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Enhancement of Cold Mix Asphalt Using Local Waste Materials for Binder Layer Pavement

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 Infrastructure Engineering

By

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بسمِ ٱللهِ ٱلرَّحمَنِ ٱلرَّحِيمِ

قَالُوا سُبْحَانَكَ لَا عِلْمَ لَنَا إِلَّا مَا عَلَّمْتَنَا ۖ إِنَّكَ أَنْتَ الْعَلِيمُ الْحَكِيمُ

صدق الله العلي العظيم

سورة البقرة الآية ﴿٣٢﴾

ABSTRACT

Increasing world’s automobiles every year lead to increase the demand for roads; therefore, lengths of roads around the world are extending. Asphalt concrete is form more than 90% of the transportation infrastructures, with the majority of these being built using Hot Mix Asphalt (HMA) technology. Then, Warm Mix Asphalt (WMA) and Cold Mix Asphalt (CMA) technologies are appeared, as they are still under development and need more investigation before they are proven as alternatives to HMA. Cold Bituminous Emulsion Mixtures (CBEMs) offer advantages over traditional HMA due to the fact that their uses are: more environmentally friendly, cost effectiveness, save energy, safe production and easy for construction processes, therefore the use of these mixtures is increased. On the other hand, its properties may be low when compared with HMA as low earlier strength and low resistance to water damage.

Previous studies reported that the mechanical properties of CBEMs were stated to be influenced by different issues including base bitumen grade, porosity of the mix, curing time and additives such as Ordinary Portland Cement (OPC). The current research was intended to use waste of biomass and by-product materials as a filler and/or activator principally to enhance the conventional CBEMs early age strength, and enhance durability. Therefore, Palm Leaf Ash (PLA) and Cement Kiln Dust (CKD) were selected to improve the properties of CBEMs. Within the new cold mix preparation process, the waste materials and the activating materials are chemically reacting with the traditional cold mixture components to produce new CBEMs.

Conventional mineral filler portion in the CBEM was replaced to the biomass waste or by-product materials, with percentages ranging from 0-100%. PLA has been proven as a material for improving the mechanical properties of the CBEMs as replacement 25% of OPC by PLA, even over. Also, replacement 75% of OPC by PLA has been proven as acceptable mechanical and durability properties when compared with other mixtures. In addition, CKD can be used as a filler by replacing 25% of OPC to gain acceptable mechanical and durability properties of the CBEMs. Additionally, collective fillers by incorporate CKD and PLA together with OPC were accessed attempt to replacement a valuable percentage of OPC by waste and by-product materials.

The results obtained from this research work appear to open up a new era of CBEMs, those results are based completely on sustainable techniques; at the same time such mixtures offer unique alternatives to hot mixtures, in both light and heavily trafficked road and highway pavements as binder layer.

SUPERVISOR CERTIFICATE

We certify that this dissertation entitled "Enhancement of Cold Mix Asphalt Using Local Waste Materials for Binder Layer Pavement" which is prepared by "Sajjad Bahjet Ahmed Al-Merzah" under our supervision at 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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Certificate of the Examining Committee

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This thesis is dedicated to:

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

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Sajjad Bahjet Ahmed Al-Merzah

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ABBREVIATIONS/ACRONYMS

AG	Ageing
A-3	Material consisting of sands deficient in coarse material and soil binder
AASHTO	American Association of State Highway and Transportation Officials
ANOVA	Analysis of Variance
A–PVAC	Asphalt–Polyvinyl Acetate
ASTM	American Society for Testing and Materials
BE	Asphalt emulsion
BEMs	Asphalt emulsion Mixtures
C	Constant
CBEMs	Cold Asphalt emulsion Mixtures
CCM	Conventional Cold Mix
CHA	Coconut Husk Ash
CKD	Cement Kiln Dust
CMA	Cold Mix Asphalt
CMF	Conventional Minerall Filler
CMS	Cationic Medium- Setting
CS	Creep stiffness
e	Residual
EVA	Ethylene Vinyl Acetate
FA	Fly Ash
GSBR	General Specification for Roads and Bridges
HMA	Hot Mix Asphalt
HWMA	Half Warm Mix Asphalt
IEC	Initial Emulsion Content
IRBC	Initial Residual Bitumen Content
ITS	Indirect Tensile Strength
ITS	Indirect tensile strength
LL	Liquid Limit
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MF	Marshall flow
MPW-Indonesia	Ministry of Public Work Republic of Indonesia
MS	Marshall stability
MS_E	Mean Square of Residual
MS_R	Mean Square of Regression
NA	Not Available
ND	Not detected
OICA	Organization International Des Constructers Automobile
OPA	Oil Palm Ash
OPC	Ordinary Portland Cement
OPWwc	Optimum Pre-Wetting Water Content
ORBC	Optimum Residual Bitumen Content
OTLC	Optimum Total Liquid Content at Compaction

PFA	Pulverized Fuel Ash
PI	Plasticity Index
PLA	Palm Leaf Ash
PVAC-E	Polyvinyl Acetate Emulsion
R^2	Coefficient of Determination
RAP	Reclaimed Asphalt Pavement
RBC	Residual Bitumen Content
RHA	Rice Husk Ash
RMSE	Root Mean Square Error
RSC	Rapid Setting Cement
SBS	Styrene Butadiene-Styrene
SEM	Scanning Electron Microscopy
SHRP	Strategic Highway Research Program
SP	Sand Poor
SPSS	Statistical Product and Service Solutions
SS_E	Residual Sum of Squares
SS_R	Regression Sum of Squares
SS_T	Total of Sum Squares
TLC	Total Liquid Content
TSR	Tensile Strength Ratio
UAPA	European Asphalt Pavement Association
USCS	Unified Soil Classification System
V	Version
VFA	Voids Filled with Asphalt
VFA	Void Filled with Asphalt
VMA	Voids in Mineral Aggregate
WMA	Warm Mix Asphalt
XRF	X-Ray Fluorescence

Chapter 1

INTRODUCTION

1.1 Background

Increasing world's automobiles every year lead to increase the demand for roads, therefore lengths of roads around the world are extending. The automobiles had been increasing for several years, this is clear from the records of International Organization of Motor Vehicle Manufacturers, (French: Organisation Internationale des Constructeurs d'Automobiles), (OICA) (OICA, 2016); as in 2010 the number of cars is about (77,583,519), whereas in 2015 is about (90,780,583) cars. Accordingly, the total production of asphalts according to European Asphalt Pavement Association, (UAPA) (EAPA, 2014a) statistics are touched (265) million tons, meanwhile asphalt industry represents an interesting figure in the current days.

Many technologies have been used to construction pavement, namely, Hot Mix Asphalt, (HMA), Warm Mix Asphalt, (WMA), and Cold Mix Asphalt, (CMA). HMA is still representing vital technology in terms of high performance, but environmental impacts and high cost are associated to such technology.

Sustainability matter of pavement construction has encouraged other technologies, such as (WMA) and (CMA). WMA and CMA are beginning to spread word wide in many countries. Whereas, CMA in contrast is taking a large area of interest according its promising sustainable and cost issues.

1.2 What is a CMA

Cold mix asphalt is a composite of aggregates and hydrocarbon binder (asphalt emulsion or cutback asphalt) which are mixed at ambient temperature. It can be produced in traditional asphalt plant, or by mobile in situ plant, with ability to store longer than HMA. Additionally, it is used normally with different gradations (open, close, or dense grade aggregates), whereas, aggregates can be blended within mixture without drying. Moreover, different aggregate sources (virgin aggregate and reclaimed asphalt pavement (RAP)) can be used.

1.3 Advantages and Disadvantages of CMA

- **Advantages of CMA**

Many advantages can be stated for CMA, such as

- Energy Consumption of CMA is compartivley lower than HMA, where HMA needs dry materials before introducing binder. Also, to ensure accaptable binder coating, aggregate and binder should be heated to certain elevated tempreature, that means HMA needs more power generators and electric.
- Emissions during production and laying in the CMA are noticably lower than other mixing technologies because of little consumption of fuel.
- Healthy, because of low emmision, less machinery, less noise and fuel needed for construction pavement of CMA less than HMA.
- Safety, CMA technology is more safety as no heating for materials is required during preparation process.
- Environmental awareness, CMA is an environmentally friendly product from what is mentioned above. Additionally, reclaimed aggregate can be used in the asphalt mixture.
- Transportation, there is high opprtunity to prepare CMA in site, accoringly less transportation is needed. Also, when the mixture is produced in plant, CMA has long deliver span in contrast to HMA, due to the limitation of drop in tempreature for HMA. whereas CMA keeps its activity for a long time; asphalt emulsion mixture can be stored or stockpile before using and compaction.

- **Disadvantages of CMA**

Unfortunately, some disadvantages are associated with CMA technology, such as:

- Low strength at early time of paving because of trapped water that rest between aggregate and binder film.
- Long curing time to get high strength.
- High air void content.
- Materials must be wetted before mixing emulsion for coating purpose.

1.4 Statement of the Problem

CMA is a promising technology which can be used for paving, although it is environmental friendly, but traditional CMA engineering characteristics still invaluable in contrast to traditionally HMA. CMA still new technology that need further laboratory and field evaluatation for more performance development in terms of mechanically , durability and volumetrically properties.

There are many steps must be considered for CMA development

1. Enhancement the current design procedure for CMA to enhance its performance and ensure the overcome or equal engineering properties to traditional HMA.
2. high moisture content; water content in asphalt emulsion and wetted aggregate results in low strength at the earlier time of paving, therefor it must be removed rapidly.
3. CMA offers high air void content compared with HMA.
4. introducing susatainable and high performance material to develop CMA for more valuable mechanical, durability and volumetric perfarmance.

However, the last area of resarch was adopted in this reseach attempt, on the hope that other points will disclose and cover by other researchers and highway research agenceis.

1.5 Aim and Objectives

The main aim of this research work is to develop new CMA using available local materials. To reach to this aim, the following objectives has been planned:

- Evaluating the traditional CMA performance in terms of mechanical and volumetrical properties, and comparing such performance with traditional HMA.
- Further Evaluating traditional CMA durability in terms of water sensitivity and ageing performance.
- Enhancing CMA performance by replacing conventional inert mineral filler with other fillers.
  - Evaluating the introduction of Ordinary Portland Cement (OPC) in local produced CMA.
  - Evaluating the addition of by-product material(Cement Kiln Dust (CKD) as a supplementary cement materials.
  - Evaluating the addition of waste material (Palm Leaf Ash (PLA)) as a supplementary cement material.
- Predicting the behaviour of the material's strength by modelling the strength properties to added filler type.

1.6 Dissertation layout

Chapter 1	states the background, research problem statement, research objectives, scope of research works, and structure of this dissertation.
Chapter 2	includes the review of asphalt emulsion and its manufacture, classification, curing and breaking CMA in general. Also, improving CMA, and methods of CMA design.
Chapter 3	presents the properties of materials used in this study, Cold mix design method that followed within this study. Also, research methodology is presented.
Chapter 4	displays analysis and results of the traditional and developed CMA
Chapter 5	Demonstrate the main conclusions, and recommendations for future works.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Everything travels, whether it be to work, play, workshop, do trade, or simply visit people. All foods and materials must be carried from their place of origin to that of their consumption and manufacturing; goods must be transported to the marketplace and to the consumer. People travelling and goods relocating:

- by road, by walking and riding, using humans and various beasts to carry goods or to pull sleds, carts, carriages and wagons, and (since the late 19th century) using cycles and motor vehicles such as cars, buses and lorries.
- by water, using (since early times) ships and boats on seas, rivers and canals.
- by rail, initially using animals (in the early 19th century) and then steam, oil or electric-powered locomotives to pull passenger carriages and goods wagons.
- by air, using airships and aeroplanes (in the 20th century) (O'Flaherty, 2002).

However, transportation facility are developing continuously to accommodate the need for travel. Whereas, the development in highway pavement is in high demand, as it represents one of the important transportation facilities. The increasing number of automobiles are clear illustrated in Figure (2-1) according to statistics of (OICA) (OICA, 2016). These increment in automobiles is associated with increase in the total production of asphalts, as example, according to statistics of (UAPA) (EAPA, 2014a); at recent years statistics shown that more than (265) million tons produce each year, as can be shown in Figure (2-2). Thus, this shows the need for continuing development in mix technology to follow up the huge continuing demand for transportation.

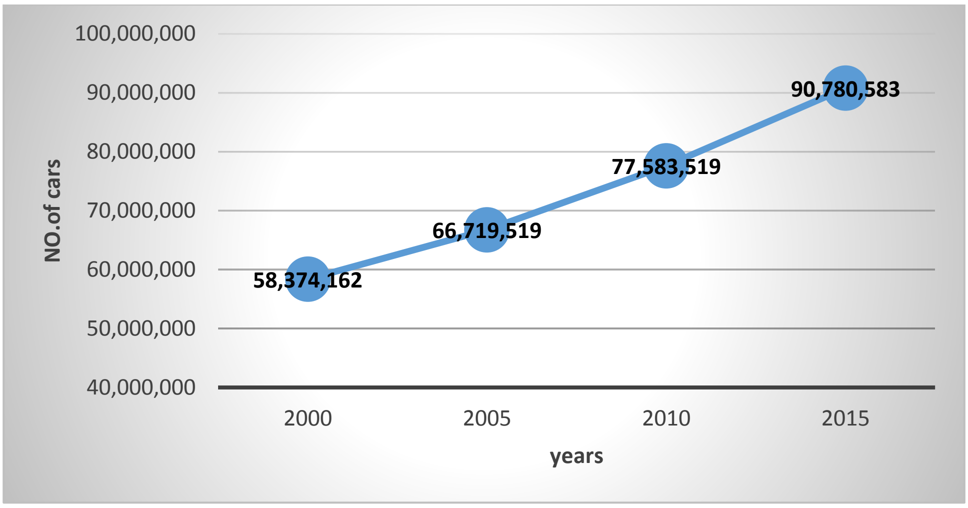


Figure 2-1 NO. of cars through the recent years (OICA, 2016)

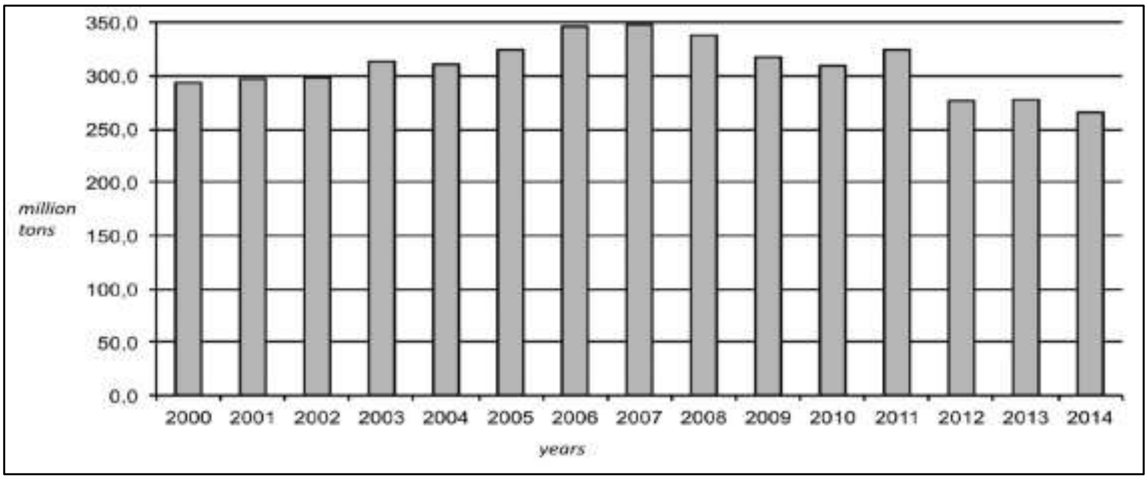


Figure 2-2 Asphalt production in the recent years (EAPA, 2014a)

2.2 Pavement technology

2.2.1 Road Construction Development

Historically, Roads developed with time through significant evolution of the nations around the world, below are the main highlights of these evolutions:

- The invention of the wheel, and the development of the axle that linked two wheels in Mesopotamia in about (5000 BC) (O'Flaherty, 2002) is the first stage of highlight for roads' need.
- The Chinese contributed in improvement of Silk Route, which is amongst the best-known roads about (2600 BC), Persian Empire also helped from this way through its lands for trade between China and Europe.

- In Europe, roads were built using log-rafts in about (2500 BC); such roads have been discovered in Britain.
- Mesopotamia and Egypt civilizations movements within the Middle East and forward. Early construction of roads were stone-paved about (4000 BC) in the Middle East, Where, Syrian troops constructed new roads through the mountains of northern Mesopotamia.
- In England about (3300 BC) the corduroy-log paths were constructed.
- In India (3000 BC) brick paving was spreading .
- In the cities of Nineveh and Babylon streets paved in asphalt, and brick also have been found.
- To construct the pyramids, the Egyptians built roads to cary the required stone (Kendrick et al., 2004).
- In fact, the Romans must be given credit for being the first ‘professional’ road-makers. They started a huge network in (312 BC) , which was based on 29 major roads radiating from Rome to the outermost fringes of the Empire, with total 52964 miles (78000 km) (O'Flaherty, 2002). Three courses of road structure built by Romans were: levelled earth, gravelled surface, and paved stones, as can be shown in Figure (2-3).

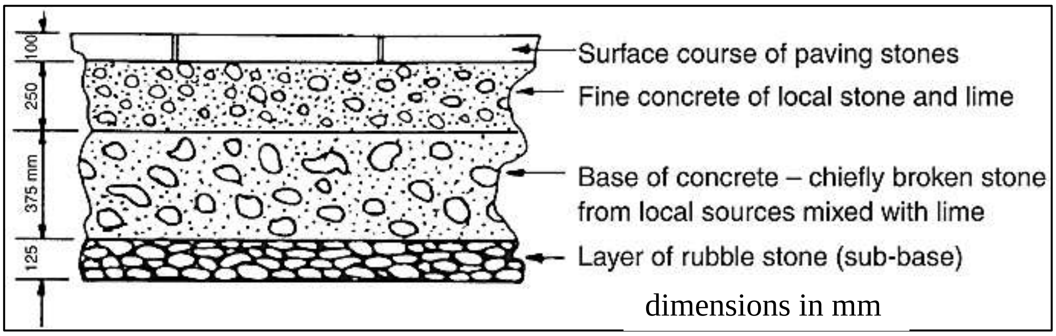


Figure 2-3 Roman road structure, (Kendrick et al., 2004).

Over later on centuries, the roads developed were slightly compatible with the development in coaches and other transportation devices, until the end of World War I when increasable interests of roads in the major impetus being given to commercial road transport, when many motor trucks became available for non-military usages (O'Flaherty, 2002). In 1930, the first conditions organized for road research in United Kingdom. After World War II, road technology appropriated huge steps to forward Momentous research programmes, which involved the improvement of distinctive trial tracks to study pavement materials, design and construction. Real research programs originated in the USA as a significance of this decision about 1950s (O'Flaherty, 2002). According to such programmes in the USA and worldwide, the pavement structure developed to accommodate the huge development in vehicle number, load and types.

2.2.2 Pavement Structures

Pavement structure consists of superimposed layers of processing materials above the natural soil (sub-grade), whose primary function is to distribute the applied vehicle loads over the sub-grade to ensure acceptable strain.

There are two types of road pavements which are generally recognized for this purpose, namely, flexible pavements rigid pavements, or it may be constructed as composite.

- **Flexible pavement**

Flexible pavements usually consist of bituminous surface underlain with a layer of granular material, then a layer of suitable mixture of coarse and fine materials. More than 90 % of roads formed flexible pavement in Europe and worldwide (NAPA and EAPA, 2011). Figure (2-4) shows typical flexible pavement.

