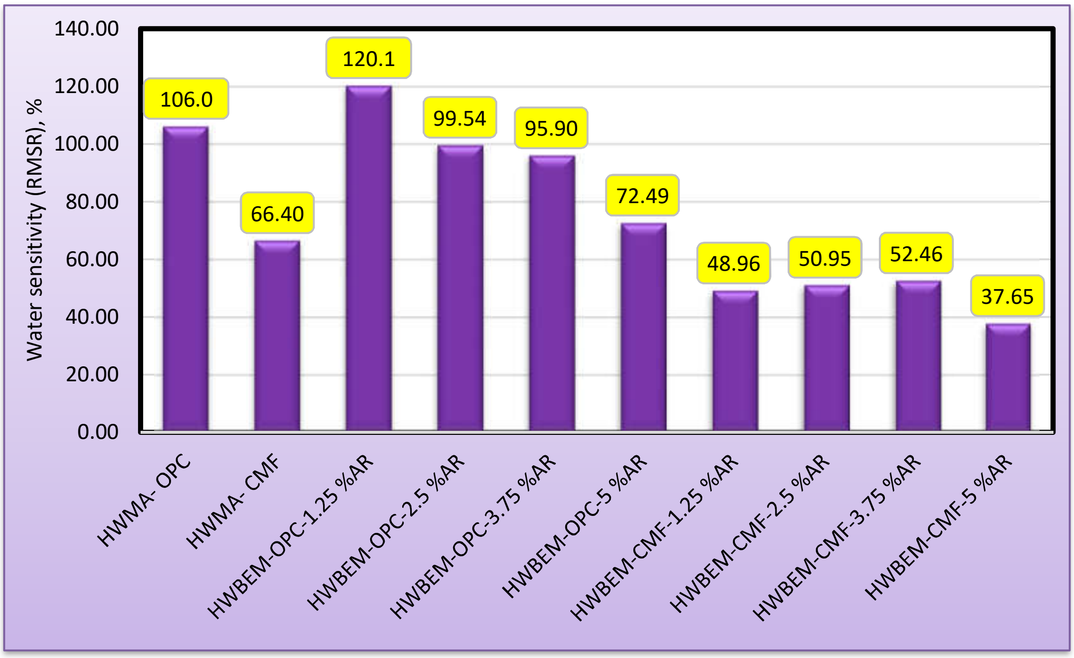


Figure 5-21 RMSR for Unmodified and Modified HWBEM

Table 5-5 Percentages Change in RMSR (Δ RMSR) Relative to Reference Mixture

Reference Mixture	**HWBEM – OPC-0.00 % AR**	**HWBEM – OPC-1.25% AR**	**HWBEM – OPC-2.50 % AR**	**HWBEM – OPC-3.75 % AR**	**HWBEM – OPC-5.00% AR**
	ΔRMSR				
HMA	107.1	134.7	94.4	87.3	41.6
HWBEM -CMF	59.7	80.9	49.9	44.4	9.2
HWBEM -OPC	0	13.3	-6.1	-9.6	-31.6
Reference Mixture	**HWBEM – CMF -0% AR**	**HWBEM – CMF -1.25% AR**	**HWBEM – CMF -2.5 % AR**	**HWBEM – CMF -3.75 % AR**	**HWBEM – CMF -5 % AR**
	ΔRMSR				
HMA	29.7	-4.4	-0.5	2.5	-26.5
HWBEM -CMF	0	-26.263	-23.3	-21.0	-43.3

5.4 Summary of the Whole Results Development Stages for CBEMs

The summary of the results is acted to simplify the comparison process of the obtained results in this research work due to the modification by AR polymer as explicating below.

5.4.1 Volumetric Properties

The volumetric properties include density, air void, VMA, and VFB of the modified and HMA, which are explicated below in Figures (5-22, 23, 24, and 25) to compare each other.

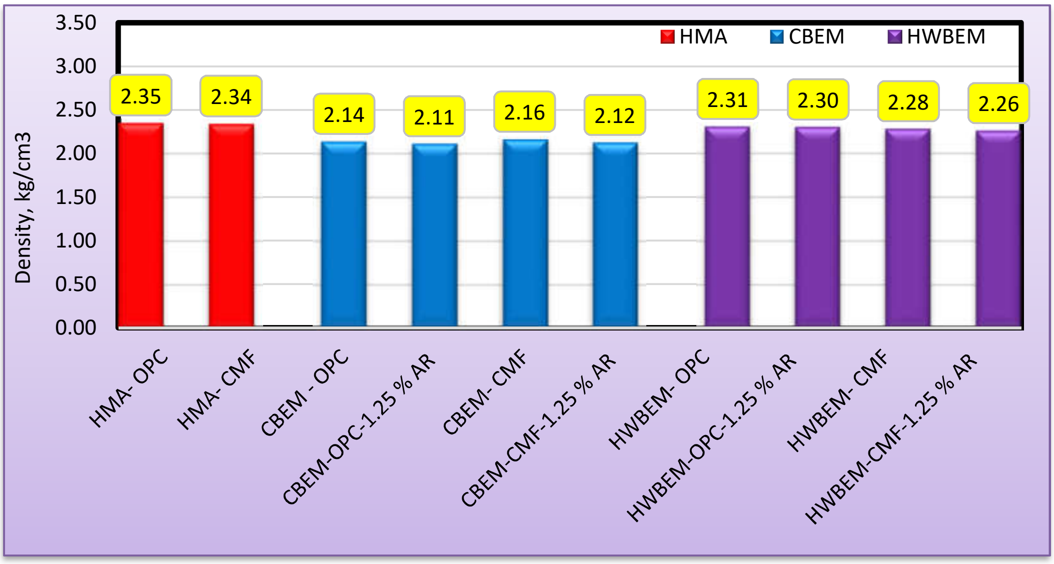


Figure 5-22 Density for All Mixtures at Optimum Percentage

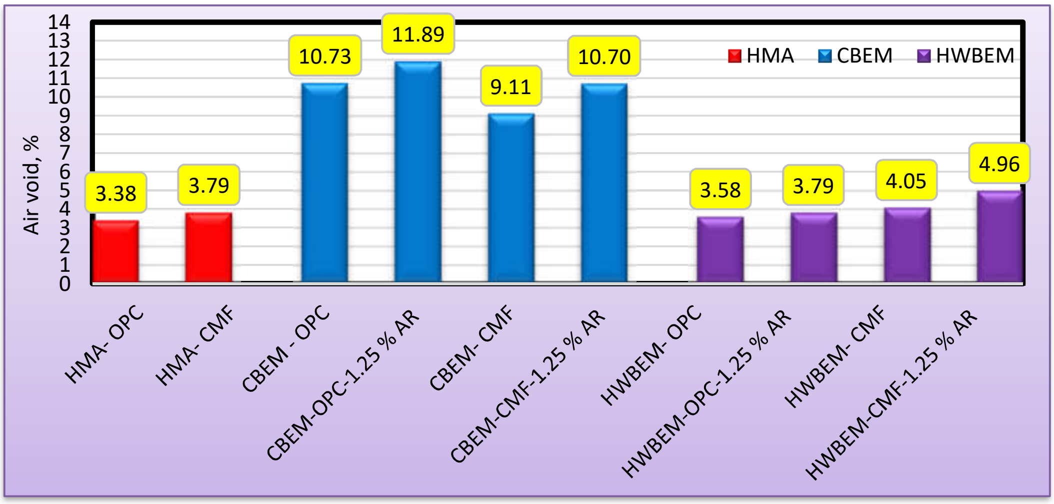


Figure 5-23 Air Void for All Mixtures at Optimum Percentage

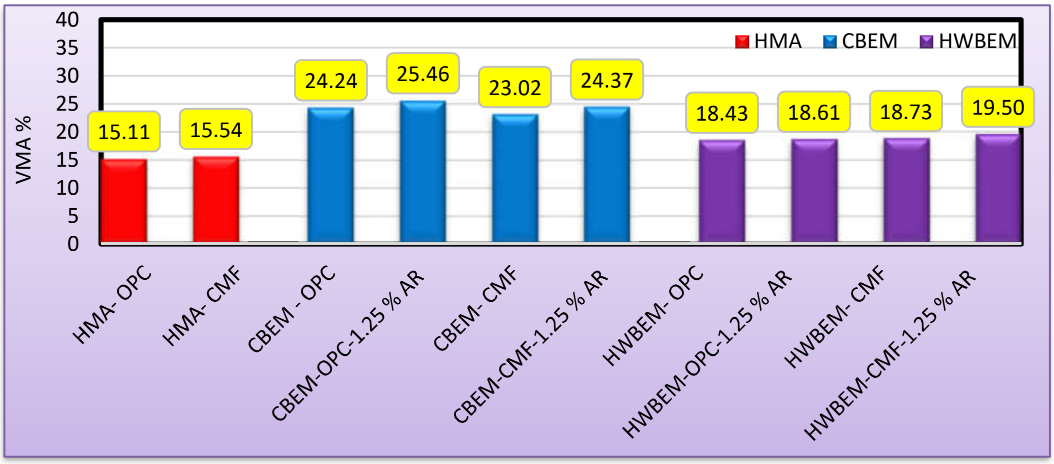


Figure 5-24 V.M.A for All Mixtures at Optimum Percentage