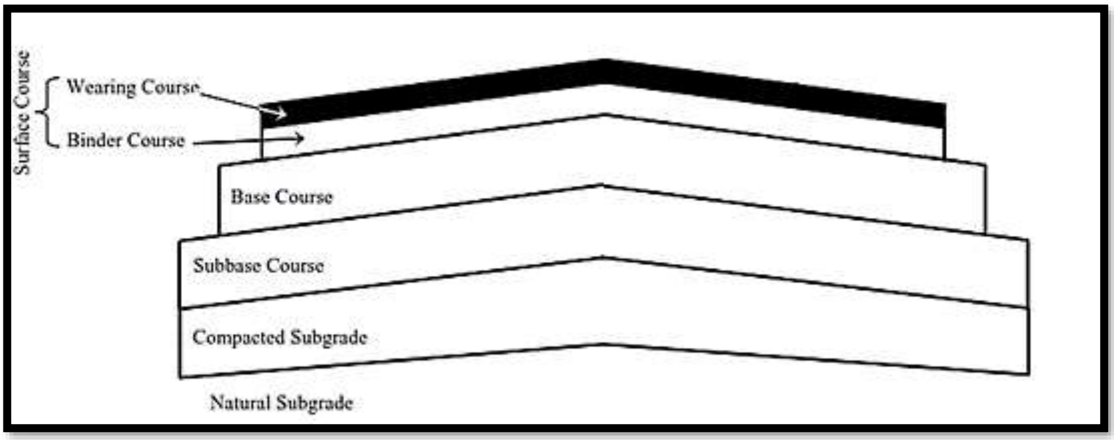


Figure 2-4 Typical cross section for flexible pavement type

- **Rigid pavement**

Rigid pavements are normally constructed of Portland cement concrete, and may or may not have a base course between the subgrade and the concrete surface. When a base course is used in rigid pavement construction, it is usually referred to as a subbase course. Typical rigid pavement is shown in Figure (2-5).

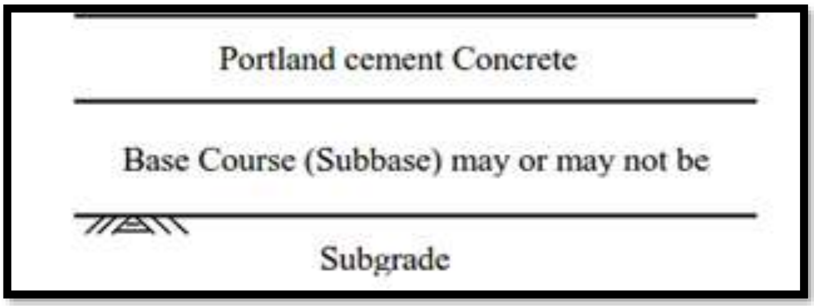


Figure 2-5 Typical cross section for rigid pavement type

- **Composite pavement**

Generally, for high performance highways, concrete course could overlay with bituminous layer to enhance ride quality in terms of noise; this is called composite pavement as it is shown in Figure (2-6). In some rare cases, concrete layer could conduct over existing flexible layer (Havens, 1966).

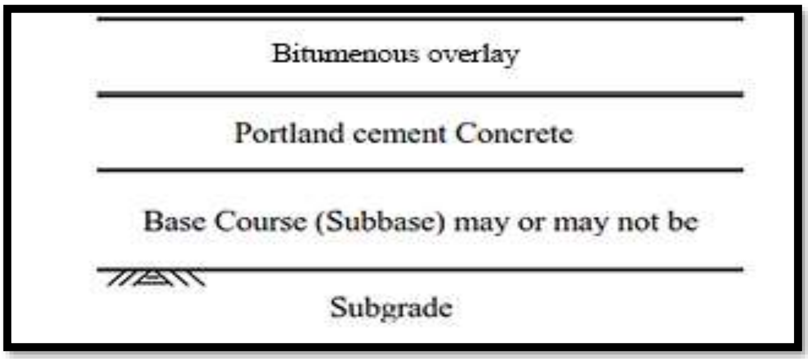


Figure 2-6 Typical cross section for composite pavement type.

2.2.3 Bitumen mixtures

Bituminous mixture is a blend of bituminous binder with aggregates and/or additives.

In highway construction, bituminous mixtures are used widely all over the world with aggregates and filler to construct pavements as defined in the previous section. The hydrocarbon bitumen is found in natural deposits or it is obtained as a product from the distillation of crude petroleum. Such materials showed high binding characteristics when introduced within bituminous mixtures in highway and airport pavement systems. However, there are many technologies used for paving roads using bitumen materials, namely, Hot Mix Asphalt (HMA), Warm Mix Asphalt (WMA), Half Warm Mix Asphalt (HWMA), and Cold Mix Asphalt (CMA)

2.2.3.1 HMA

It is a bitumen mixture achieved by adding hot bitumen to hot aggregate blend (coarse, fine, and filler) through certain preparing, mixing, laying, and compaction processes. High temperature between 140 to 180 °C needed within such processes (Kristjansdottir, 2006) and it may reach 250°C, according to the hardness grade of the bitumen being used, ensure dry aggregate, and ensure complete coating of aggregates with bitumen (NAPA and EAPA, 2011). Furthermore, the ambient temperature in the paving region is highly related to the selection of bitumen grade. Generally, the hard bitumen is suitable for hot climate regions and the soft bitumen is more suitable for cold regions. In other words, the bitumen mixture should be hard enough during hot seasons to prevent bleeding; at the same time, it should be relatively soft in cold seasons to prevent cracking. The hot material is transported to the site for laying in insulated wagons and must be laid and compacted, but before laying and compacting the mix's temperature must be within certain ranges to ensure effective compaction and the air void within limited range. After the compaction, the road could be opened to traffic as soon as the mixture cooled down to the ambient temperature. HMA paving process is shown in Figure (2-7)

Figure 2-7 HMA paving process.

2.2.3.2 WMA/HWMA

WMA is an asphalt concrete mixture which produced at temperatures of about 20˚C - 40˚C lower than those used in the production of conventional HMA; WMA is produced and mixed at temperatures roughly between 100 and 140 °C (EAPA, 2014b). It has at least the same properties as conventional HMA (Tutu, 2016). In order to lower temperature at mixing, it needs to reduce binder viscosity which should be sufficient for completing the aggregates coating. Thus, different techniques have been invented for gaining the required viscosity by low energy consumption. They are namely, water base, organic base, and chemical base (Rubio et al., 2012, EAPA, 2015). However, the early results stimulated researchers to develop a number of WMA technologies that mixtures could be mixed and compacted at considerably lower temperatures. They demonstrated its advantages for economically, environmentally purpose and saving energy (Rubio et al., 2012, EAPA, 2014b, Su et al., 2009, Needham, 1996). Also, it is anticipated that WMA will soon become the standard practice within the paving industry (Nicholls, 2013, Croteau, 2008).

HWMA is produced with heated aggregate at a mixing temperature between approximately 70 °C and roughly 100 °C (EAPA, 2014b). "Half-Warm Foamed Bitumen Treatment" was introduced by Jenkins et al. (Jenkins, 2000a). This process includes applying the foamed bitumen on heated aggregate of less than 100 ºC.

2.2.3.3 CMA

This mixture is produced by mixing aggregates with hydrocarbon binder, with or without additives. The aggregates can be coated with no drying or heating (Serfass, 2002). The hydrocarbon binder could be cutback, emulsified bitumen or foamed asphalt; because of risky and soil contamination effects of cutback, its use is limited according to the modern global regulations (Leech, 1994a). However, asphalt emulsion applications in the CMA is associated with no such worries.

The largest producer of asphalt emulsion is France in Western Europe, they used CMA applications since the 1960s (Read and Whiteoak, 2015), the United States was followed in the 1970s where bitumen emulsified used to stabilize paving mixtures (Chevron, 1977). The Asphalt Institute made different manuals relating to asphalt emulsion MS-19 (Asphalt Institute, 1979), CMA, MS-14(Asphalt Institute, 1989), and its thickness design, MS-1(Asphalt Institute, 1991). Generally, cold bituminous emulsion mixtures (CBEM) have recognized with noticeable benefits in terms of easiness in production and using, energy savings, and environmental friendliness (Al-Busaltan, 2012, D'Angelo et al., 2008): as they practically produce no gas emissions to the atmosphere during production, and other benefits as described thereinafter (Kristjansdottir, 2006).

2.2.3.4 Challenges to asphalt technologies

Until now, HMA occupies the main market of the pavement industry, globally (EAPA, 2014a), but its production associates with cost and environmental impacts; whereas high temperature, CO_2 emissions, and high energy consumption. Therefore, paving agencies, engineers and researchers have been beginning to develop more economically and environmentally friendly technologies than traditionally HMA. Techniques such as WMA and CMA have been developed to overcome the mentioned impacts of HMA. The following characteristics may indicate the most significant challenges in present asphalt technologies:

- **CO_2 emissions**

In fact, increasing asphalt mix preparation temperature brings increasing in CO_2 emissions, therefor the emission in HMA is more than other technologies, while the emissions of WMA is more than that of CMA. Bouteiller reported that each metric ton is associated with 21, 13, and 3 kg of CO_2 for HMA, WMA, and CMA, respectively (Bouteiller, 2010). As long as technology is of lower emissions; thus, it's a good alternative. Recent regulations restrict the emissions to the lowest level especially the emission due to industries.

- **Energy saving**

Figure (2-8) below shows the huge difference in energy consumption for HMA when compared with WMA and CMA; 11-35% saving in fuel could be achieved by WMA technology (D'Angelo et al., 2008), while another study designated the saving of WMA by 60 to 80% (Kristjansdottir, 2006). However, this saving is so far dissipated due to the requirements for plant modification. Of course, for CMA it is a 100% saving in burner fuel (Al-Busaltan, 2012).

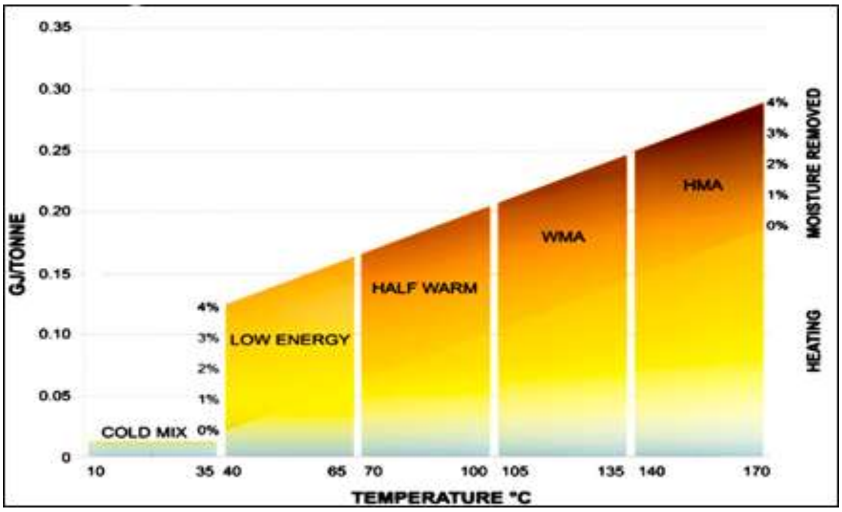


Figure 2-8 Energy consumption for each mixture technology(EAPA, 2014b).

- **Hauling distance and paving season**

Hauling distance and paving season signified a restriction on paving engineers, whereas high variances between cold season ambient temperatures and delivered HMA may cause dramatic drop in mixture temperature. But with WMA this restriction has been reduced (Rubio et al., 2012). Accordingly, this facilitates more hauling distances and lengthens the paving season (Goh et al., 2007). On the other side, CMA could offer greater characteristics where no significant difference to be seen between mix and ambient temperatures. Additionally CMA may remain workable for some days or weeks (Read and Whiteoak, 2015). Actually, hauling distance signifies no problem for CMA (Needham, 1996).

- **Using recycled and waste materials**

Reusing the recycled or waste materials brings high interest recently in the paving industry sector to achieve economic, environmental, and sustainable planned goals. For example, numerous advantages can be picked up by introducing Reclaimed Asphalt Pavement (RAP) into HMA (Al-Busaltan, 2012). Past studies suggested that the utilization of RAP can help with adjusting the ascent in initial expenses, support characteristic assets, and minimize sway on landfill (Aravind and Das, 2007, Karlsson and Isacsson, 2006, McDaniel et al., 2002). Moreover, the properties of RAP blends have been turned out to compare new asphalt concrete pavements (Al-Busaltan et al., 2012a). Research studies have shown the chance to incorporate 75% of RAP into WMA with comparable properties to virgin mixtures (Mallick et al., 2008).Simultaneously, RAP can be achieved in site, cold recycling has been developed and its validity has been provided worldwide (Bergeron, 2005). Also range of selected waste materials were also tested as partial and full replacement to the virgin mineral aggregates, including: Pulverized Fuel Ash (PFA), synthetic aggregates, crushed glass, steel slag, and crumb rubber (Thanaya, 2003).

- **Cost**

The initial cost to produce high performance WMA and CMA may be more in comparison to HMA although there is a lower energy consumption is required (Al-Busaltan, 2012). Also, limited experience of such mixes could add other costs. But, more development of WMA and CMA, and optimizing their performance could reduce their cost; thus, in the future could interchange HMA and meet the environmental and economic challenges (Al-Busaltan, 2012).

2.3 Asphalt emulsion

An emulsion is a dispersion of small droplets of one liquid in another liquid. Emulsions can be formed by any two immiscible liquids stabilized by an emulsifier. Asphalt emulsions were used in the early part of the 20th century (Salomon, 2006, Ebels and Jenkins, 2007). Various advantages recognised when bitumen emulation is applied in construction processes in contrast to other materials like save energy, easier handling and Storage (Low viscosity), safe, environmentally friendly, low-cost on-site and in-place techniques; therefore, the use of asphalt emulsion has increased significantly (Salomon, 2006).

In fact, low bitumen viscosity allows low temperature application; in contrast, asphalt emulsion dynamic viscosities are 0.5-10 poise at 60 ºC, where bitumen is (1-40)$x10^2$ poise at the same temperature (Salomon, 2006). The bitumen droplets range from 1 to 10 micron in diameter (REA, 2015). There is a spreading of particle sizes in the emulsion, and this distribution of the particle size of the emulsion droplets toughly effect the physical properties of the emulsion, such as viscosity and storage stability; bigger average particle size leads to lesser emulsion viscosity. The particle size distribution of asphalt emulsion is shown in Figure (2-9).

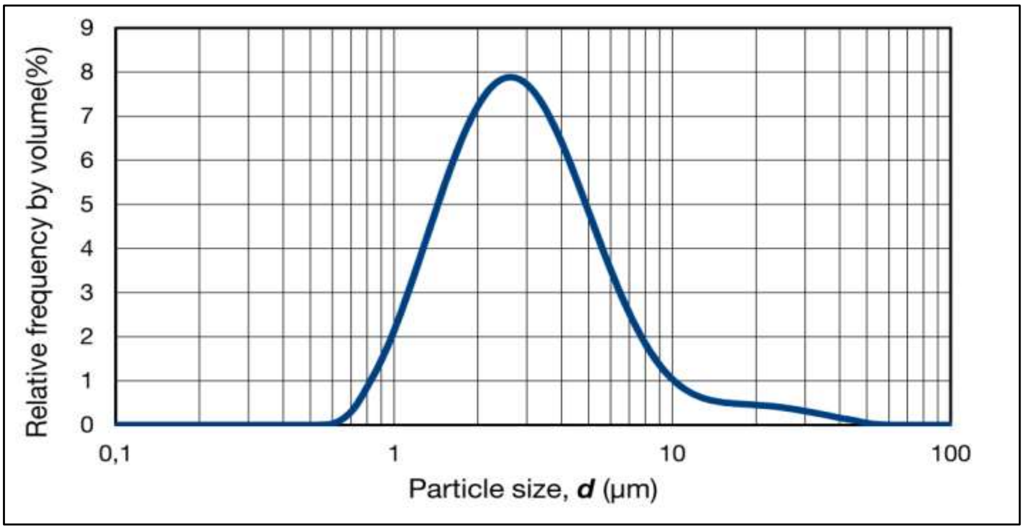
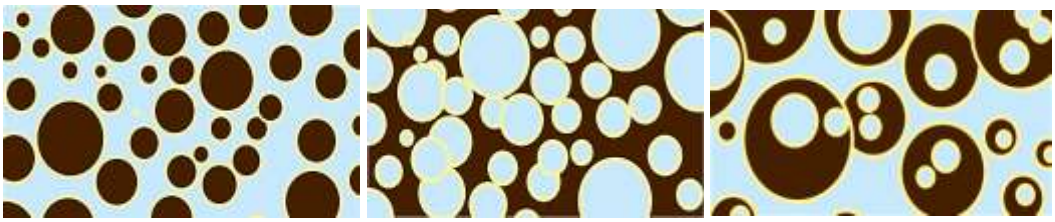


Figure 2-9 Typical particle size distribution of asphalt emulsion droplets(Miljković, 2014).

There are many formations of emulsion such as Oil-in-water (O/W), Water-in-oil (W/O), and Multiple phase emulsions. (O/W) emulsions are those in which the continuous phase is water, and the disappear phase is a water-insoluble 'oily' liquid. Whereas, (W/O) emulsions are those in which the continuous phase is an oil and the disperse phase water that may be called 'inverted emulsions'. Multiple phase emulsions can be shaped in which the spread droplets themselves contain smaller droplets of a third phase. Figure (2-10) shows the formation types of emulsion.

The emulsion is a chemically steadied system; all constituents contribute in the constancy of the system, whereas the system is components of continuous phases such as water, non-continuous phase such as asphalt (dispersed phase), and surfactant - emulsifying agent. Figure (2-11) below illustrates the percentage ranges of emulsion component, and Table (2-1) defines its component briefly (Read and Whiteoak, 2015).



(a) (b) (c)

Figure 2-10 Type of emulsions : (a)O/W emulsion, (b) W/O emulsion, and (c) Multiple emulsion (Kavussi and Modarres, 2010).

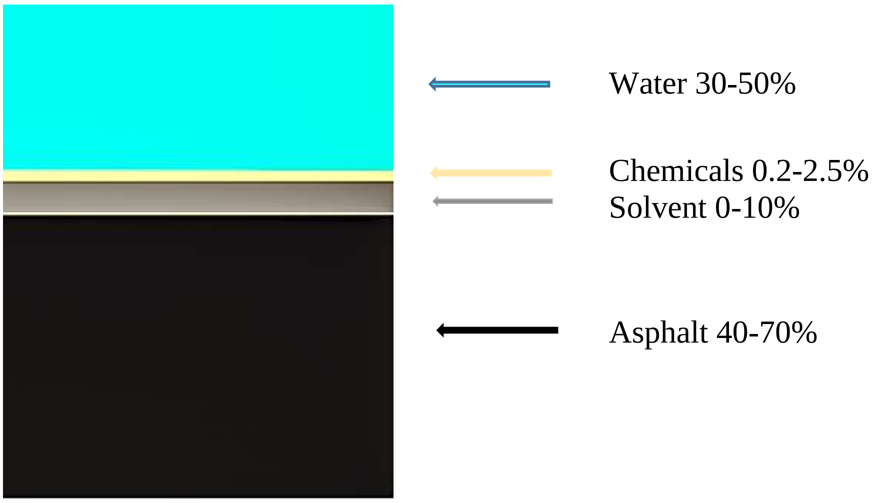


Figure 2-11 Asphalt Emulsion composition (Delmar Salomon, 2008).