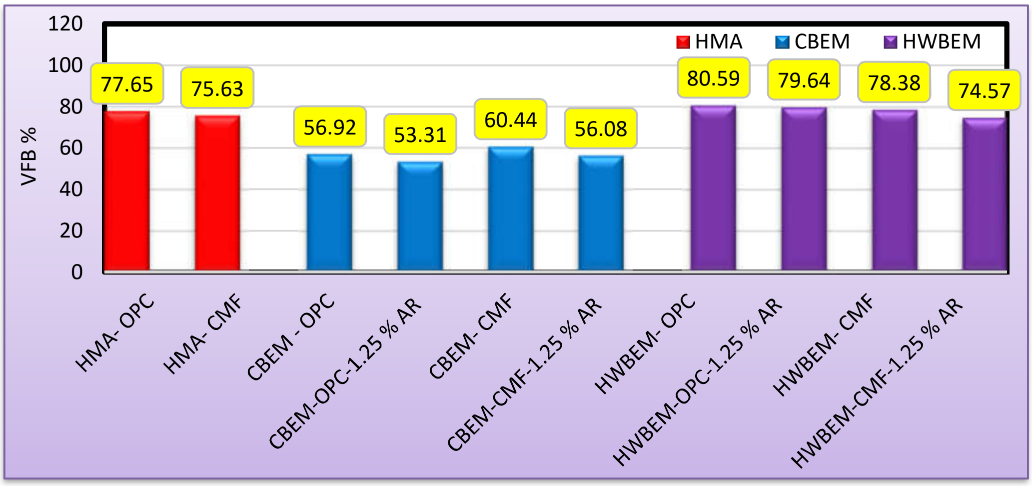


Figure 5-25 V.M.A for All Mixtures at Optimum Percentage

5.4.2 Mechanical properties

5.4.2.1 Marshall Test

Marshall and flow stability that obtained from this test are explained in Figures (5-26, 27) respectively for the modified and unmodified CBEMs and HMA at the optimum percentage.