Table 2-1 Emulsion components and their functions (Petrauskas and Ullah, 2015)

Bitumen	Commonly, bitumen is used as 180/200 pen grade; heavier grades such as 15/25 for special tack coats or 50/100 for micro surfacing or slurry seals
Solvent	Solvents may be involved with bitumen to develop emulsification to reduce settlement, curing rate at low temperatures, or to provide the right binder viscosity after curing.
Water	The water used must be contain a minimum amount of mineral and organic impurities
Adhesion promoters	They are used to adhere emulsion with aggregates; that the cured film from some anionic emulsions and sometimes also cationic emulsions.
Calcium chlorides and sodium chlorides	Calcium chloride or sodium chloride (anionic emulsions) are included (0.1–0.2%) to decrease the osmosis of water into the bitumen and to reduce changes in the viscosity

2.3.1 Classification of Asphalt emulsions

Asphalt emulsions can be divided into Four classes: cationic emulsions, anionic emulsions, non-ionic emulsions, and clay-stabilized emulsions. Generally, the first two are commonly used, especially in highway industries (Petrauskas and Ullah, 2015). The terms anionic and cationic stem from the electrical charges on the bitumen globules. The cationic emulsion is designated when an electrical potential is applied between two immersed electrodes in an emulsion containing positively charged particles of bitumen, they will migrate to the cathode, the emulsion then is described as cationic. But when the emulsion containing negative charged particles of bitumen, they will move to the anode, and the emulsion is described as anionic. When the bitumen particles in emulsion is not migrated to any pole, that means, the emulsion is neutral, and the emulsion is described as a non-ionic. This type is infrequently used in highway works. The last type, clay-stabilized emulsion is used in industrial purpose

(Read and Whiteoak, 2015). Figure (2-12) below illustrates cationic and anionic asphalt emulsions.

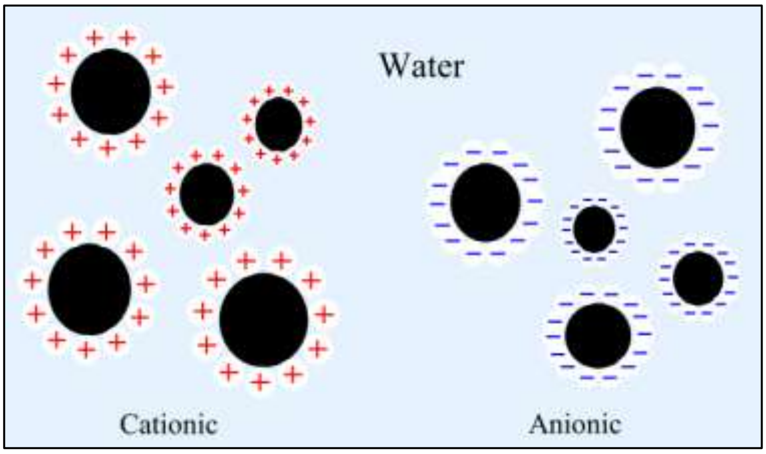


Figure 2-12 An illustration of cationic and anionic asphalt emulsion (Yaacob et al., 2013)

2.3.2 Emulsifier

The emulsifier is the most essential constituent that provides bitumen droplet surfaces with electrical charges. It is the most important element of emulsion component where assist to stable the two immiscible liquids. Emulsifiers can be used singulary or in combination to provide special properties of asphalt emulsion. Emulsifiers perform some functions within a asphalt emulsion as follows (Read and Whiteoak, 2015):

- Make emulsification easier by reducing the interfacial tension between the bitumen and water.
- Determine whether the emulsion formed is the water-in-oil or oil-in-water type.
- Stabilize the emulsion by preventing the coalescence of droplets.
- Command the performance characteristics of the emulsion such as setting rate and adhesion.

Fundamentally, the emulsifier molecules have two portions: hydrophobic and hydrophilic. When emulsifier is soluble in the water; hydrophobic orient to the bitumen phases, while hydrophilic orient to the water phases, as can be seen in Figure (2-13). In the emulsion, unbound emulsifier may appear, and this can affect the final properties of emulsion.

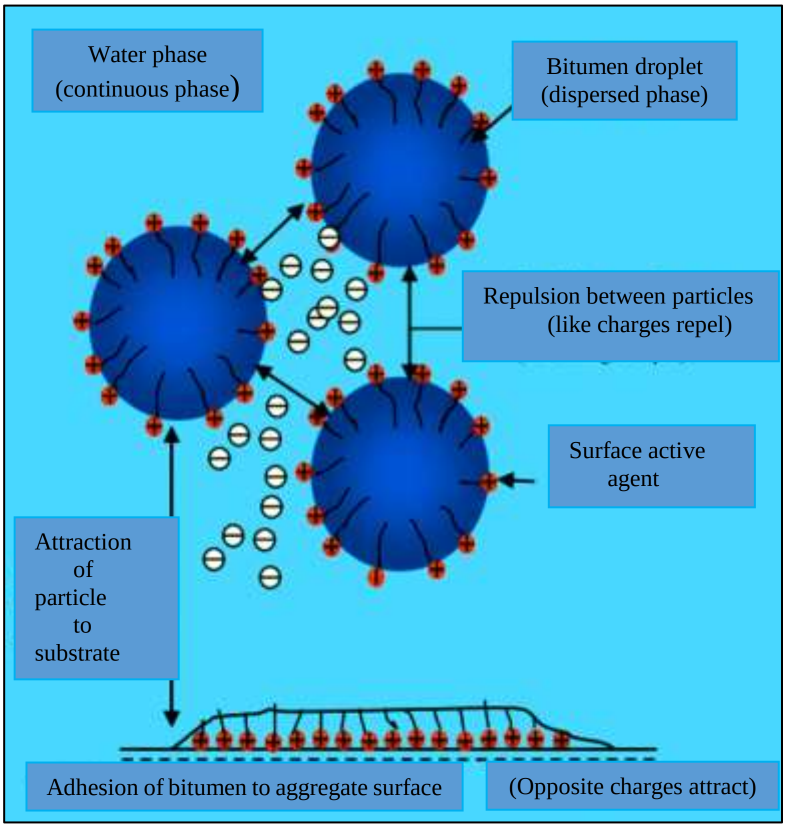
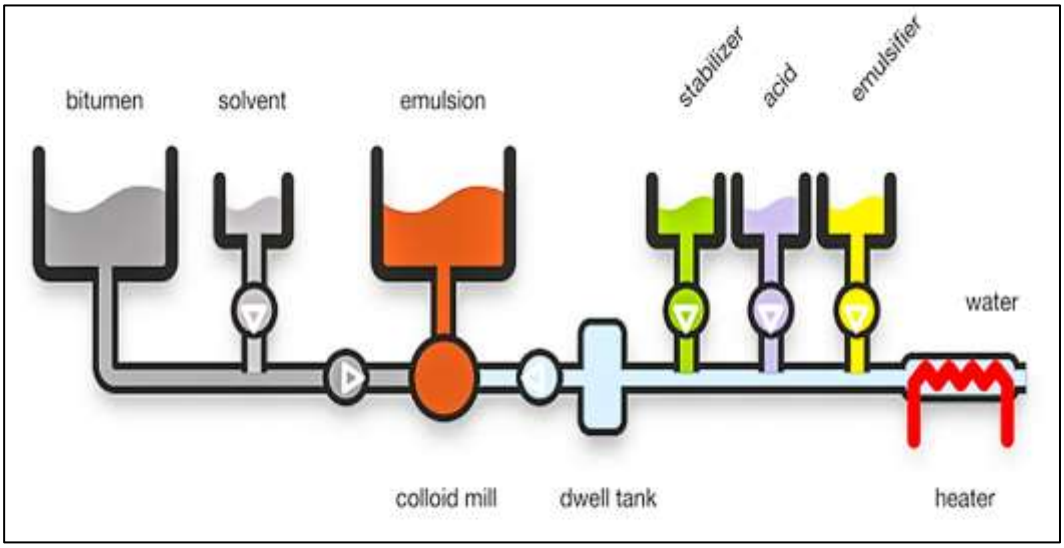


Figure 2-13 Schematic diagrams of charges on bitumen droplets

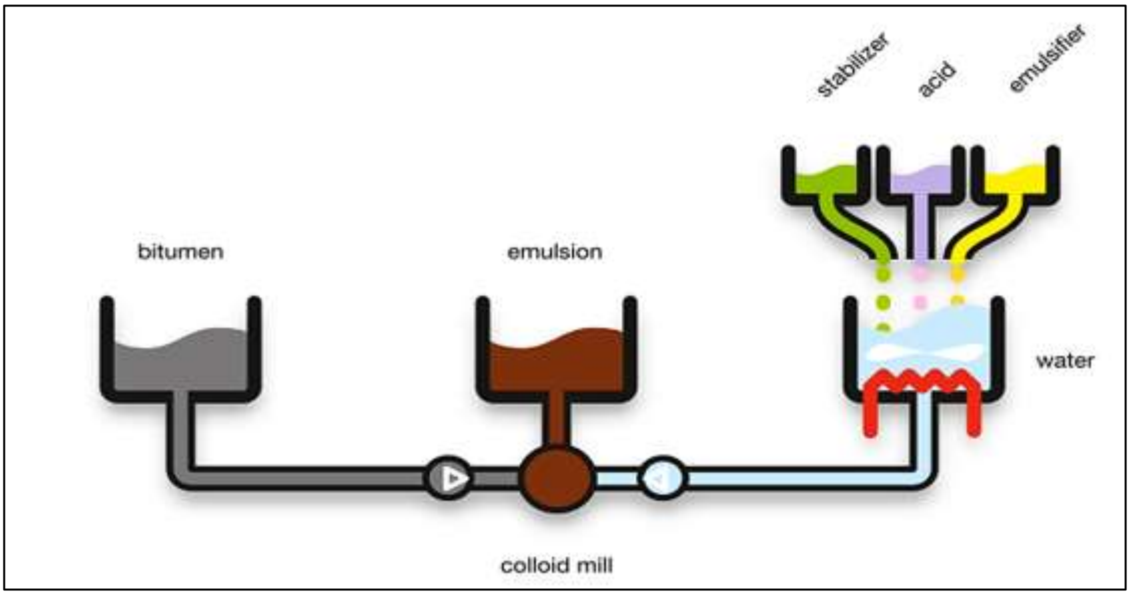
2.3.3 Manufacturing of Asphalt emulsion

Emulsions are prepared by mixing hot bitumen with water containing emulsifying agents and applying mechanical energy sufficient to break up the bitumen into droplets. There are many processes to manufacture asphalt emulsion, the most well-known of which are continuous process and batch process.

Continuous process is largely used. It is needed to equip with a high speed rotor (1-6×10^3 revs/min) in a stator of a colloid mill. The bituminous materials are pumped within temperatures about 100-140 ºC to make bitumen viscosity of no more than 2 poise, while water are pumped at a temperature of less than 90 ºC in order to prevent the boiling of the water phase through the emulsion. In order to break up the bitumen and emulsifier solutions into small globules, the colloid mill must be applied in sufficient intense shear forces. Furthermore, this process supports to coat the bitumen globules with emulsifiers and initiate the electrical charges on the bitumen globules. When the bitumen is a hard grade bitumen or when a polymer modified binder is used, it becomes more difficult for process, higher temperatures are needed to allow the bitumen to be pumped to and dispersed in the mill, and more power is required for dispersing the bitumen into the mill. While static mixer may be used for small volume production of emulsions and used to produce emulsion with specific consistency (Read and Whiteoak, 2015). Figure (2-14) shows the two manufacturing processes.



(a)



(b)

Figure 2-14 Schematic diagrams of emulsions, (a) continuous emulsion plant and (b) batch emulsion plant (Industrial, 2014)

2.3.4 Breaking and Setting of Asphalt emulsion

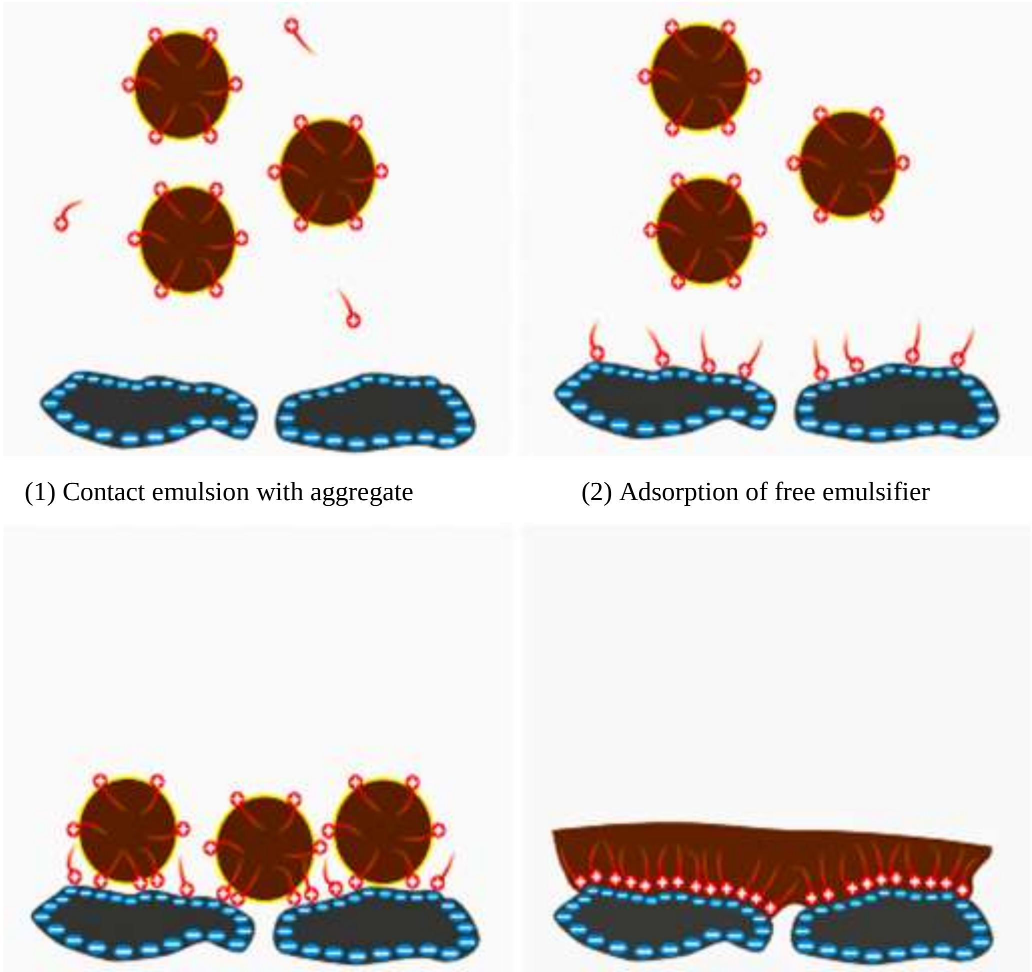
In order to achieve asphalt emulsions whose its purpose as a binder of materials in road construction or protective coatings, it must be returned to a continuous bitumen film. The emulsion's pace of setting and curing process depends on reactivity, where, temperature and humidity may represente the reactivity of the aggregate and the environmental conditions. Asphalt emulsions for road use are classified depending on their reactivity (Industrial, 2014):

- **Rapid-setting emulsions**
  Set quickly in contact with clean aggregates of low surface area such as those used in chip seals (surface dressings).
- **Medium-setting emulsions**
  Set sufficiently less quickly that they can be mixed with aggregates of low surface area such as those used in open-graded mixes.
- **Slow-setting emulsions**
  It mixes with aggregates of high surface area.

Some of the breaking process steps may include:

1. **Adsorption of emulsifier onto the aggregate surface**
   Generally, Cationic emulsifiers adsorb much more toughly on siliceous minerals than anionic or nonionic emulsifiers, and free emulsifier adsorbs more rapidly to aggregate surface.
2. **Movement of the emulsion droplets to the aggregate surface**
   Ordinary, the bitumen droplets are small particle, which move to an aggregate surface that have opposite charge, when the connection appears, it begin to flocculation, coalescence, and spreading over the surface of aggregate.
3. **PH**
   The charge on the emulsion droplets depends on pH, with acid emulsions generally cationic and alkaline emulsions generally anionic. The change in PH may be destabilized in the emulsion; when aggregates or fillers have neutralized the acid and mixed with cationic emulsion is causing rise the PH, and the vise verse for anionic emulsion may be decrease in PH. The solution for this problem is by providing calcium or magnesium ions which tend to neutralize the charge on anionic emulsions.
4. **Evaporation of water**
   The system is became more stability when the water is leaved by evaporation, that leading to concentrate droplets and coalescence.

Figure (2-15) below illustrates the mechanism of breaking and setting of asphalt emulsion as cationic emulsions.



(1) Contact emulsion with aggregate (2) Adsorption of free emulsifier

(3) Electrophoresis of droplets to surface (4) Coagulation/spreading over surface

Figure 2-15 The setting of a cationic asphalt emulsion (Industrial, 2014).

2.4 Cold mix asphalt (CMA)

Cold mix asphalt is prepared by blending and mixing graded aggregates with bitumen. This mixture is layed and compacted within ambient temperature, with no heating needed; neither preparation nor compaction. But, ordinary bitumen has hard viscosity at ambient temperature, therefor many ways appear to reduce viscosity of bitumen, these ways are: mixing with flux oil (cut back bitumen), foaming the bitumen (foamed bitumen) and emulsifying the bitumen (asphalt emulsion) (Thanaya, 2003). There are several types of cold mixture that are currently used in the world:

2.4.1 Cold Lay Macadam

In order to obtain cold lay macadam mixture, it must be mixing low viscosity bitumen with aggregates. Low viscosity bitumen is obtained by flux oil to bitumen (cutback bitumen). Flux oil must be contented of non-volatile fraction as a diluent to soften bitumen to the preferred consistency. It is clear that the viscosity of cutback depends on the amount of flux oil which is added to bitumen. Then after cutback application the flux oil evaporated according to climatic condition and the volatility of the flux oil. There are many type of flux oils used for lowered viscosity, such as: white spirit, kerosene, gas oil, and coal tar oils. These may be used individually or collectively (Green, 1998).

Cold lay macadam is used for surface dressings and surface macadam (Thanaya, 2003). Also, it is used to fill temporary reinstatement work, but this use is limited for such a purpose related to the risk. Additionally, Cold lay macadam mixture have low stiffness due to the existence of flux oil (Robinson, 1997). Moreover, Cold lay macadam mixtures are harmful to the environmental, expensive and flammable because of the solvents(Thanaya, 2003).

2.4.2 Foamed Bituminous Mixtures

The first production and usage of foamed bitumen technique was introduced by Professor Ladis H. Csanyi from Iowa State University, USA in 1956 (Transportek, 1998). He produced foamed mixture by injecting steam into hot bitumen to create thousands of small bitumen bubbles as illustrated in Figure (2-16). The foam dissipates in less than one minute, and the bitumen repossesses its original characteristics.

The bitumen must be merged with the aggregates while it is remaining in foamed state. This process may be used at plant or in situ, noticeably it is convenient for plant operations as steam is easily provided, and it is impractical for in situ operations which need special equipment such as steam boilers (Thanaya, 2003). In 1968 development was introduced for this technique by Mobil oil in Australia, they added cold water instead of steam to the hot bitumen, Figure (2-17) shows an application of modified process. This modification on the method makes it easy and economic (Muthen, 1998, Button et al., 2007). Foamed bitumen could be expanded between 10 to 15 times of its origin volume when used 2 % of water and 98% of hot bitumen (Ruckel et al., 1980).

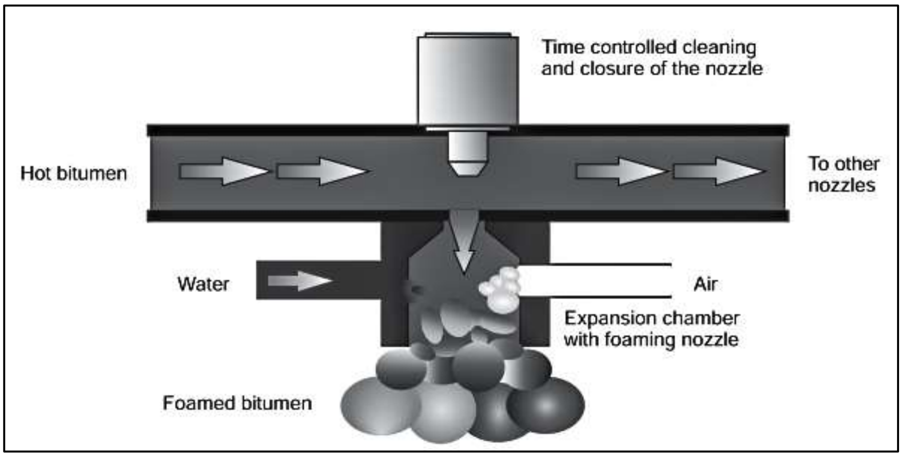


Figure 2-16 Mechanism of the bitumen foaming process (Read and Whiteoak, 2015).

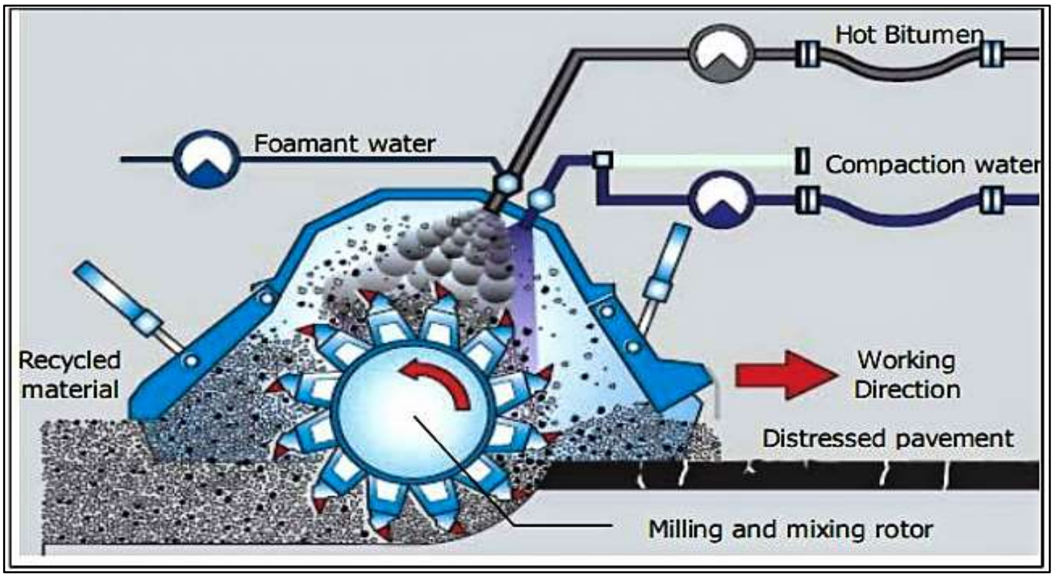


Figure 2-17 Foamed Asphalt application for cold pavement by using Mobil oil (Al-Busaltan, 2012)

2.4.3 Cold Bituminous Emulsion Mixtures (CBEMs)

CBEMs are produced by mixing bituminous emulsions with the graded mineral aggregates. Production CBEMs is relatively easy in comparison with other technologies, where it is less energy consumption and fewer emissions production during preparation and applications. But, their inadequate early strength represent an obstacle, therefor it was restricted to road pavements that have low or medium traffics, reinstatements, and footways (Read and Whiteoak, 2015, Leech, 1994b). CBEMs can be used in all pavement layers under low to medium traffic conditions (Arya Thanaya, 2009). However, CBEMs can be used for heavily trafficked, but it is needed to be overlaid with at least a 40mm hot bituminous mix layer (Ibrahim and Thom, 1997).

Different aggregates gradations were recommended in the preparation of CBEMs, such as:

- Open or semi-dense aggregates gradation to allow suitable ventilation within the high air void mixture and evaporation of the surrounded water and reduce curing time (Nikolaides, 1983).
- Dense graded aggregate gradations used as a result of the modification and improvement in emulsion production technologies and mixing techniques (Thanaya, 2003).
- Continuous graded or gap graded aggregate gradations used in the mixture of CBEMs (Ibrahim and Thom, 1997).

The properties of CBEMs depended on the characteristics of aggregate gradation, asphalt emulsion, and added pre-wetting water. Therefor according to the properties needed, the designer select a suitable aggregate grade, type of bitumen, and water. In general, CBEMs production process have three stages (Taylor, 1997):

1. The first stage is preparation and mixing the emulsion with the aggregates. The emulsion must remain suitably stable and coat the coarse and the fine aggregates.
2. The second stage is storage or laying of the mixed materials. At this stage the emulsion must remain workable and be partially broken or set, so that the emulsion can resist moisture and rain. Also the emulsion must have suitable viscosity to un-drained after mixing with the aggregates.
3. The third stage is compacting the mixture, where the emulsion should break quickly and revert back to its original base bitumen.

Usually, emulsions require long curing times for evaporation of the volatiles to achieve maximum strength of the mixture (Nikolaides, 1983). Also this is due to two main concerns with respect to CBEMs, namely: high air void; weak early life strength (caused mainly by the trapped water) required to achieve maximum performance (Arya Thanaya, 2009).

2.5 Improving Cold Mix Asphalt

Relatively, little laboratories have embarked on wide studies to understand the performance of CBEMs and then tried to improve their performance in contrast to HMA. While HMA was developed by high investments and advanced practices in long-term all over the world. Along with inferiority of CBEMs' performance and due to recent economic and environmental impacts, many agencies and researchers have been beginning to study CBEMs characterizations to develop this technology (Al-Busaltan, 2012).

Generally, the performance of the cold mixes depends on the rheological properties of their mastics; the mastic is composed of a mix of bitumen and filler. Therefor it has recognized the importance of more understanding for the fillers properties and role beside the effect of the binder behavior (Dondi et al., 2014). Fillers can be classified into two type for cold bituminous mixtures as follows (Cabrera, 1997):

- **Active fillers,** type of filler that reacts when mixing with asphalt emulsion, for example Portland cement, where a hydration reaction happens when the emulsion added to a mixture containing these fillers because of existence of water in the emulsion.
- **Non-active fillers**, type of filler that will not react when the emulsion added to mixture which contained these fillers, as Silica filler.

However, different techniques have been introduced to improve CBEMs, which is summarized as follows:

2.5.1 Improving by OPC and Lime

Both OPC and lime are used with CBEMs for their advantages for many purposes, as follows (Ebels and Jenkins, 2007):

- Catalyst for breaking asphalt emulsion;
- Stabilizing agent (early strength and cementitious bonds);
- Modifier (reduction of plasticity index PI);
- Anti-stripping agent.

Researchers have indicated that OPC and lime can reduce the breaking time of bituminous emulsions (Brown and Needham, 2000b). Terrell and Wang reported that Portland cement and lime content is led to increase the maximum stability and maximum bulk specific gravity (Terrell and Wang, 1971). Oke at el., demonstrated that limestone filler significantly reduces the water susceptibility of CBEMs, and limestone has been known to be good at inhibiting stripping (Oke, 2011). Another study proved that the lime was added to the mixtures to inhibit stripping (Chatterjee et al., 2006). Through other studies, ordinary Portland cement was used with asphalt emulsions to control the braking behavior, and to increase mixture strength at the early time and stiffness by binding an excessive water released by the emulsion breaking

(Niazi and Jalili, 2009, Miljković and Radenberg, 2015, Tan et al., 2013). The addition of the cement can reduce mixture water sensitivity, and really influenced the development of mechanical properties over time (Wang et al., 2014), which is a result of reacting cement with the water and interacting with the emulsifier that effect the emulsion breaking (Zhang et al., 2012, Tan et al., 2013). OPC decreases the negative influence of the free water and improves the adhesion of the binder to the aggregate (Hu et al., 2009). The hydration of the cement increases the rate of coalescence and increase the binder viscosity (Brown and Needham, 2000a). Figure (2-18) shows that the cement was splitting between emulsified asphalt particles gradually and formed block cement particles hydration to stick the mixture.

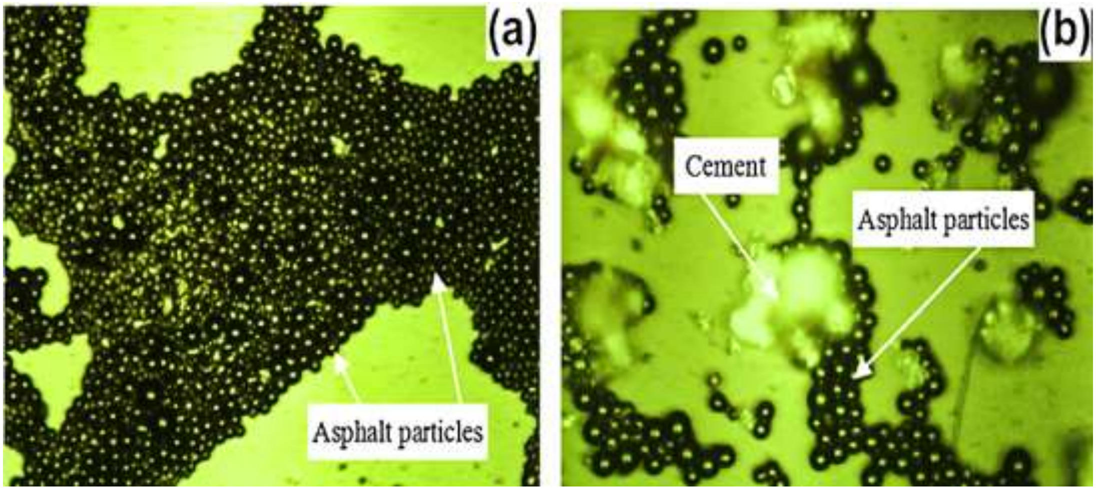


Figure 2-18 Optical images of fresh emulsified asphalt (×200):

(a) without cement and (b) with cement (Wang et al., 2014).

As illustrated by Head who specified that the addition of cement had a very significant influence on mix stability; addition of 1% cement created an increase in stability of 250-300% over that of untreated samples (Head, 1974). Brown and Needham stated that addition OPC improved stiffness modulus, permanent deformation resistance, and fatigue strength (Brown and Needham, 2000a).

2.5.2 Improving CBEMs by Waste and by–Product materials

The waste or by-product materials can be used as a modifier of the CBEM's to enhance the inferior mechanical properties such as weak earlier strength and high air void. In general, the use of waste or by product materials can achieve many benefits especially sustainable issue. Kibert (Gambatese and Rajendran, 2005) reported that waste and by-product materials offer many principles for sustainable construction:

1. Minimization of source consumption (Conserve)

2. Maximize resource reuse (Reuse)
3. Use renewable or recyclable resources (Renew/Recycle)
4. Protect the natural environment (Protect Nature)
5. Create a healthy, non-toxic environment (Non-Toxics)
6. Pursue quality in creating the built environment (Quality)

Thanaya (Thanaya, 2003) reported advantages of use waste and by-products materials to improve cold mixes, such as enhancement of ultimate strength due to the cementitious effect, economic benefit and environmental benefit. These materials can facilitate absorption of the trapped water via the hydration process, and powder physical and chemical properties (Al-Busaltan et al., 2012a).

The technique uses of waste materials in asphalt mixtures appeared for about 80 years ago (Al-Abdul-Wahhab and Al-Amri, 1991), They are combined in asphalt mixtures as fillers or additives to enhance the properties and performance of asphalt concrete pavements. Researcher used various waste and by-products materials in the CBEMs as follows:

- **Rubber Tires**

  Since the late 1960's, asphalt-rubber binder has been used in asphalt mixtures. Study conducted large scale trial section comprising rubber from waste tires were paved, where attractive and promising opportunities gained from the engineering and environmental point of view (Thanaya, 2003). In comparison to conventional asphalt pavements, pavements made of rubber and plastic modified asphalt concrete have better skid resistance, less cracking and a longer pavement life (Al-Abdul-Wahhab and Al-Amri, 1991). Rubber must be reduced into small size before using in asphalt applications by crashing at low temperature; These rubbers are classified into two type according to particle size (Thanaya, 2003):

  - **crumb rubber** that have size about 10 mm.
  - **chunk rubber** that have size larger than 10 mm to 125 mm.

- **Ash**

  One of the most well-known ash is a by-products of coke combustion from power stations in which the coke is pulverized to a fine powder then burnt in a furnace of the power station for various industrials activities. This practice produces a very fine ash which is carried out of the furnace with the flue gases that are called Pulverized Fuel Ash (PFA) or known Fly Ash (FA).

Fly ash is used as a filler material. Traditionally, fly ashes have been used in a range of applications, namely filling materials, grouting, and soil stabilization . Fly ash has also been used in road pavements as road bases, sub-bases and for sub-grade formation (Dash, 2013). Thanaya et al., indicated that (PFA) can be used as proper filler in cold mixes at full curing conditions (Thanaya et al., 2006). Fly ash type C results in higher Marshall stability of a chunk rubber asphalt concrete (Thanaya et al., 2006, Hossain et al., 1995). Fly Ash Type C is the by-product materials of coal combustion using Lignite Coal or Sub-Bituminous Coal. It has pozzolanic properties that give cementitious effects in the presence of water and active Ca. Therefore, it showed its suitable to be used in cold bituminous mixtures (Thanaya, 2003). They found that the stiffness of the cold mix was very comparable to hot mixtures. PFA can be incorporated into CBEMs within a specific range (Thanaya, 2003). Al-Busaltan et al. attempted to develop CBEMs comprising Paper sludge ash PSA, which is a waste domestic fly ash. They improved the CBEM's mechanical properties, in terms of Indirect Tensile Stiffness Modulus and Creep Stiffness (Al-Busaltan et al., 2012b). Dulaimi et al. reported that LJMU-A2 which is a type of fly ash that has proven the possibility of working as a supplementary cementing material (SCM), which can be substituted for ordinary Portland cement OPC. This deals a positive effect in sustainability by reducing the cement content of cold asphalt mixtures (Dulaimi et al., 2015b), where research proved partial replacement of OPC by pozzolans from industrial waste has been executed to improve the performance of the binder course mixtures by the formation of cementitious hydrated products through activating pozzolanic materials.

- **Fiber**

The addition polypropylene fibers to CBEMs may reduce the dry density and Marshall stability and reduce resilient moduli of the mixture when compared to plain mixtures (de S. Bueno et al., 2003).

Other waste and by-product materials are also used with some notes, as follows:

- Steel slag, but it is risky due to volume expansion of steel slag in wet conditions (Thanaya, 2003).

- Crushed glass may be incorporated into CBEMs (Thanaya, 2003). Fines, and crushed glass provide some improvement to CBEMs' mechanical properties, especially when Rapid Setting Cement (RSC) is added to CBEM (Al-Busaltan, 2012).
- Red porphyry sand, synthetic aggregates made from sintering quarry were used CBEM (Thanaya, 2003).
- **Cement kiln dust (CKD)**

CKD which is a by-product material, where thousands of tons of dust discharge in the air from rotated kiln during the manufacture of Portland cement. CKD is estimated by (3 – 4) % of the total produced cement depending on the source of raw materials and manufacturing process (Najim et al., 2016). In Iraq the amount of generated CKD is higher in contrast to global scale due to plants being outdated. The average quantity of generated CKD from Iraq plants can be estimated by about (8 – 33) % of the production output, depending on the condition of each plant; most plants adopted CKD as land-disposal alternative (Adnan et al., 2010). Now Karbala cement plant which is one of the newest Iraqi plants deposed approximately (3 – 4) % CKD of total cement production. Where CKD accumulated as an irregular piles and accumulations which are usually disposed or spread near or around the plants site. All these landfill and piles are unlined and uncovered. Dust particles may be suspended in the air by either wind erosion or a mechanical disturbance which causes environmental impacts (Adnan et al., 2010). Therefore, exploiting the CKD for the road construction reduces its environmental harmfulness .CKD is a product that does not finish the calcination process, which mean that its properties are not like cement clinkers.

CKD is a cheap alternative to cement or lime for soil stabilization, its use is not limited for road construction work, but also other civil engineering works such as the construction of earth dams and rendering of walls (Baghdadi and Rahman, 1990). However, the following use is practically suggested by previous researchers:

- **Recycled CKD**

  The majority of CKD is recycled back into the cement kiln (Adaska and Taubert, 2008).
- **Using in concrete**

  The replacing of OPC with CKD appears to have negative influence for both rheological and mechanical properties of cement concrete (Najim et al., 2016, Pratik D Viramgama et al., 2016). El-Sayed et al. established that substituting up to 5% wt. of cement with CKD did not significantly distress the compressive strength of cement paste, also did not influence the inactivity of the embedded steel reinforcement (El-Sayed et al., 1991). Maslehuddin et al., suggested that the percentage of replacement should not exceed 5 % wt., but if using 10–15% CKD with cement concrete has not significantly affected to compressive strength (Maslehuddin et al., 2009). Nevertheless, 30% CKD replacement in special cases could be achieved (Najim et al., 2016). Where, other studies showed that the compressive strength, split tensile strength, and modulus of rupture reduced with an increase in CKD content instead of cement (Udoeyo and Hyee, 2002).

- **Stabilized pavement layers**

CKD may be added to soils to improve its engineering characteristics, kaolinite and bentonite clay soil materials were stabilized by CKD for pavement construction, where improvement reported in engineering properties of the stabilized soils by CKD (Baghdadi, 1990). CKD increased unconfined compressive strength of the soils, and useful to prevent erosion of soils in slopes (Button, 2003). Peethamparan and Olek reported that the CKD reduced the plasticity index (PI) and liquid limit (LL), and may increase PL of the clay soil. Unconfined compressive strength and stiffness properties of the soil were increased too (Peethamparan and Olek, 2008). Oduola Stated that the addition of CKD decreased the LL and PI, also improvement in the engineering properties of the soil was reported (Oduola, 2010).

AASHTO(AASHTO, 2002) and USCS(ASTM, 2000a) methods of soil classification classified dune sand as A-3 and SP respectively. Therefore, it is not used in road construction without enhancement on its properties; thus, addition of CKD to sands offered 30% higher compressive strength and California bearing ratio which facilitate using it for base materials (Baghdadi and Rahman, 1990). Another study portrayed that stabilization by CKD improves seismic Young’s modulus and resilient modulus from 5 to 30 times depending on the CKD content and type of base material (Ebrahimi et al., 2011). Edeh et al. obtained that CKD effectively stabilize reclaimed asphalt pavement (RAP) by using 60% CKD and 40% RAP for subgrade materials in road construction (Edeh et al.).

- **Biomass materials**

Biomass is an organic and biological material that resulting from living; these materials have been used for various civil engineering applications (Melotti et al., 2013). In fact, using biomass materials facilitates the prevention of getting environmental infection. Biomass may be used as aggregates or fillers for cement concrete construction and asphalt concrete (Pels et al., 2005), as well as, for stabilized soil materials (Nordmark et al., 2011, Basha et al., 2005). Biomass has been mixed at appropriate quantity with OPC for concrete production to provide a low-cost, environmentally, and more friendly binders (Arum et al., 2013), which its effect is positively observed, because of having essential pozzolans.

Ash materials such as Rice Husk (RHA), Coconut Husk (CHA), Palm Leaf, Bamboo Leaf, and Peanut Shell have shown such effect. Chinwuba Arum at el., have proven that replacing OPC by RHA and CHA up to 15% resulted in 100% higher compressive strength than concrete having OPC alone (Arum et al., 2013). On other side, Oil Palm Ash (OPA) investigated as a filler in concrete, as partial replacement of OPC, where greater strengths, fewer drying shrinkage, less water permeability, a smaller amount of water absorption, and more resistance to sulphate attack than traditional mixes were recorded (Al-mulali et al., 2015).