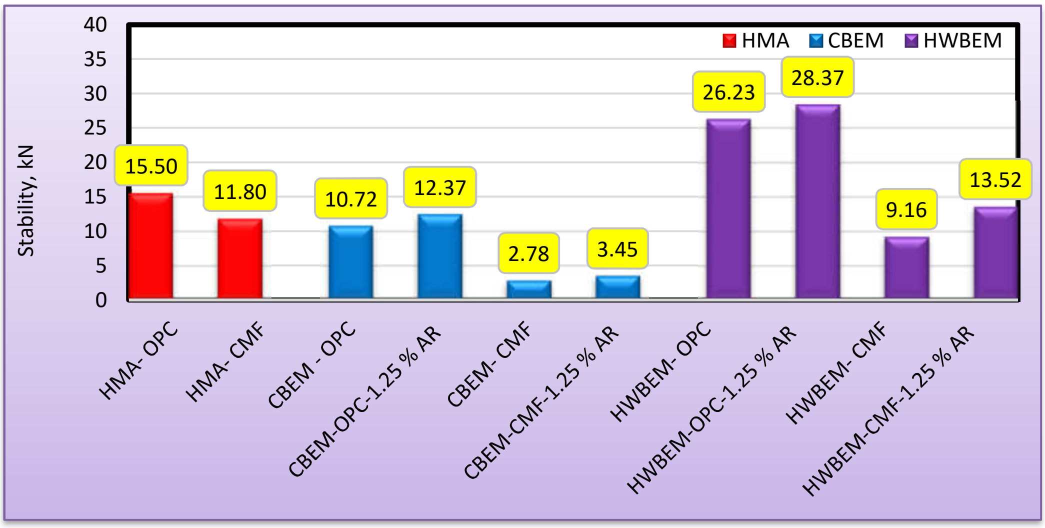


Figure 5-26 Stability for All Mixtures at Optimum Percentage

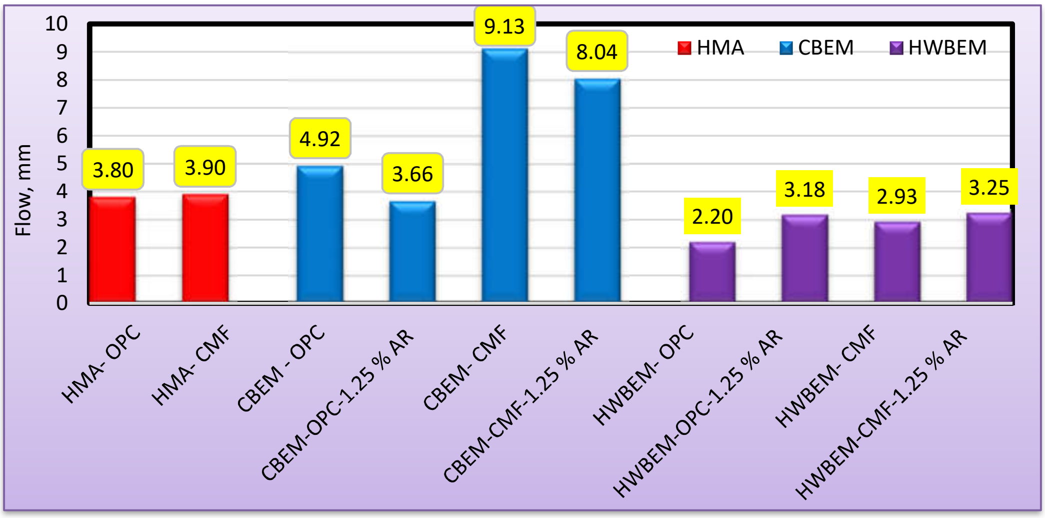


Figure 5-27 Flow for All Mixtures at Optimum Percentage

5.4.2.2 Indirect tensile strength ITS

Results of tensile strength for the modified and unmodified CBEMs at the optimum percentage is shown in Figure (5-28).

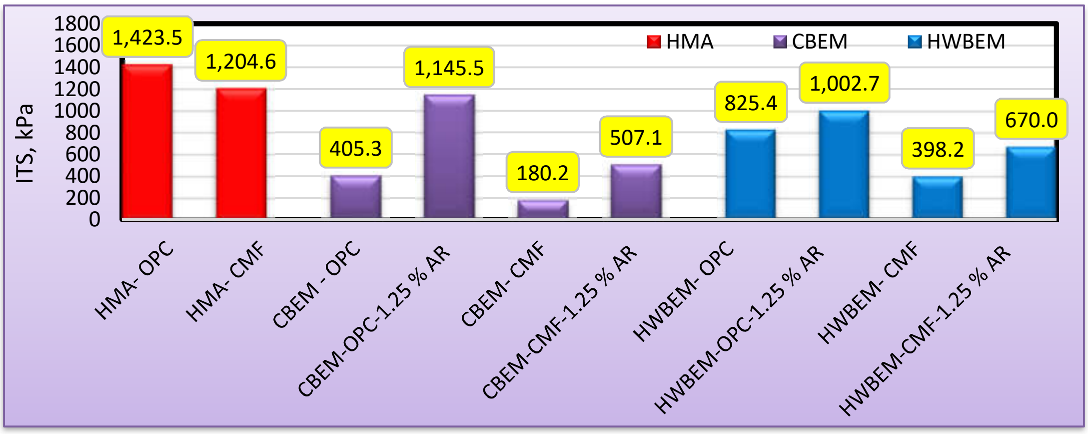


Figure 5-28 ITS for All Mixtures at Optimum Percentage

5.4.2.3 Creep Compliance Test

Creep compliance values and Creep stiffness for the modified and unmodified CBEMs and HMA at the optimum percentage is explicated in Figure and (5-30), respectively.