Sargın studied the use of the RHA in the HMA as mineral filler, he demonstrated that RHA can be used as mineral filler in the asphalt concrete (Sargın et al., 2013). Ahmad et al. reported the value of Marshall stability for HMA with palm oil fly ash were found generally higher than the mixtures have OPC alone (Ahmad et al., 2012).Al-Busaltan successfully introduced Paper Sludge Ash (PSA) as a filler for CBEMs instead of OPC for producing quick curing CBEMs, and improving their mechanical and durability properties (Al-Busaltan, 2012). In this research, Palm Leaf Ash (PLA) is suggested as filler replacement for OPC in the CBEMs production.

2.5.3 Improving CBEMs by polymers

Polymer is chains of repeated small molecules. It is added to asphalt mixture to enhance performance. The use of polymers as modifiers with asphalt pavement was useful for various points; decrease fatigue damage, increase resistance to rutting and thermal cracking, and improve temperature susceptibility (Yildirim, 2007). Additionally, they are useful for coating aggregates and binder modification (Asadi et al., 2016). The modified emulsion bitumen macadam by polymers of Ethylene Vinyl

Acetate (EVA) and Styrene Butadiene-Styrene (SBS) improved stiffness, permanent deformation characteristics and increased the fatigue life of CBEM (KHALID and Eta, 1997). Chávez-Valencia et al. created polyvinyl acetate emulsion (PVAC-E) which was added to a cationic quick set emulsified asphalt to modify CMA (Chavez-Valencia et al., 2007). They used special technique to cover aggregates by polymer and mixing by diluted PVAC-E, then they added asphalt–polyvinyl acetate (A–PVAC) binder. This procedure resulted in an increase in the compressive strength by 31% in contrast to untreated mixtures. When the cold asphalt emulsion mixtures containing bitumen modified with Ethylene vinyl acetate (EVA) and Styrene butadiene styrene (SBS) polymers the stiffness increased significantly compared with unmodified binders (Needham, 1996).

2.6 Cold Mix Asphalt Design

Currently, there is no universally accepted cold mix design procedure that can be followed like hot mix asphalt design, therefore various road authorities and researches attempt to develop design methods:

2.6.1 Design Procedure covered by the Asphalt Institute

The American Asphalt Institute in its Asphalt Cold Manual MS-14 (Asphalt Institute, 1989) presented two mix design methods for CBEMs:

- Modified Hveem method for emulsified asphalt-aggregate cold mixture design. This method needs some specific equipment, which is not widely obtainable in asphalt laboratories.
- Marshall method for emulsified asphalt-aggregate cold mixture design.This design method fundamentally consists of the following steps:

1) Determination of a suitable aggregates gradation.

2) Determination of Initial Residual Bitumen Content (IRBC), which may be trailed by an empirical formula of dense graded.

$$P = (0.05A + 0.1B + 0.5C)x0.7 \quad \textit{Equation 2-1}$$

Where:

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

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

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

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

3) Initial Emulsion Content (IEC).

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

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

Where:

IEC = Initial Emulsion Content by mass of total mixture %

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

4) Coating test

Coating test shall be carried out by mixing all of dry aggregates and filler about 1 minute, and pre-wetted with varied amount of water with IEC value obtained from above section. The asphalt emulsion is added later and then mixed for about 2-3 minutes, repeated these steps until adequate coating. The degree of coating should not be less than 50 % by visual observation.

5) Optimum Pre-Wetting Water Content (OPWwc)

The optimum pre- wetting moisture could be obtained according to the coating test, which the lowest pre-wetting water content was selected when the coating achieved. The purpose of pre-wetting is to get over balling of the asphalt with the fines and avoid insufficient coating, mean pre-wetting water content was referred to as the optimum pre-wetting water content for best coating (OPWwc) in which the mixture was neither too sloppy nor too stiff. Then found Total Liquid Content (TLC), that definite as the percentage of (OPWwc + IEC) by mass of total mixture during the mixing stage (Thanaya, 2007).

6) Determine optimum residual bitumen content (RBC)

Operating mixture by using OTLC value obtained from section above with various residual bitumen content RBC at two points above and two points below the RBC in steps of 0.50 according to IRBC that calculated in point (2). The mixture compacted and then tested for each RBC. Then the determination of the optimum residual bitumen content ORBC was according to tests such as volumetric characteristic and Marshall stability after subjecting these specimens to specific curing protocol.

7) Determination of Optimum Total Liquid Content at Compaction (OTLC)

Compacted mixture density is related to moisture content of the mixture; therefore, it is necessary to determine the optimum water content at compaction to get high mixture properties. The mixture design procedure uses standard Marshall specimens in the estimate of compacted mixture properties, highest density and lowest porosity are selected. The TLC in the selected mixture used as OTL during compaction.

2.6.2 Design Procedure of the Ministry of Public Work Republic of Indonesia (MPW-Indonesia, 1990)

Generally, this method depended on AASHTO and Marshall test procedure for the design that covered in the Asphalt Institute MS-14 (1989) with some modifications (Thanaya, 2003).

2.6.3 Design Procedure of Nikolaides A. F

Fundamentally, there was not new procedure, but combining the American Standard and the specifications of the Ministry of Public Work Republic of Indonesia (MPW- Indonesia, 1990), and the addition of a method of illustrating the permanent deformation performance (Thanaya, 2003).

2.6.4 Thanaya and Zoorob procedure (2002)

This procedure was no new method for design cold mix asphalt, but it was an adjustment to the existing methods as design procedure covered by the Asphalt Institute, CAEMs Design Procedures of the Ministry of Public Works of Indonesia and some modifications (Thanaya, 2007). This procedure or recommendation was found to be accepted by many researchers (Dash, 2013)..

2.7 Statistical Analysis Model

2.7.1 Introduction

Statistical analysis used to develop model which relates between dependent variables and independent variables; the aim of this section is to illustrate sufficient knowledge of how parameters affects the depended variable, this dissertation uses last version of Statistical Product and Service Solutions (SPSS) software (Version 24). Mecha

nical tests indicators such as Marshall stability, flow, Indirect Tensile Strength and Creep Stiffness, and durability test as water sensitivity and ageing tests represented as depended variables, while fillers as CMF, OPC, CKD and PLA represented as independent variables for all modeling, in addition to cycle number of wheel track in creep stiffness modeling.

Regression analysis of linear and nonlinear were conducted to find the most valid statistical models. Predictive modeling is a name given to a collection of mathematical techniques having in common the goal of finding a mathematical relationship between a target dependent variable and various predictor or independent variables, with the goal in mind of measuring future values of those predictors and inserting them into the mathematical relationship to predict future values of the target variable. Perfect in practice, it is desirable to give some measure of uncertainty for the predictions; typically a prediction interval that has some assigned level of confidence like 95% another task in the process is model building. Model selection, fitting and validation are the basic steps of the model building process.

The main purpose of this analysis research is developing models of mechanical and durability characteristics to use variable additives.

2.7.2 Some definition about statistical and Goodness of fit

In order to better understand performance of any model, it is needed to understand some parameters of models.

Coefficient of Determination (R^2): is the square of the correlation between observed and calculated value of the dependent variable $0 \leq R^2 \leq 1$. It is an approach for modeling the relationship between a scalar dependent variable and one or more independent variables. The case of one explanatory variable is called simple linear regression. For more than one explanatory variable, the process is called multiple linear regressions. Large value of R^2 suggests that the model has been successful in explaining the variability in the response (Douglas C. Montgomery, 2011).

The residual (e) describes the error in the fit of the model to the observation. Subsequently, we will use the residuals to provide information about the adequacy of the fitted model.

Analysis of Variance (ANOVA): The analysis of variance can also be used to test the significance of regression. The ANOVA test for significance of regression is usually summarized in a table, such as shown in Table (3-13).

Table 2-2 Analysis of Variance for Testing Significance of Regression

Source of Variation	Sum of Squares	Mean Square
Regression	SS_R	MS_R
Error or residual	SS_E	MS_E
Total	SS_T	

(SS_R) Regression sum of squares, or the model sum of squares

(SS_E) Error or residual sum of squares

(SS_T) Total of Sum squares

(MS_R) Mean Square of regression

(MS_E) Mean square of residual or error.

Also by SPSS can prove the terms of fit goodness of statistical model as: Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE), these are calculated to compare the performance of estimation models.

It is important to evaluate forecast accuracy using genuine forecasts, the following terms used for this purpose (Hyndman, 2014):

RMSE: is a frequently used measure of the differences between values (sample and population values) predicted by a model or an estimator and the values actually observed.

MAE: is a quantity used to measure how close forecasts or predictions are to the eventual outcomes. The main absolute error is on the same scale of data being measured. This is known as a scale-dependent accuracy measure and therefore cannot be used to make comparisons between series on different scales. The mathematical challenge usually finds this an easier statistic to understand than the RMSE.

MAPE: is a measure of prediction accuracy of a forecasting method in statistics, for example in trend estimation. It usually expresses accuracy as a percentage. Measures based on percentage errors have the disadvantage of being infinite or undefined if predicted value is zero or close to zero for any observation in the test set. However, if y_i is close to zero, $y_i^{\wedge}$ is also likely to be close to zero.

The model is good when MAPE good when away from zero (De Myttenaere et al., 2016). Both the RMSE and the MAE are regularly employed in model evaluation studies (Chai and Draxler, 2014). A low RMSE value means that the error is characterized by a low dispersion (Capozzoli et al., 2015). It can be assured of good model finding by the model that have minimizes MS_E (Douglas C. Montgomery, 2011).

2.8 Summary

HMA negatively influences the environment, cost and safety, therefor CBEM may be depended on to overcome these problems, but CBEMs were shown to have low earlier mechanical properties unless developing conventional CBEMs.

The improvement may include enhancement by using higher performance emulsion and additives or replacement conventional mineral aggregates by other. Replacement conventional fillers with pozzolanic cementitious materials as natural, product, waste or by-product materials according to current practice of achieved research works draw a promising way to overcome the inferiority of CBEM.

Chapter 3

Experimental Work

3.1 Introduction

This chapter deals with the experimental works which were conducted during the research. It presents the materials used, the adopted testing methods, and CBEMs development method by comprising waste and by-product materials.

3.2 Materials

Local materials were used in this research work as much as they are available to ensure economic side.

3.2.1 Aggregates

Aggregates (coarse and fine) used in this research work were provided from local Karbala quarries. The aggregates were sieved, separated and graded to agree with the gradation required for binder layer coarse according to the stated Iraqi specification; General Specification for Roads and Bridges (GSRB), section R9 (GSRB, 2003). The gradation of binder layer according to GSRB section R9 is shown in Table (3-1). The gradation provided for HMA is adopted as no local standard gradation for cold mix asphalt is available yet. Figure (3-1) illustrates the adopted gradation, which classified as dense grade.

Table 3-1 Asphalt mixture gradation for binder course (GSRB, 2003)

Sieve size	mm	% passing by weight of total aggregate + filler	Used
1	25.0	100	100
¾	19.0	90-100	95
½	12.5	76-90	83
⅜	9.5	56-80	68
No. 4	4.75	35-65	50
No. 8	2.36	23-49	36
No. 50	300 µm	5-19	12
No. 200	75 µm	3-9	6

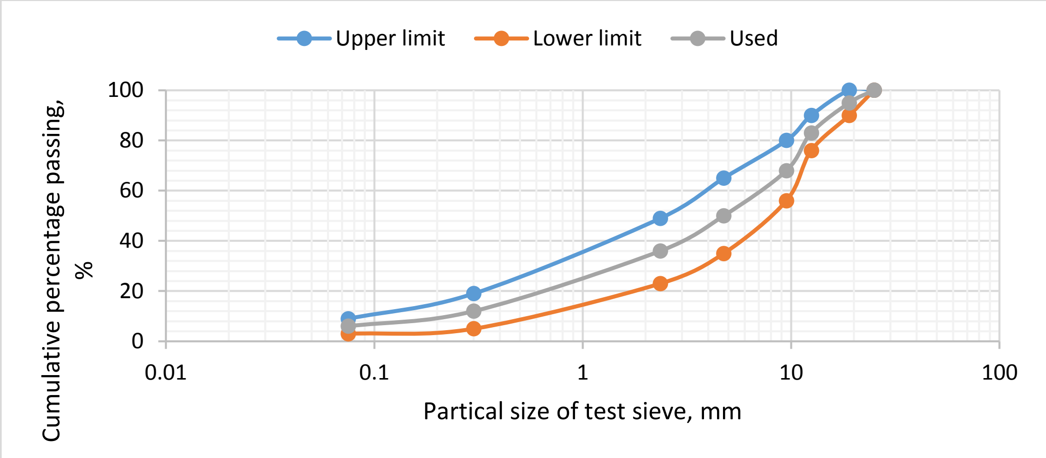


Figure 3-1 Particle size distribution of the selected gradation

3.2.1.1 Coarse Aggregates

The coarse aggregate used in this study was limestone, crushed angular close to whiteness. Its properties were compliance to the GSRB; Table (3-2) shows coarse aggregate properties. The results were obtained from experiments achieved in laboratory of the university of Kerbala.

Table 3-2 physical properties of coarse aggregate

Property	ASTM designation	Crushed Coarse agg.	GSRB Specification, (binder course)
Bulk specific gravity, gm/cm^3	C127 (ASTM, 2015c)	2.6	-
Apparent specific gravity, gm/cm^3	C127	2.64	-
Water absorption, %	C127	1.36	-
Percent wear by Los Angeles abrasion , %	C131 (ASTM, 2014c)	9.1	35% Max
Soundness loss by sodium sulfate ,%	C88 (ASTM, 2013d)	4.1	12% Max
Clay lumps, %	C142 (ASTM, 2010b)	0.05%	-

3.2.1.2 Fine Aggregates

Two types of fine aggregate were used, namely, crushed sand and natural sand; natural sand is considered to be less than 25% according to GSRB. Table (3-3) shows fine aggregate physical properties.

Table 3-3 Physical Properties of Fine Aggregates

Property	ASTM & AASHTO designation	Fine agg.	GSRB Specification for binder course
Bulk specific gravity, gm/cm^3	C128 (ASTM, 2015d)	2.64	-
Apparent specific gravity, gm/cm^3	C128	2.65	-
Water absorption,%	C128	0.7	-
Clay lumps , %	C142 (ASTM, 2010b)	1.9%	-
Passing sieve NO.200,%	C117 (ASTM, 2013c)	3.52%	-

3.2.2 Filler

Fillers are added within construction materials to provide certain properties and complete the mixture required skeleton and finalize aggregate gradation requirements. Four types of fillers were used in this study, namely, conventional mineral filler (CMF), ordinary Portland cement, by-product material, and waste material. Such variation was adopted to verify the role of filler in CMA, also to satisfy the main aim of this study; the validity of replacing hydraulic filler by waste or by-product filler.
Scanning Electron Microscopy (SEM) images was used for better to understand the physical properties of fillers.

SEM, Microscopy vision reveals the details of very fine objects, and its quality is highly dependent on its resolution and also its ability to distinguish an examined sample from the background, In fact, SEM has been used extensively to investigate the microstructure of materials. Additionally, electron microscopy is able to analyze the elemental composition for a selected area of the tested sample (Al-Busaltan, 2012).

3.2.2.1 Conventional Mineral Filler (CMF)

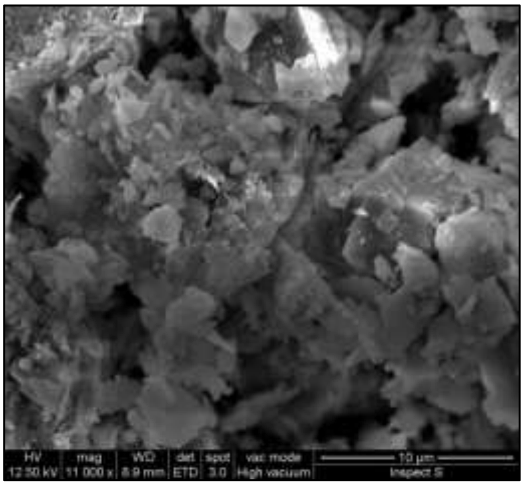
CMF was obtained from the by-pass collector of the crushing process of aggregate. This material is used normally in HMA locally. So, it was adopted for control CMA in comparison with other mixtures that have different fillers. Its properties are illustrated in Table (3-4). CMF is used for both hot and cold control mixtures. Figure (3-2) shows SEM analysis of CMF.

3.2.2.2 Ordinary Portland Cement (OPC)

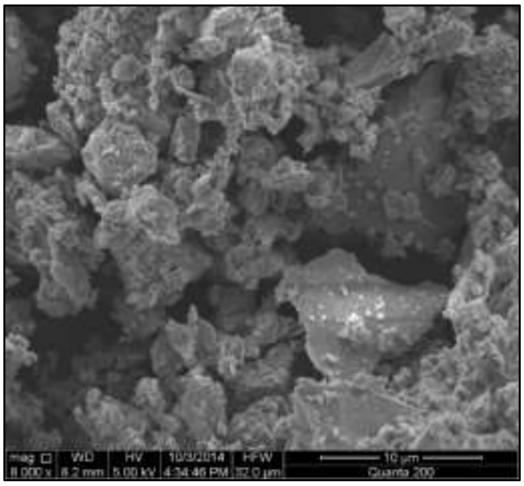
OPC was supplied from Karbala cement plant. Its properties illustrates in Table (3-4) below. OPC used as a filler for both mixtures; HMA and CMA. Figure (3-2) shows SEM analysis of OPC. The physical and chemical properties were tested in Karbala cement plant laboratory for CMF and PLA and other fillers tested in Liverpool John Moores University.

Table 3-4 Properties of the used fillers

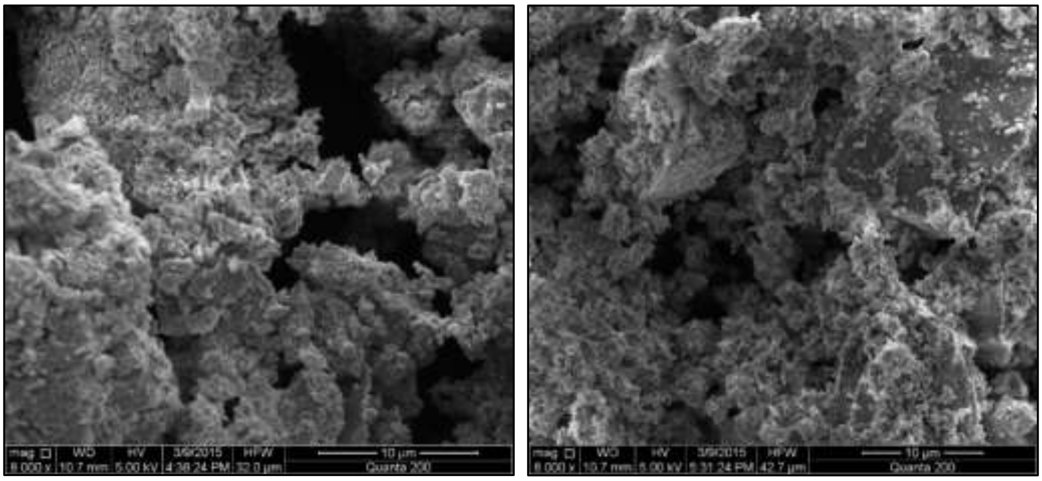
Physical Properties				
Property	*Filler type*			
	CMF	*OPC*	*CKD*	*PLA*
Specific surface area (m^2/kg)	225	410	485	932
Density (gm/cm^3)	2.610	2.987	3.012	2.015
Mineral composition (XRF)				
SiO2	21.60	24.910	17.011	66.643
Al2O3	3.78	2.324	3.653	8.548
Fe2O3	1.92	1.125	3.684	1.870
CaO	31.40	64.148	57.451	18.902
MgO	2.90	1.326	1.424	1.412
K2O	0.73	0.760	1.036	3.0407
Na2O	0.19	1.714	0.143	2.052



(a)



(b)



(c) (d)

Figure 3-2 SEM of the used fillers: (a) CMF, (b) OPC, (c) CKD, (d) PLA

3.2.2.3 By-product material

CKD of this study was supplied from Karbala cement plant. This filler is defined as by-product material, globally, but in Iraq it through as waste material. One of the main objective of this study is to prove the feasibility to use CKD as an active filler, or as a replacement to OPC, partially or totally, in CMA. The local CKD properties are shown Table (3-4). Only the CKD that passed sieve No. 200 was used for this study to simulate filler portion in the asphalt mix. Figure (3-2) shows SEM analysis of CKD.

3.2.2.4 Biomass materials

PLA is a waste material produced from burning of the palm leaf. Normally cleaning Palm tree produces high quantities of such leaf. According to Central Statistical Organization in 2015, there are 15 million palm trees in Iraq (Iraq, 2015), each one dispose an average of 25 kg leafs each year, which mean that there is approximately 384,536 Tons of such leaf each year. The used PLA was obtained from combusted palm leaves, then sieved on No. 200 sieve. Its properties are shown in Table (3-4). Figure (3-2) shows SEM analysis of PLA.

3.2.3 Bitumen Materials

Two types of bituminous materials were used in this research; grade asphalt cement for HMA, and asphalt emulsion for CBEM.

3.2.3.1 Asphalt Cement

Grade asphalt cement was supplied from Al-Nasseria factory, its grade was 40-50 and other properties are shown in Table (3-5). The tests was taken from Karbala labrotary.

Table 3-5 Properties of Asphalt cement

property	ASTM designation	Test results	GSRB requirements
Penetration,100 gm. ,25 °C,5sec (1/10 mm)	D5 (ASTM, 2015b)	43	40-50
Specific Gravity, 25 °C (gm/cm^3)	D70 (ASTM, 2009a)	1.03	-
Ductility, 25 °C , 5 cm/min, (cm)	D113 (ASTM, 2007)	130	>100
Flash point, (°C)	D92 (ASTM, 2005)	318	>232
Softening point (°C)	D36 (ASTM, 2000b)	38	-
Solubility in trichloroethylene, (%)	D2042 (ASTM, 2015e)	99.9	>99
After Thin Film Oven test			
Penetration of Residue (%)	D 1754 (ASTM, 2014b)	70.2	>55
Ductility of Residue, (cm)		68.4	>25

3.2.3.2 Asphalt emulsion

Asphalt emulsion (BE) was supplied from Conmix company (under the trade name Moya Shield BE). Its properties are shown in Table (3-6).

Table 3-6 Properties of asphalt emulsion

Property	Specification, ASTM	Limits	Results
Emulsion type	D2397(ASTM, 2013a)	Rapid, medium and slow-setting	Medium- setting (CMS)
Color appearance			Dark brown liquid
Residue by Evaporation, %	D6934(ASTM, 2008)	Min. 57	54.37
Specific gravity, gm/cm^3	D70(ASTM, 2009a)		1.05
Penetration, mm	D5(ASTM, 2015b)	100-250	230
Ductility, cm	D113(ASTM, 2007)	Min. 40	42
Viscosity, rotational paddle viscometer 50 ℃ , mPa.s	D7226(ASTM, 2013b)	110-990	220
Freezing	D6929(ASTM, 2010a)	Homogenous, broken	Homogenous
Solubility in Trichloroethylene,%	D2042(ASTM, 2015e)	Min. 97.5	97.7
Emulsified asphalt/job aggregate coating practice	D244(ASTM, 2009b)	Good, fair, poor	Fair

Miscibility	D6999(ASTM, 2012a)		Non-miscible
Evaluating aggregate coating	D6998(ASTM, 2011)		uniformly and thoroughly coated

3.3 Hot Mix Asphalt Design

Traditional Marshall design method was used for designing HMA. The job mix formula was conducted within the requirement of GSRB, six asphalt cement contents with the binder layer gradation (type II) is adopted to specify the optimum asphalt cement content.

3.4 Cold Mix Design Method

Very few methods are known for the design of CMA, to date, there is no globally accepted procedure. Thus, some modifications should be added to accommodate necessarily conditions, such as high climatic condition in Iraq, gradation type, maximum size, etc. The adopted procedure may be described as the American Asphalt Institute Marshall design method with some modifications; mostly adopted from the GSRB. However, it can be stated as follows:

3.4.1 Determination of a suitable aggregates gradation.

Maximum size and gradation type were as described in GSRB (GSRB, 2003). Such gradations have proved their suitability to facilitate both load carrying mechanism of high interlock and strong mastic. Actually, binder layer gradation (type II) was tested under this research work.

3.4.2 Determination of Initial Residual Bitumen Content (IRBC)

IRBC determined by applying MS-14 (Asphalt Institute, 1989) suggested empirical formula to estimate percent of asphalt emulsion required for dense graded mixes.

$$P = (0.05A + 0.1B + 0.5C) * 0.7$$ *Equation 3-1*

Where:

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

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

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

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

IEC value was determined by dividing P by the percentage of the residual bitumen content in the emulsion.

$$IEC = \frac{P}{X}$$ *Equation 3-2*

Where:

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

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

X = residual bitumen content of the emulsion,%.

According to ASTM D6934 (ASTM, 2008), the residual bitumen was found to be 54.37 %, thus:

3.4.3 Determination Optimum Pre-Wetting Water Content (OPWwc)

After determining the IEC, five mixtures with different pre-wetting water content specimens are prepared. It is recommended by MS-14 to start with 3% (Asphalt Institute, 1989). Increment steps are 0.5 %. Specimens were manufactured and tested at each of these water content values to obtain optimum coating aggregates by asphalt emulsion, then choosing the minimum percentage that achieved maximum coating. The results vary according to aggregate type, gradation, filler type, and emulsion type.

According to the Asphalt Institute MS-14, visual estimation is used to determine the lowest percentage of water that gives highest coating of the mixture. In this research work, maximum Marshall stability is used to confirm the results.

3.4.4 Determinate Optimum Asphalt Emulsion Content (OAEC)

By using optimum pre-wetting water content (OPWwc) as described previously, additional sets of specimens were prepared with various asphalt emulsion content according to Initial Residual Bitumen Content (IRBC). IRBC described in section 2.6.1 and get its value according to section 3.4.2 used as a middle value for five sets of mixtures specimens, two points below and two points above the (IRBC). Interval steps of 0.5 % are recommended (Thanaya, 2003). Each set represents three specimens. Specimens were manufactured and tested at each of these values, then the emulsion content according to best Marshall test results is chosen.

3.4.5 Determine Total Liquid Content (TLC)

TLC represents the summation of Optimum Pre-Wetting Water Content (OPWwc) and Optimum Asphalt emulsion Content (OAEC).

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

It has to be said that almost the optimum total liquid content at compaction is relatively smaller than TLC, thus, either the mix left for some time or van is used to minimize the total liquid content before compaction, in order to gain the highest mechanical and volumetric properties for the prepared mix.

3.5 CMA Testing

Three significant materials properties are described the various CBEMs in this research work, namely, volumetric and mechanical properties. Almost, HMA testing procedures were adopted with some modification for characterizing the developed CBEMs.

3.5.1 Volumetric Properties

According to the MS-14 , CBEMs volumetric properties can be determined as follows (Asphalt Institute, 1989):

$$G = \frac{D}{F-E}$$ *Equation 3-4*

$$G_d = G\times\frac{(100+A)}{(100+A+K)}$$ *Equation 3-5*

$$K\ \% = \frac{mass\ of\ water,gm}{mass\ of\ dry\ mixture,gm} * (100 + A)$$ *Equation 3-6*

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

$$V.T.M\ \% = \left[\left(\frac{100+A+K}{G} - \frac{100}{C} - \frac{A}{B}\right) \div \left(\frac{100+A+K}{G}\right)\right]\times 100$$ *Equation 3-8*

$$Air\ Voids\ \% = V - \left[\left(\frac{K\times 100}{L}\right) \div \left(\frac{100+A+K}{G}\right)\right]$$ *Equation 3-9*

$$V.F.B\ \% = \frac{V.M.A\ \% - V.T.M\ \%}{V.M.A\ \%}$$ *Equation 3-10*

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.

3.5.2 Mechanical Properties

There are many tests which described the mechanical characteristics of CBEM in laboratory. In this research work, Marshall tests, indirect tensile strength test, and wheel track test were adopted.

3.5.2.1 Marshall Test

This method measures the resistance to plastic flow of cylindrical specimens of asphalt paving mixture. Whereas, load is applied in direction perpendicular to the cylindrical axis by means of the Marshall apparatus.

3.5.2.1.1 Marshall test for HMA

Marshall Criteria was used to determine the optimum asphalt content for HMA. Based upon Marshall method, the optimum asphalt content is determined by averaging the values of: Asphalt content at maximum stability, maximum unit weight, limited range of air voids, and limited range of flow.

Six sets of HMA samples are prepared in the laboratory with different binder content; each set contains three samples. Asphalt cement content ranges from 3.5−6 by steps 0.5%. Table (3-7) describes the setup of Marshall test. Marshall test procedure is based on ASTM D6927 (ASTM, 2015a).

Table 3-7 Marshall test condition according to ASTM D6927

Item	range	Used
Asphalt temperature ℃	150−165	165
Aggregate heated °C	170	170
Number of required specimens	3	3
Rate of load application mm/min	50 ± 5	50
Measuring device accuracy	Min. 50 N	0.01 N
Test temperature °C	60 ± 1	60
Specimen diameters mm	101.6-101.7	101.6
Specimen thickness mm	63.5 ± 2.5	63.5
Compaction	Marshall 75x 2	75x2
Specimen conditioning before test in water bath or an oven	30-40 min. 120−130 min.	30 min.

The optimum asphalt content was compared with Iraqi specification requirements as described in Table (3-8).

Table 3-8 Iraqi roads design requirement for Marshall test of binder coarse

Property	Binder Course
Resistance to plastic flow (ASTM D6927), 75 Blows/End	
Marshall Stability (kN), min Marshall Flow (mm)	7 2-4

Voids in Marshall specimen (%)	3-5
Voids in mineral aggregate (%), min.	13

3.5.2.1.2 Marshall test for CMA

In principle, the procedure was similar to that followed in HMA, but with some differences, as follows:

- The materials prepared and mixed with ambient temperature.
- After compaction the specimen was subjected to curing protocol ; 24 hrs.@ 25 ℃ in mold, then another 24 hrs. in the oven @ 40 ℃ as illustrated in Figure (3-3).

After curing, the specimen is subjected to volumetric measurement then placed for 30 min. in water bath at temperature 60 ℃ before being subjected to Marshall test. It has to be said that MS-14 recommend the testing of Marshall stability should conduct @ 25℃, where 60 ℃ was adopted in this research work to accommodate the local environment. However, the details about getting the optimum emulsion content and other details are as described in section 3.4.

Figure 3-3 Curing CBEMs, (a) @ after removed from mold @ 25 ℃, (b) @ 40 ℃

3.5.2.2 Indirect Tensile Strength ITS

Indirect tensile strength test is an indicator for cracking (Kim and Wen, 2002). It is also used to determine pavement moisture damage (ASTM, 2012b).

- ITS test for HMA

  The tensile characteristics of bituminous mixtures are evaluated by loading the Marshall specimen along a diametric plane with a compressive load at a constant rate acting parallel and along the vertical diametrical plane of the specimen through two opposite loading strips. The procedure of the test is followed ASTM D6931(ASTM, 2012b). Figure (3-4) shows the test setup, whereas Figure (3-5) illustrates the configuration of failure according the test.The test procedure is summarized as shown in Table (3-9).

Table 3-9 Test conditions of ITS (ASTM, 2012b)

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

Equation formula

$$ITS = \frac{2000\,P}{\pi\, t\, D} \qquad \text{Equation 3-11}$$

Where:

ITS = indirect tensile strength, kPa

P = maximum load, N

t = specimen hieght immediatly brefore test, mm

$D = specimen\ diameter$, mm

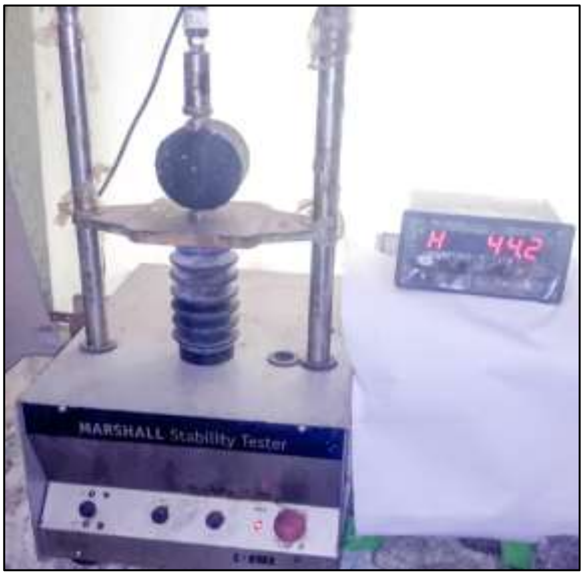


Figure 3-4 Testing ITS

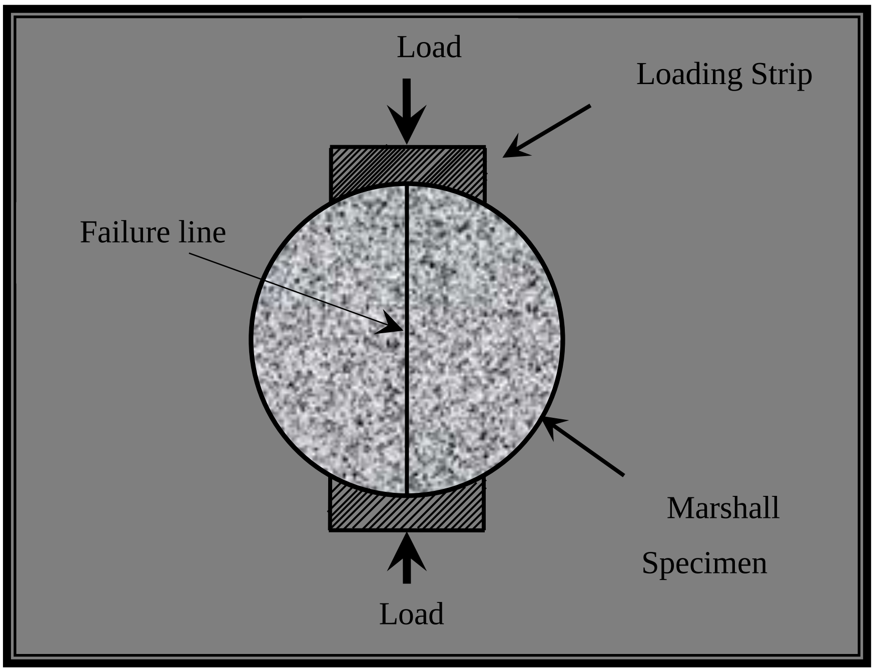


Figure 3-5 Load Configuration and Failure Plane for Specimen in ITS

- ITS for CMA

  The procedure was similar as to that followed for HMA, except the curing protocol, which is recommended to be as those adopted for Marshall stability for CBEM.

3.5.2.3 Wheel Track Test (WTT)

WTT is testing a compacted bituminous mixtures in a reciprocating rolling wheel device. This test provides information about the rate of permanent deformation from a moving concentrated load. A laboratory compactor is used to prepare slab or cylindrical specimens. The procedure of this test is described in a specification AASHTO T324 (AASHTO, 2004). The testing conditions are summarized in Table (3-10). This procedure is covered for HMA. The wheel-tracking equipment used by National Center for Construction Laboratories were used

Table 3-10 Test conditions for Wheel Track Testing for HMA

Item	range	value
No. of required specimens	2	2
Diameter of rubber wheel	203.2 mm	203.2 mm
Wide rubber wheel	50 mm	50 mm
No. wheel pass per min.	50 ∓5	50
Speed of wheel	Max. 0.305 m/s	0.305 m/s
Load on the wheel	705∓4.5 N	705.5 N
No. of cycles	10,000	5,000
Specimen thickness	38 - 100 mm	63.5
Air void content specimens	7∓2 %	4% as a middle value according to Iraqi specifications (GSRB, 2003)
Test temperature °C	25-70 °C	40 °C
Specimens type	Rectangular or Cylindrical	Cylindrical
Specimens diameter	150 mm	150
Compaction	According to air void, Figure (3-6)*	133x2

*suggested by auther

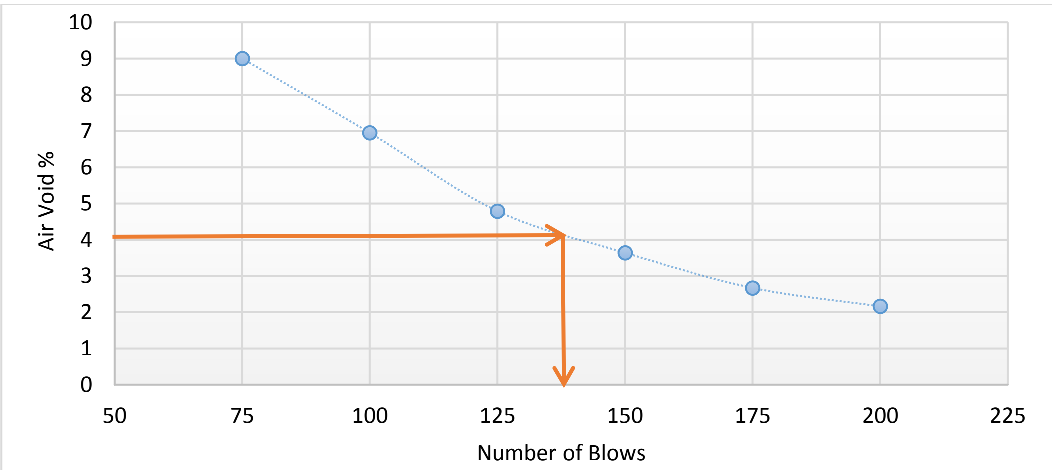


Figure 3-6 Optimum number of blows for wheel track samples

For cold mix asphalt CMA the same procedure and specification can be used, only curing should differ in contrast to HMA, where the rutting occur accusatively within mixture life, thus full curing should be adopted for CBEM. However, full curing time can be obtained by 1day @25ºC+14 day @40ºC as recommended by Thanaya (Thanaya, 2003). Figures (3-7 and 8) below illustrate the mold, specimens and the Wheel Track tester which were used in this research work.