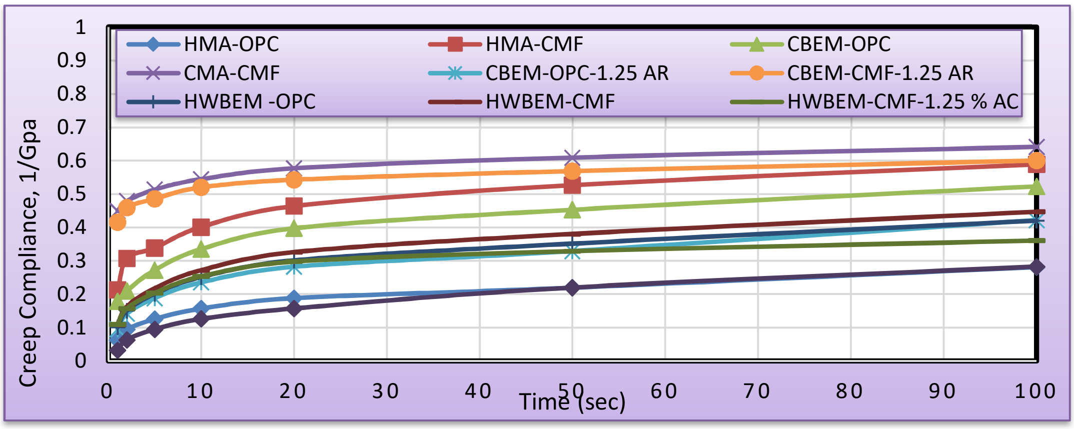


Figure 5-29 Creep Compliance for All Mixtures at Optimum Percentage

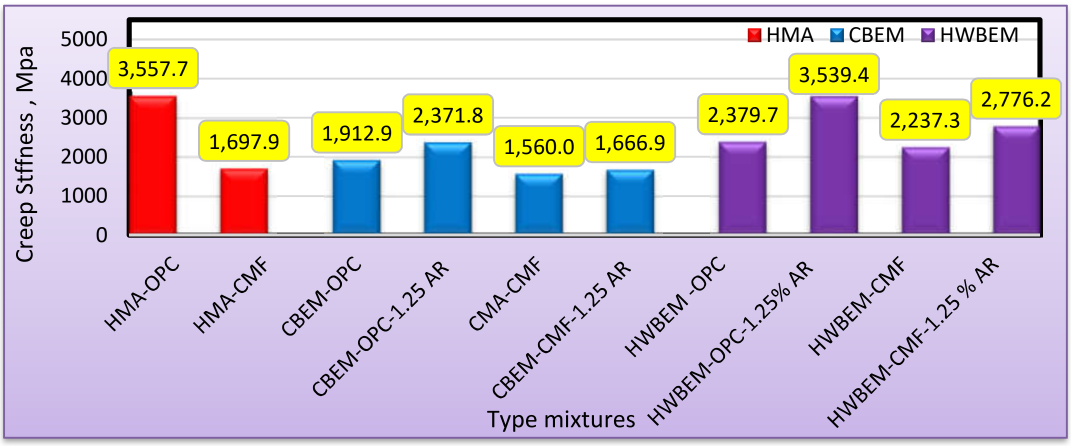


Figure 5-30 Creep Stiffness for All Mixtures at Optimum Percentage

5.4.2.4 Wheel Track Test

Rutting depth values with cycle number for the modified and unmodified CBEMs and HMA with the optimum values are illustrated in Figure (5-31). The dynamic stability values can be seen in Figure (5-32).