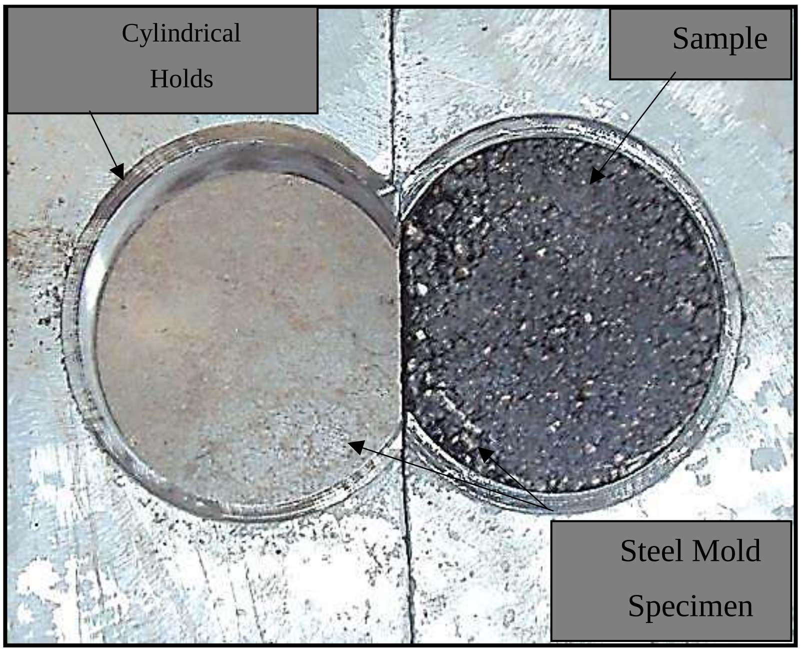


Figure 3-7 Cylindrical Steel Compaction Mold and Sample

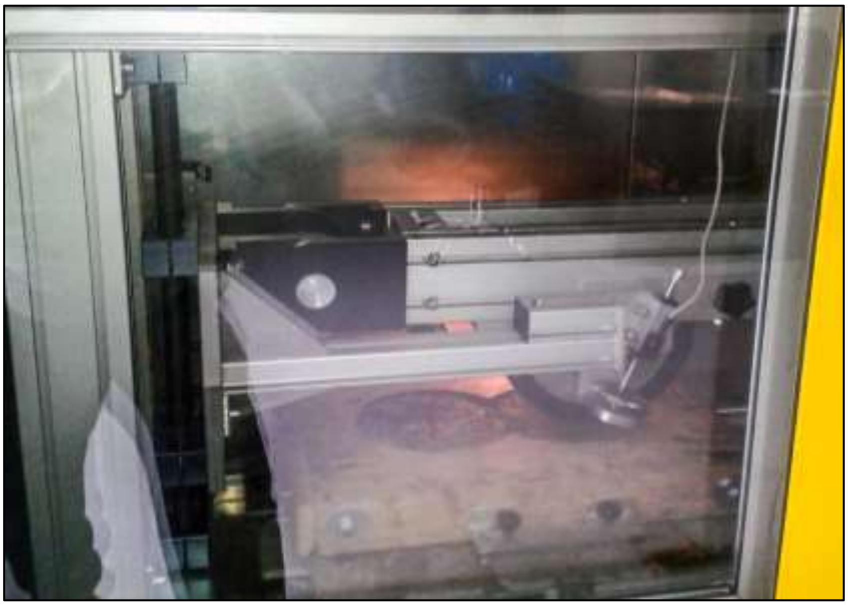


Figure 3-8 Wheel Track tester

3.5.3 Durability Testings

The ability of an asphalt material to resist weathering is described as the durability. When asphaltic materials are exposed to environmental elements, natural deterioration gradually takes place, and the materials eventually lose their plasticity and become brittle. This change is caused primarily by chemical and physical reactions that take place in the material. This natural deterioration of the asphalt material is known as weathering. For paving asphalt to act successfully as a binder, the weathering must be minimized as much as possible. In this research work, water damage and ageing deterioration are adopted as durability as recommended by various studies conducted for CBEM.

3.5.3.1 Water sensitivity Test

Water-induced damage of asphalt concrete mixtures has produced serious poor pavement performance and pavement distress. This damage is mainly attributable to stripping of asphalt cement from aggregate and may be softening of the asphalt matrix (Kennedy et al., 1983).

3.5.3.1.1 Water damage for HMA

Water damage test for HMA is described by ASTM, D4867/D4867M (ASTM, 2014a). Although, GSRB specified compressive testing for water damage characterization, in this research work ITS test is adopted as recent research and highway agencies adopted this research (Solaimanian et al., 2003), it is better for evaluating the possible moisture damage (MORENO-NAVARRO et al., 2014, Al-Busaltan et al., 2012b).The test conditions of water sensitivity are given in Table (3-11). However, the value of conditional over unconditional strength ratio of not less than 70% according to Iraqi specification GSRB, R/9 was adopted (GSRB, 2003).

Table 3-11 Water damage testing conditions

Item	range
Number of required specimens	3
Rate of load application mm/min	50
Specimen diameters mm	100
Specimen height mm	37-100
Compaction	Marshall 75x 2
Test temperature ºC	25 ± 1
Unconditioned specimen protocol	Cooling the specimen at room temp. after compaction + 20 min. in water bath 25 ± 1 ºC
Conditioned specimen protocol	Cooling the specimen at room temp. after compaction + 24 hr. in water bath 60 ± 1 ºC + 1 hr. in water bath at 25 ± 1°C

Calculate the tensile strength ratio

$$TSR = \frac{S_{tm}}{S_{td}} \quad \text{Equation 3-12}$$

Where:

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

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

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

3.5.3.1.2 Water damage for CMA

Water sensitivity can be investigated for CBEM by the same procedure as in HMA, except curing protocol to ensure full strength of the specimens. The following curing protocol cab be directed

- For un conditioned protocol, 24 hrs. in the mold @ 25 °C after compaction, then 24 hrs. in an oven @ 40 °C.
- For conditioned protocol. Additional to what follow for un condition protocol, the specimens place in water bath for 24 hrs. @ 60 °C.

3.5.3.2 Ageing Test

Durability of bituminous mixtures with detail to ageing are more commonly evaluated with HMA compared to CMA. One of the main concern of CBEMs is their low early life strength. This has prompted many researchers to explore ways of accelerating the rate of increase of CBEMs early life strength [26(Thanaya, 2003). In theory, once a CBEMs achieves full curing, it should behave like a hot mixture (Thanaya, 2003).

According to SHRP A383 (Bell et al., 1994), there are two types of ageing, namely short-term ageing to simulate mixture ageing during the mixture manufacture stage, and long-term ageing for simulating the ageing of the mixture on the road during service.

It is obviously agreed that short-term ageing may not be applicable to CBEMs, as no heating exists during the manufacturing process (Al-Busaltan et al., 2012a). However, to simulate long-term ageing, the method recommended by the SHRP A383 programmer can be adopted. Some modification in specimen conditioning was introduced to make it more applicable for CBEMs, where specimens were subjected to full curing protocol before long-term oven ageing is applied. This is recommended in order to overcome the low early life strength which makes the compression unreasonable between conditioned and unconditioned ageing specimens (Thanaya, 2003). The testing conditions are summarized in Table (3-12). This procedure was covered for HMA.

Table 3-12 Test conditions for ageing

item	values
No. of required specimens	3

Test temperature ºC	25
Specimen diameter	100
Specimen thickness	30-75 mm
Compaction	Marshall 75X2
Specimen temp. conditioning before testing	2hr.
Conditioned specimen protocol	Cooling @25ºC + (5) day @85ºC
Unconditioned specimen protocol	Cooling @25ºC

Calculate the tensile strength ratio

$$TSR = \frac{S_{ta}}{S_{tb}}$$ Equation 3-13

Where:

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

$S_{ta} = average\ tensile\ strength\ before\ ageing, kPa$

$S_{tb} = average\ tensile\ strength\ after\ ageing, kPa$

For CMA curing time again adopted as follow

- Unconditioned specimen protocol 24hrs.@25ºC+14 days @40ºC (Jenkins, 2000b).
- Conditioned specimen protocol 24hrs.@25ºC+14 days @40ºC +(5) days @85ºC.

3.6 Mathematical models

The some terms used in previous section can be expressed as mathematical model

$$SS_E = \sum_{i=1}^{n} e_i^2 = (y_i - y_i^{\wedge})^2$$ Equation 3-14

$$SS_T = SS_R + SS_E$$ Equation 3-15

$$R^2 = 1 - \frac{SS_E}{SS_T}$$ Equation 3-16

$$MS_R = \frac{SS_R}{k}$$ Equation 3-17

$$MS_E = \frac{SS_E}{n-p}$$ Equation 3-18

$$MAE = \frac{\sum_{i=1}^{n} |y_i - y_i^{\wedge}|}{n}$$ Equation 3-19

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_i - y_i^{\wedge})^2}{n}}$$ Equation 3-20

$$MAPE = \frac{1}{n} * \frac{\sum_{T=1}^{P} |y_i - y_i^{\wedge}|}{y_i}$$ Equation 3-21

Where:

y_i : Observation value

$y_i^\wedge$: Predicted value

y^- : Mean of observed values

n: Number of samples, 1,2,….

k: Number of regressor variables

p: Number of parameters

3.7 Methodology

This research is an attempt to develop a new CBEM using different environmental and sustainable means. flowchart in Figure (3-9) summarizes the research methodology, which includes the following stages:

- Identifying the current CBEMs best practices in terms of techniques and materials from the literature and industrial advisers.
- Identifying some local filler materials to upgrading CBEMs
- Incorporating the candidate materials and investigating the most appropriate one in terms of mechanical properties.
- Exploring the potential of different waste materials to activate each other and provide suitable cementitious products.
- Introducing filler replacement candidate to obtain further improvement in other volumetric and mechanical properties.
- Optimizing the candidate materials.
- Explaining the reasons behind the enhanced mechanical and durability properties of CBEMs.
- Summarizing best practice guide for utilization each material or technique to produce CBEMs with properties similar to HMA.
- Statically analysis of results by SPSS software to build modeling for forecasting the developed CBEMs' mechanical and durability properties from laboratory results.

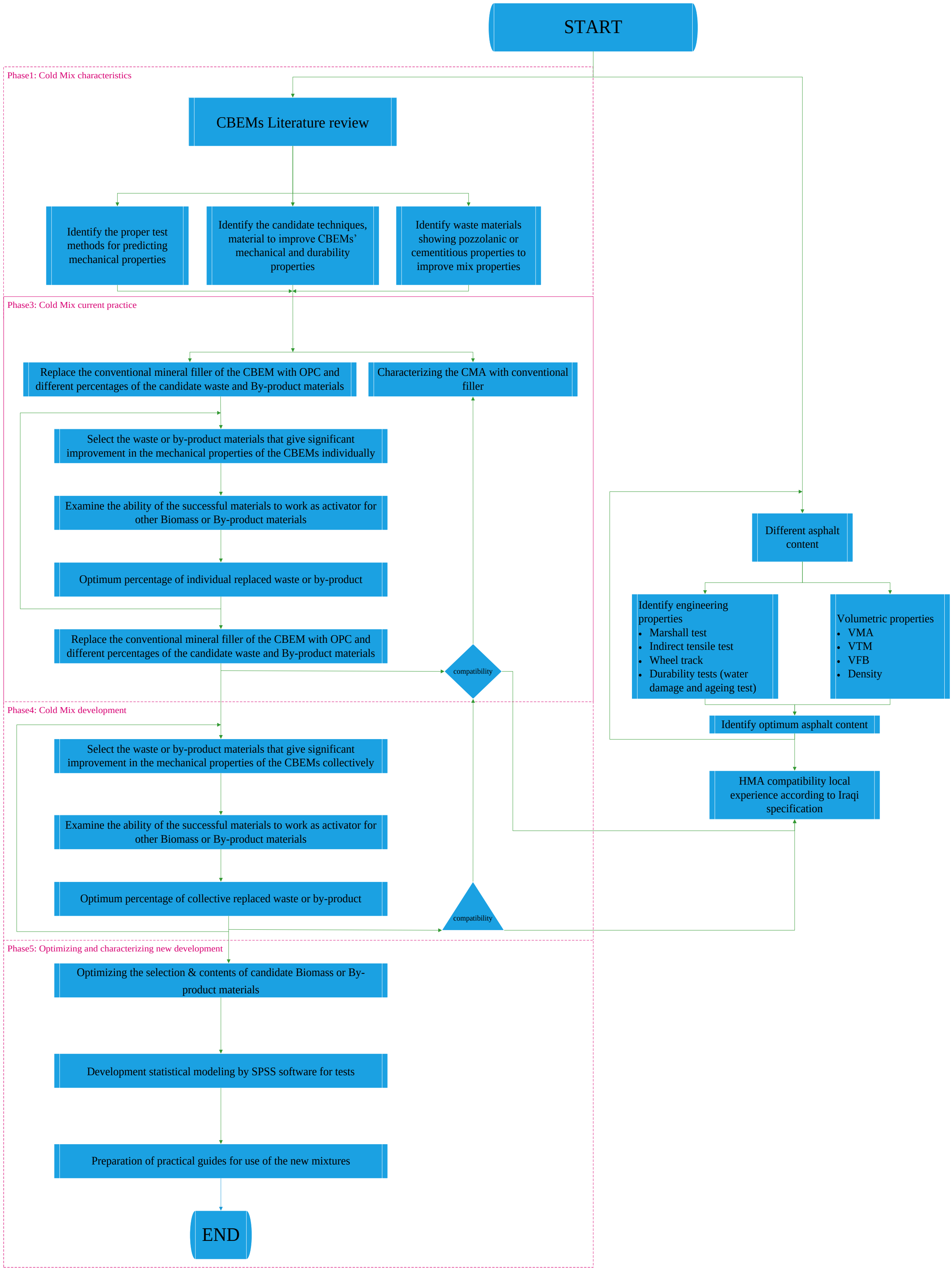


Figure 3-9 Research methodology

3.8 Summary

Until now there is no standard mix design method or test procedures universally accepted in CBEMs. However, this study tried to confirm the use of Asphalt Institute design method (MS-14) with GSRB standards to characterize CBEMs suitable for local applications. However, under available local materials, well-known testing methods, and some promising sustainable materials there is a feasible opportunity to produce comparative CMA to HMA, this will be investigated and proved in the next chapter.

Chapter 4

Data Analysis and Results

4.1 Introduction

In this research work, the results obtained for compacted samples are presented with details analyses to the effect of tested parameters. HMA was used as a control mixture to CMA, simultaneously conventional CBEM (CCM) used as control mixture for other cold mixtures. The researcher started the investigation by incorporating the OPC only as a filler, then incorporating OPC with waste and/or by-product material instead of CMF. The waste and by-product materials are represented by PLA and CKD respectively.

4.2 Hot Mix Asphalt

Traditional HMA is prepared to compare its characteristics with traditional and developed CBEMs. CMF and OPC fillers were used to prepare HMA.

4.2.1 Preparation of mixture

- Graded aggregate was prepared according to GSRB, R9 (GSRB, 2003) as shown in Figure (3-1) previously.
- Determination the optimum bitumen content by using range of asphalt content (3.5% - 6%) with 0.5% increment step. The optimum asphalt content was found to be 4.84 % for OPC and 4.54 % for CMF according to Marshall method, depending on Stability, flow, density, air void, void in mineral aggregate (V.M.A) and voids filled with binder (V.F.A), as can be shown in Figures (4-1, 2, 3, 4, 5, and 6), respectively.

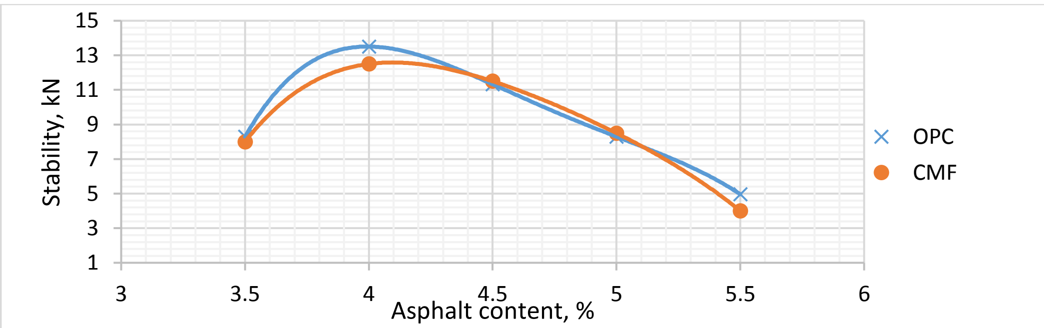


Figure 4-1 Stability vs asphalt content for HMA

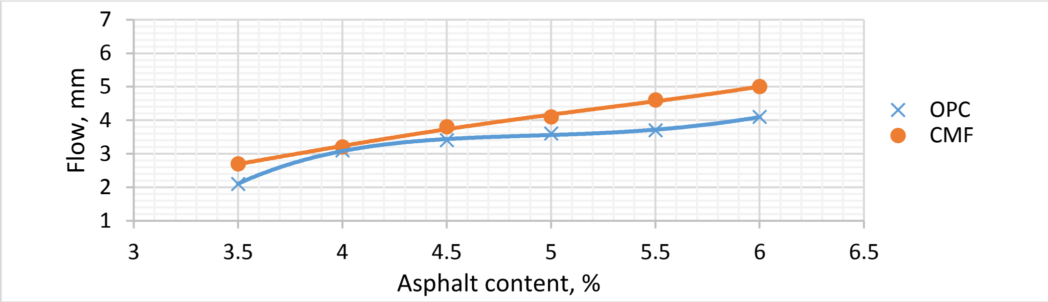


Figure 4-2 Flow vs asphalt content for HMA

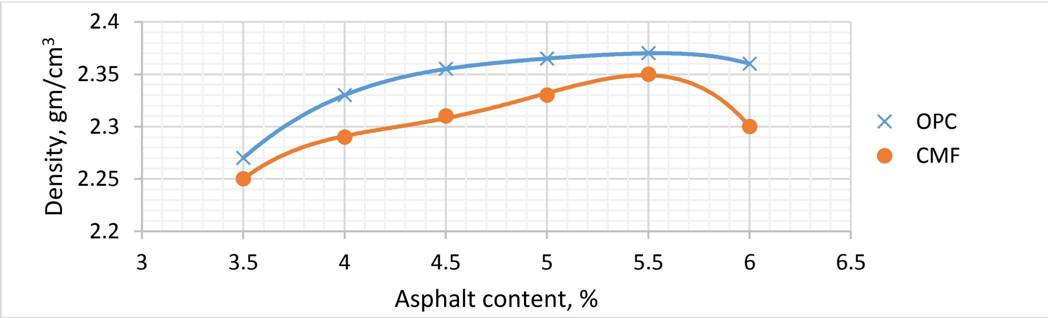


Figure 4-3 Density vs asphalt content for HMA

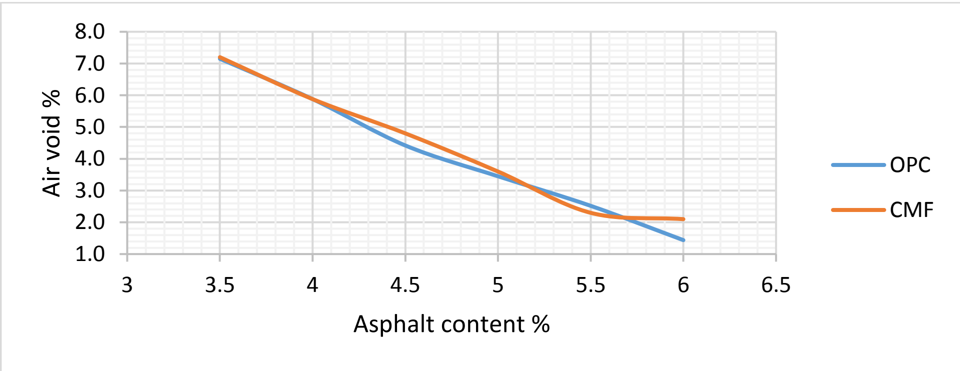


Figure 4-4 Air void vs asphalt content for HMA

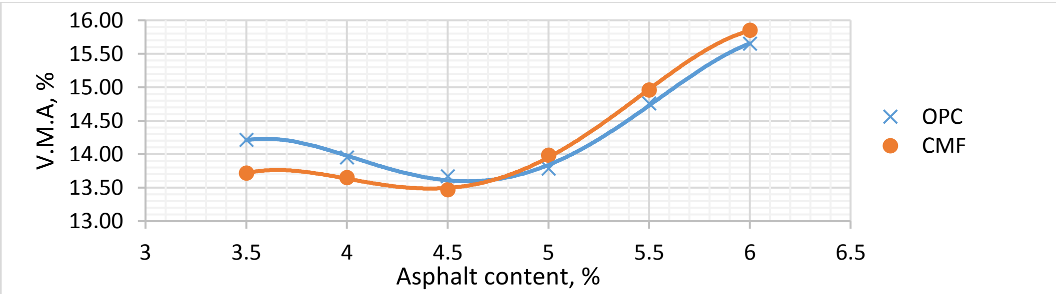


Figure 4-5 V.M.A vs asphalt content for HMA

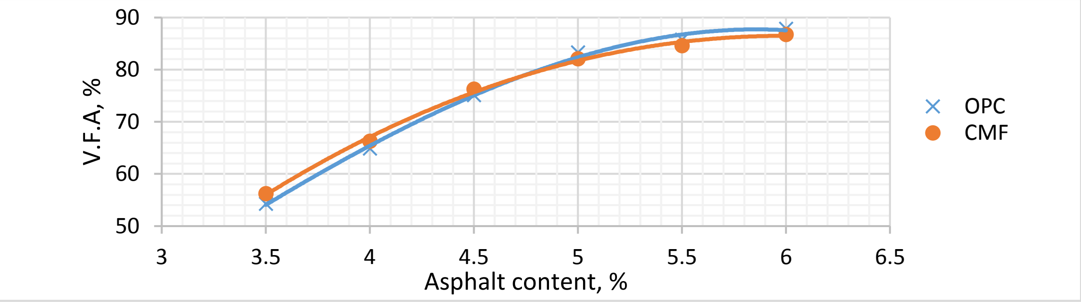


Figure 4-6 V.F.A vs asphalt content for HMA

asphalt content%	OPC	CMF
3.5	6.5	6.00
4	5.0	5.40
4.5	4.5	4.90
5	3.0	3.10
5.5	2.5	2.80
6	2.0	2.30