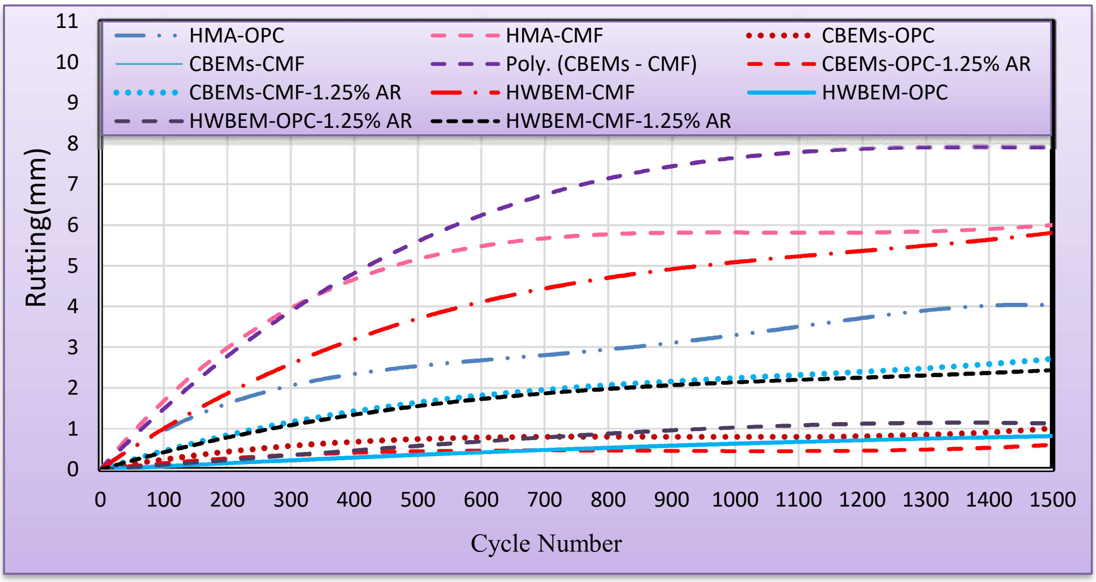


Figure 5-31 Rutting versus Cycle Number for All Mixtures at Optimum Percentage

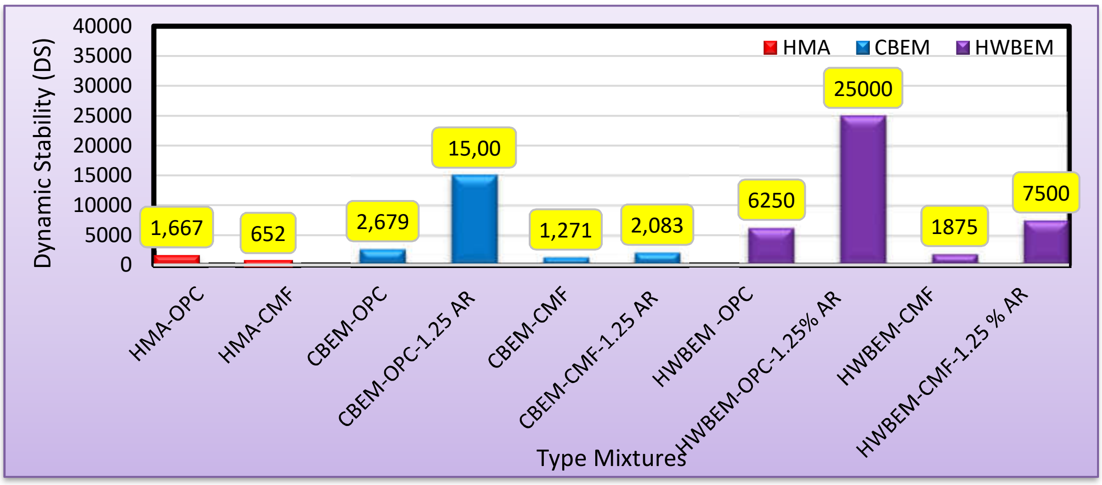


Figure 5-32 Dynamic Stability for All Mixtures at Optimum Percentage

5.4.3 Durability Test

The water damage values (represented by RMSR) were utilized to evaluate the durability test for the modified and unmodified CBEMs, HWBEM and HMA with the optimum values percentage are explicated in Figure (5-33).

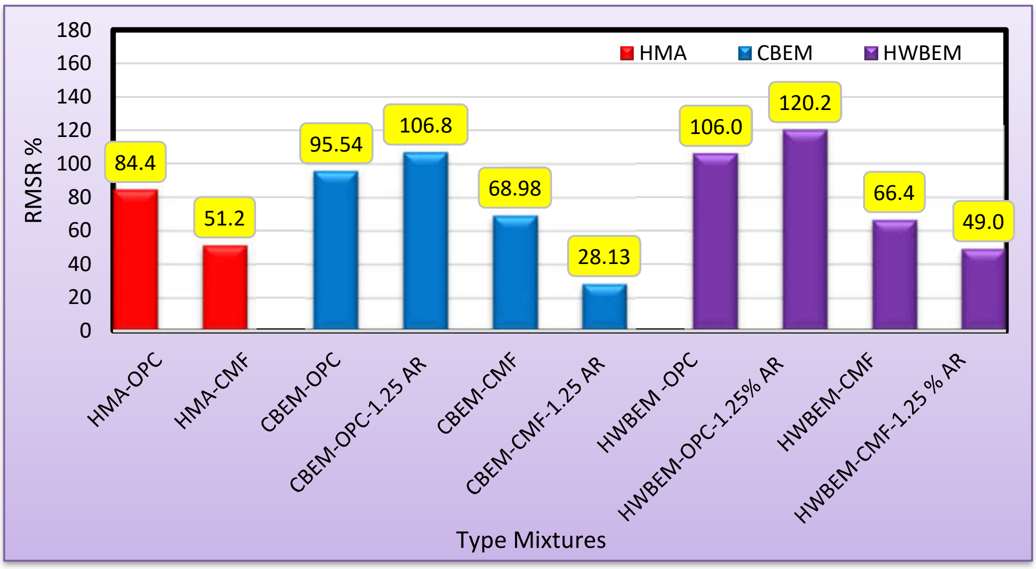


Figure 5-33 RMSR for All Mixtures at Optimum Percentage

5.5 Summary

This chapter included the testing results of the pre–compaction heating treatment as described above for CBEMs comprising CMF or AR polymer, or AR polymer with OPC. The results can be summarized as follow:

1. The optimum heating temperature for gaining the best improvement for the new mixture is about 90 °C. Therefore, the new mix could be called as Half Warm Bitumen Emulsion Mixture (HWBEM)
2. The heating of CBEM facilitates a significant improvement in the volumetric properties of HWBEM, without significant inferiority in the mechanical and durability of the mixes. Almost, all significant improvements are recorded according to the new technique.
3. The modified HWBEM by OPC and 1,25% AR polymer showed the best characteristic, even better than conventional HMA in some characteristics as Marshall stability, creep compliance and durability properties (represented by RMSR) by 140,52 and 135, respectively. Also, this percentage demonstrate same air void content of conventional HMA.

Chapter Six

Conclusions, Recommendations and Future Work

6.1 Introduction

This research study focused on achieving possible investigations for evaluation the performance of CBEM comprising AR polymer with additional treatment for further improvement.

6.2 Conclusions

According to the achieved research works, the main conclusions for this research are listed below.

1. Utilizing ordinary Portland cement (OPC) as filler in CBEM demonstrates significant positive effect on mechanical as Marshall stability, creep compliance, rutting resistance, and durability properties (represented by RMSR) comparable with conventional CBEM 285,125,18,88 and 39%, respectively, but does not improvements volumetric characteristics. This effect of OPC because it is an effective adhesive and acts as a secondary binder.
2. AR polymer can add further improvement to CBEM-OPC. Experimental lab works reveal that the optimum percentage of AR polymer for modified was 1.25% by weight of residual asphalt. This percentage caused the maximum expected increase in Marshall Stability, creep compliance, rutting resistance, and water damage resistance (represented by RMSR) by 5, 28,90 and 109%, respectively. But no significant improvement for the volumetric characteristics can be achieved by introducing AR polymer.
3. The introduction of AR polymer to CBEM-CMF offers some improvement but to un comparative level in contrast to HMA.
4. Pre-compaction treatment by low energy heating technique introduce new mix type called Half Warm Bitumen Emulsion Mixture (HWBEM), as the new mix prepare at a temperature under (100 °C).
5. Pre-compaction heating offers a significant improvement to volumetric properties of the HWBEM whereas their levels reach to comparative values to HMA, of

course no inferiority in mechanical or durability recognized due to new treatment. HWBEM-OPC demonstrate significantly improve in Marshall Stability, creep compliance, rutting resistance, and water damage resistance (represented by RMSR) by 122,29,84 and 107%, respectively.

6. The gathering of OPC, 1.25% AR polymer and Pre-compaction heating introduce new era asphalt mixtures, which could be better than HMA in terms of volumetric, mechanical and durability properties. This new technology demonstrates improve in Marshall Stability, creep compliance and water damage resistance (represented by RMSR) by 140,52 and 135, respectively comparable with conventional HMA.

6.3 Recommendations

The new asphalt technology that obtained from this research study can be compared to conventional paving mixtures (HMA) in many respects as performance (represented by mechanical, volumetric and durability characteristic, economic and environmental aspects. Consequently, this mixture is suggested to use with the following

1. Encouraging the concerned municipal directories to Activate utilized the new asphalt technique as alternative to HMA in surfaced (wearing) layer or on less for surface treatments of flexible pavement, or for the maintenance of highway pavement.
2. Move from lab scale to real highway trail section investigation for discovering the conditioning of such mix to field scale.
3. Encouraging the standard directorates to start an intensive program to prepare a specification of such new mixture.

6.4 Further work

Based on laboratory experiments obtained during this research, a number of possible future studies can be recommended, as listed below:

1. Evaluating effect of AR polymer on other properties as the fatigue and thermal cracking, which not achieved due to un availability of testing devices.
2. Utilizing suitable software to analysis induced stresses for the new mixes that demonstrate scope effect of AR polymer in increased the resistance to various forms of traffic-induced stress.

3. Trying to utilize this polymer with other fillers than OPC and CMF such as fillers produced from waste biomass and by-product materials to solve problem the high air void for CBEMs, wherever biomass materials may absorbed the water that focused between aggregate particles and the film binder.
4. Trying other polymer types to optimizing the best practices of such polymers.

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الخلاصة

في الاونة الاخيرة زاد استخدام الخلطه الاسفلتية الحاره وذلك لتغطية الاحتياج السنوي المتزايد لانشاء الطرق الحديثة في مشاريع البنى التحتية .على الرغم من أن الخلطه الاسفلتية الحاره تملك وبشكل واضح أداء هندسي ملائم ، إلا أن تأثيرها السلبي على البيئة شجع الباحثين في البحث عن تقنيات أخرى مثل الخلطة الاسفلتية الباردة والخلطة الاسفلتيه الدافئة كبديل ناجح . ركزت هذه الرسالة على تطوير خلطات المستحلب البتيوميني الباردة كنوع من الخلطة الاسفلتية الباردة المحسنة بإضافة الأكريليك بوليمر.

تضمن البرنامج التجريبي مرحلتين؛ المرحلة الأولى هي تقييم خصائص الأداء لخلطات المستحلب البتيوميني الباردة ذات الرابط الاسفلتي المحسن بواسطة الأكريليك بوليمرمع نوعين من الفلرالأسمنت البورتلاندي الاعتيادي والفلر العادي بواسطة عدة فحوصات (على سبيل المثال، اختبار مارشال، قوة الشد غير المباشرة، وزحف الامتثال ، مسار العجلة ، والأضرار الناجمة عن تأثيرالمياه . استخدم الأكريليك بوليمرفي النسب المئوية من 1.25، 2.5، 3.75 و 5 من البيتيومين المتبقي . تحسينات الخواص الحجمية، والميكانيكية، والديمومة فحصت لمثل هذا الاستخدام . في حين أن المرحلة الثانية تضمنت تقييم تأثير التسخين بالطاقة المنخفضة (تحت 100درجة مئوية) عن طريق تقنية الميكروويف على خلطات المستحلب البيتيومين الباردة المتقدمة كمحاولة لتحسين الخصواص الحجمية لخلطات المستحلب البيتيومين الباردة ، دون آثار سلبية على الخواص الميكانيكية والديمومة.

بينت نتائج المرحلة الأولى أن خلطات المستحلب البيتيومين الباردة مع ٪ 1.25 اكريليك بوليمر من البيتيومين المتبقي تقدم أعلى؛ ثبات، قوة الشد غير المباشرة، وصلابة زحف عالية ومقاومة والأضرار الناجمة عن المياه .أيضا، مقاومة التخدد (ممثلة بتقدم عمق التخدد) لخلطات المستحلب البيتيومين الباردة مع الأسمنت البورتلاندي العادي و٪ 1.25 اكريليك ، تكون متزايدة بنسبة ٪ 90 و٪ 93 مقارنة مع الخلطه الاسفلتية الحاره التقليدية وخلطات المستحلب البيتيومين الباردة المتضمنة الفلر العادي و٪ 1.25 اكريليك بوليمر ، على التوالي .وعلاوة على ذلك، خواص الديمومة (ممثلة بأضرار المياه) تكون متزايدة بنسبة٪ 109 و ٪55 مقارنة مع الخلطه الاسفلتية الحاره التقليدية وخلطات المستحلب البيتيومين الباردة المتضمنة للفلر العادي، على التوالي. على الرغم من تحقيق التحسينات في الخصواص الميكانيكية والديمومة، مشكلة محتوى الفجوات الهوائية العالي لخلطات المستحلب البيتيومين الباردة المتضمنة الأسمنت البورتلاندي العادي و٪ 1.25 اكريليك بوليمر تكون مستمرة مع وجود البوليمر.

في المرحلة الثانية من العمل، تم تطوير خلطات المستحلب البيتيومين الباردة بواسط المعالجة الحرارية قبل الرص بواسطة تقنية الميكروويف، وتدعى خلطة المستحلب البيتيومين نصف دافئ. نجحت هذه التقنية في تقليل محتوى الفجوات الهوائية لخلطة المستحلب البيتيومين نصف دافئ المتضمنة الأسمنت البورتلاندي العادي و٪ 1.25اكريليك بوليمر و بنسبة ٪ 6 بالمقارنة مع خلطة المستحلب البيتيومين نصف دافئ المتضمنة الفلر العادي و٪ 1.25اكريليك بوليمر ، في حين أنه أظهرت تقريبا نفس محتوى الفجوات الهوائية للخلطه الاسفلتية الحاره التقليدية .من ناحية أخرى، أظهرت هذا الخلطة تحسينات كبيرة لمقاومة التخدد وخواص الديمومة . مقاومة التخدد لخلطة المستحلب البيتيومين

نصف دافئ المتضمنة الأسمنت البورتلاندي العادي و٪ 1.25 اكريليك بوليمر بنسبة٪ 81 و٪ 80 بالمقارنة مع الخلطه الاسفلتية الحاره التقليدية و خلطة المستحلب البيتيومين نصف دافئ المتضمنة الفلر العادي و ٪ 1.25 اكريليك بوليمر ،على التوالي .وعلاوة على ذلك، خواص الديمومة تزداد نسبة ٪ 135 و٪ 81 مقارنة مع الخلطه الاسفلتية الحاره التقليدية و خلطة المستحلب البيتيومين نصف دافئ ، على التوالي.

وأخيرا، يمكن الاستنتاج أن خلطة المستحلب البيتيومين نصف دافئ المعدلة مع الأسمنت البورتلاندي العادي و٪ 1.25 اكريليك بوليمر يمكن اعتبارها بديل حيوي مستدام للخلطه الاسفلتية الحاره التقليدية في الطبقة السطحية للطريق لمشاريع البنى التحتية من الطرق السريعة ذات الاحمال الخفيفة والعالية . وتكتسب فوائد عديدة في فقرة؛ صديقة للبيئة، فعالية التكلفة، وأقل استهلاك الطاقة.

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كلية الهندسة
قسم الهندسة المدنية

تقييم الخلطات الأسفلتية الحاوية على البوليمر

رسالــــــــــة
مقدمة إلى كلية الهندسة في جامعة كربلاء
وهي جزء من متطلبات نيل درجة ماجستير في هندسة البنى التحتية
من قبل :
منى فاضل عبد الاميرعباس الخفاجي
(بكالوريوس علوم في الهندسة المدنية 2014)

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