4.2.2 Volumetric Properties of HMA

Volumetric properties for HMA illustrated in the previously figurers demonstrated, and discussed the following:

- Density: from Figure (4-3) it can be observed that the density of HMAs comprised OPC and CMF increase with the increasing of asphalt content until certain extent, because voids continuously filled with bitumen materials which result in increase in weight with fixed volume of mixture, after that when increasing asphalt content density decreased because over increasing asphalt content increasing the volume and decrease the weight relatively according to low specific gravity of asphalt when compared to aggregates. Also, it can be recognized that HMA with OPC have the highest density values, which might be a result of the difference in filler density that is obviously shown in Table (3-4).
- Air void: it was decreased when increasing asphalt content according to filled voids with bituminous materials as shown in Figure (4-4). However, mixture with middle asphalt contents within GSRB, R9 Air Void limitations, and almost both HMA mixtures have matching curves.
- Voids in the mineral aggregate (VMA): are the void spaces between the aggregate particles of the compacted mix. This void space includes the air voids and the effective asphalt content. As shown in Figure (4-5), no significant

difference between both HMAs, also the value combatable to GSRB requirement were obtained.

- Voids filled with asphalt (VFA): are the void spaces that exist between the aggregate particles in the compacted paving asphalt mixture that are filled with binder. VFA is expressed as a percentage of the VMA that contains binder. As illustrated in Figure (4-6) identical curves were obtained for both mixtures.

4.2.3 Mechanical Properties

4.2.3.1 Marshall test

The Marshall test is an indication of the strength of the mixture. Specimens' production were prepared by a specified procedure of heating, mixing, and compacting to mixture of asphalt and aggregates which is then subjected to a stability-flow test and a density-voids analysis, the specifications described in chapter 3. From the test program the following characteristics can be draw:

- Marshall stability: the results of Marshall stability of mixtures as shown in Figure (4-1). From this figure, it can initially observe an increasing in stability with increasing asphalt content; that means asphalt increased bonding between materials in addition to the exist internal friction between aggregates, but continuing increment of asphalt content lead to separation aggregates by asphalt and caused weakness in bonding aggregates and low friction between them. At optimum value OPC exhibited higher stability value which could be a result of angular particle shape of the OPC (as can be seen in Figure (3-2)) that increase the resistance to deformation.
- Marshal Flow: Figure (4-2) illustrates flow of the mixtures. Normally, increasing asphalt content leads to increase flow according to nature of asphalt to flow and decreasing friction between materials of mixture. Also, mixture with OPC exhibited little bit better flow resistance, as a results of angular particle shape that clearly shown in Figure (3-2).

4.2.3.2 Indirect tensile strength (ITS)

The tensile properties of bituminous mixtures are of interest to pavement engineers because of the problems associated with cracking. After preparation of specimens as described in Marshall test, for this test only the specimens with optimum asphalt content value were chosen for ITS.

From Figure (4-7) the ITS for HMA comprising OPC looks better than the one with CMF because of the nature of OPC angular particles that facilitate high bonding mastic between coarse aggregate of mixture.

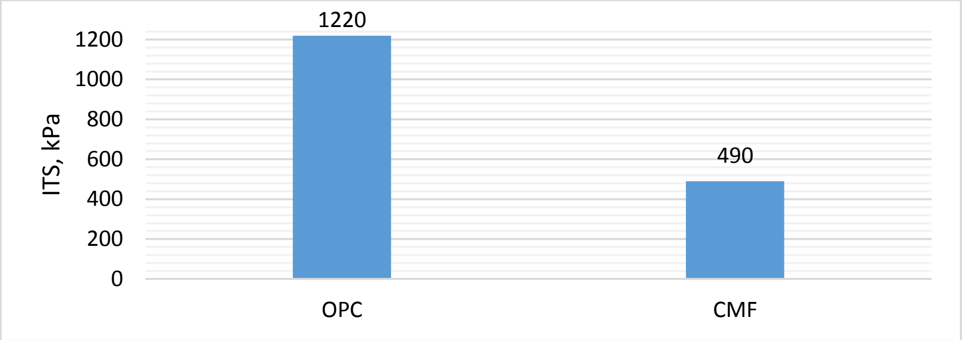


Figure 4-7 ITS results for HMA

4.2.3.3 Wheel Track Test (WTT)

In this test concentrated rolling wheel applied over specimens to state permanent deformation. It is abundantly clear that the rutting deformation increased when the No. of cycles of wheel track load increased. Figure (4-8) shows WTT for HMA that having OPC filler. Total Creep stiffness value of this mixture is 7.59 MPa.

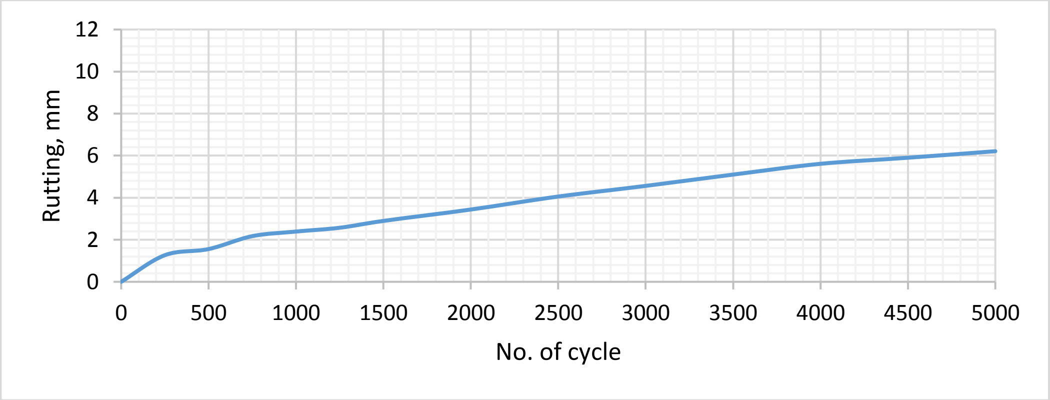


Figure 4-8 WTT for HMA with OPC filler

4.2.4 Durability Tests

4.2.4.1 Water sensitivity test

The Tensile Strength Ratio (TSR) of bituminous mixtures is an indicator of their resistance to moisture susceptibility and a measure of water sensitivity. The ITS was used to prepare condition and uncondition curing protocol samples as described in section 3.5.3.1. The relative ratio between condition and un condition was indicator water damage of specimens. The results demonstrated in Figures (4-9) for OPC and

CMF mixtures. TSR for specimens comprising OPC was less influenced to water damage than these with CMF because cement interacting with exist water that leads to increased bonding relatively, while CMF with exist water disassembly the mixture component without resisting as happened in OPC.

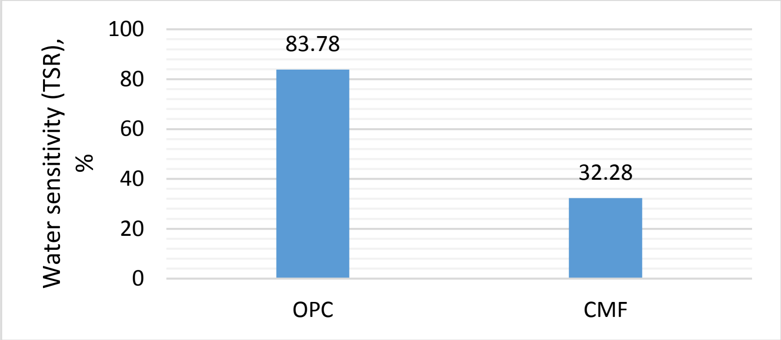


Figure 4-9 Water sensitivity results for HMA

4.2.4.2 Ageing test

In this work used long-term ageing for simulating the ageing of the mixture on the road during service according to SHRP A383 method was adopted. The results are shown in Figures (4-10) for OPC and CMF mixtures. Long-term ageing for HMA with OPC was effected by ageing more than these with the mixtures comprising CMF. High surface area of OPC comparatively to CMF may be supported the absorption of oily constituents, resins or asphaltenes and separation happened from the asphalt binder and led to high brittle and hardening, in other words the OPC increased the viscosity, thus more hard. Also Figure (4-3) illustrated that the density of OPC mixtures higher than CMF, this may be caused to thinning film thick. High surface area of OPC and angularity shape of particles may restrict moving of bitumen particles and lead to more hardness, as opposed to CMF is low surface area and, this may be not restricted bitumen particles from moving during heating, thus may be bitumen molecule integration with to other and making continuous phase and more flexible.

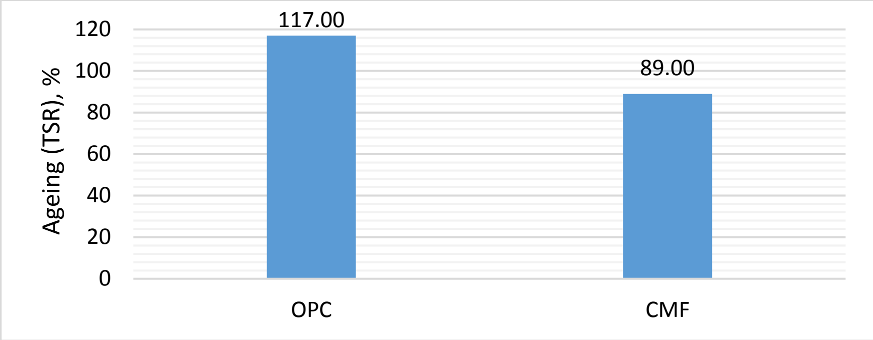


Figure 4-10 Ageing test results for HMA

4.3 Conventional Cold Mix (CCM)

Traditional CCM used as a control mixture for CMA. CMF is used in this study to prepare CCM; in fact CMF does not react with water, so it is inert filler. This section of the study is to identify the scales of volumetric and mechanical properties of traditional CCM, which helps to validate the improvement techniques by active fillers which will explore in the next sections.

4.3.1 Preparation of mixture

- Asphalt emulsion

  Cationic medium setting bituminous emulsion was selected for the CBEMs and other properties of this emulsion as shown in Table (3-6).

- Aggregates

  The aggregate used in this study is crushed from Karbala quarry and the aggregate gradation is given in Table (3-1). Physical properties of the coarse and fine aggregates are given in Table (3-2) and Table (3-3), respectively. The aggregate was dried and bagged with the sieve analysis according to Iraqi specification GSRB, R9.

- Initial emulsion content (IEC)

  After aggregate gradation was chosen and applied the empirical Equation (2-1), the initial residual Emulsion Content was found to be approximately 6.44% of the aggregate weight as described obviously in section 3.4. The Initial Residual Bitumen Content (IRBC) according to ASTM D6934 residue by evaporation of emulsified asphalt results 54.37 %. From this values (6.44, 54.37) % IEC could be obtained by application Equation (2-2), IEC was equal to 11.8% of aggregate weight.

$$IEC = \frac{P}{X} = \frac{6.44}{54.37} = 11.8 \approx 12\ \%$$

- Optimum Pre-Wetting Water Content (OPWwc)

  The Optimum Pre-Wetting Water Content of CCM was determined by using four pre-wetting water contents, i.e., 2, 2.5, 3 and 3.5% of aggregate weight. 3% was selected as it was represented the lowest percentage that gave the highest coating percentage. Additionally, in this work Marshall test was used to evaluate the optimum Pre-Wetting Water Content, where the selected value was combatable to maximum stability as shown in Figure (4-11).

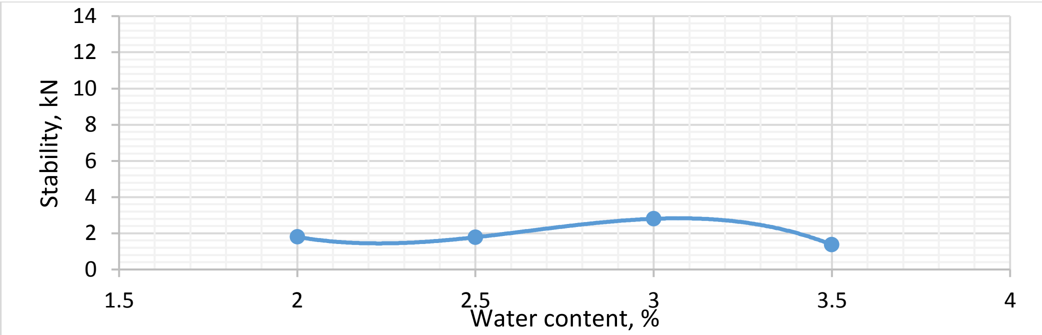


Figure 4-11 Stability vs water content of CCM

- Optimum Asphalt Emulsion (OAEC)

  By fixing OPWwc as 3% and using Five different emulsion content two above and two below the calculated IRBC , the Marshall specimens prepared with steps of 5.5, 6, 6.5, 7 and 7.5 %. 6 % was found to be the optimum value. In other words, the OAEC was approximately 11.2 %.

- Total Liquid Content (TLC)

  TLC was obtained according to Equation (3-2) and approximately equal 14.2% of aggregate weight.

4.3.2 Volumetric properties

The volumetric properties can be obtained by applying the equations as described in section 3.5.1.

- Relative density results as shows in Figure (4-12) demonstrated that the density was increased with increasing asphalt emulsion content until certain extent to providing filed voids with bitumen. Then, the density decreased with continuance increasing emulsion content because over water left the mixture matrix with extra void after curing, and this minimize the density.

- Air void results as shows in Figure (4-13) demonstrated that the air void decreased with increasing emulsion content. This may be attributed to good coating aggregate with bitumen materials and filled voids between aggregates with bituminous.
- Void in mineral aggregate (V.M.A), Figure (4-14). VMA is represents of volume of air and volume of net binder, therefore Initially increasing bitumen content leads to decreasing air void that caused to decreasing VMA, then increased VMA relatively because of increasing amount of volume of net binder. It is agree with GSRB limits.
- Voids filled with Asphalt (V.F.A), Figure (4-15). It is clear that increase value of VFA, where VFA is expressed as a percentage of the VMA that contains binder. This percentage increased with increasing volume of net binder as described previously.

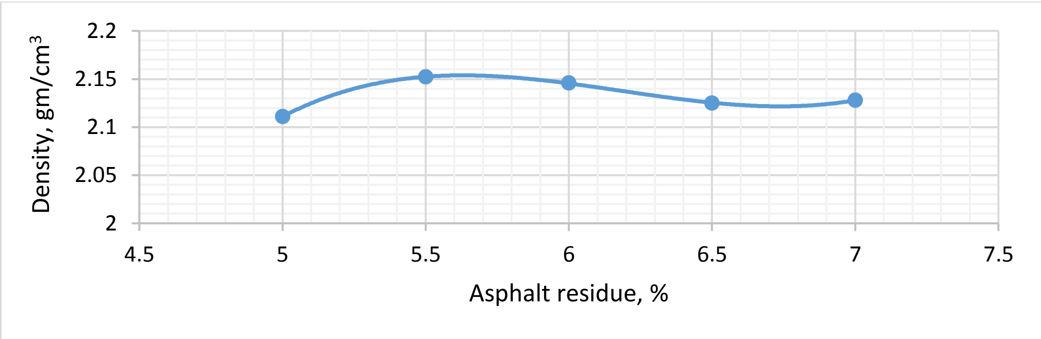


Figure 4-12 Density vs asphalt emulsion content of CCM

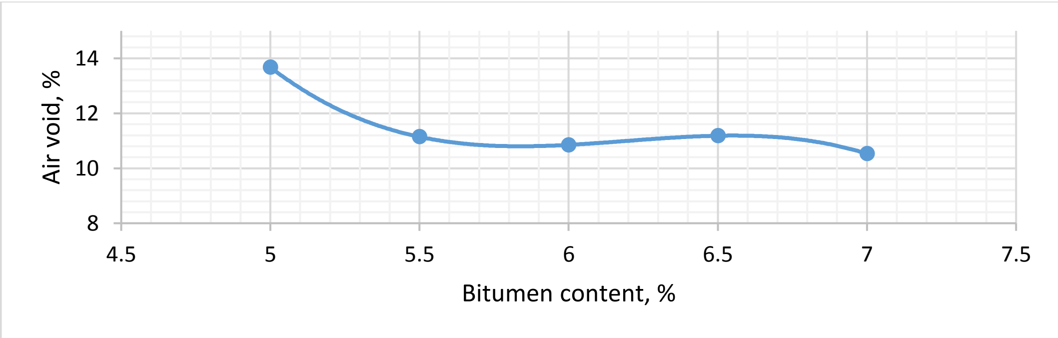


Figure 4-13 Air void vs bitumen emulsion content of CCM

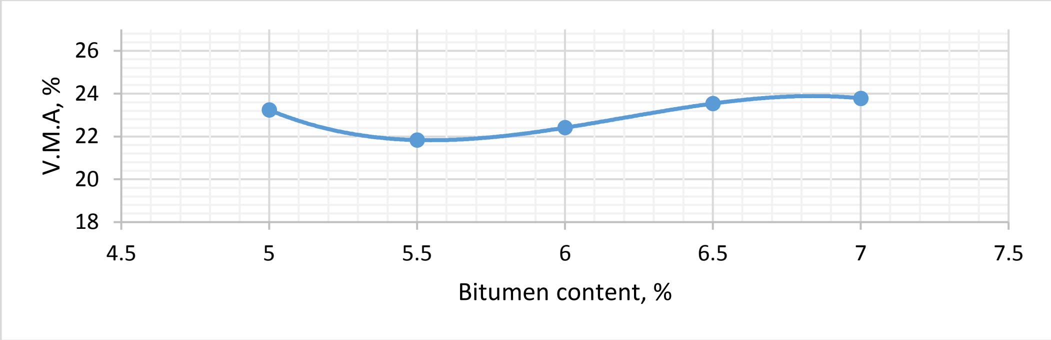


Figure 4-14 V.M.A vs asphalt emulsion content of CCM

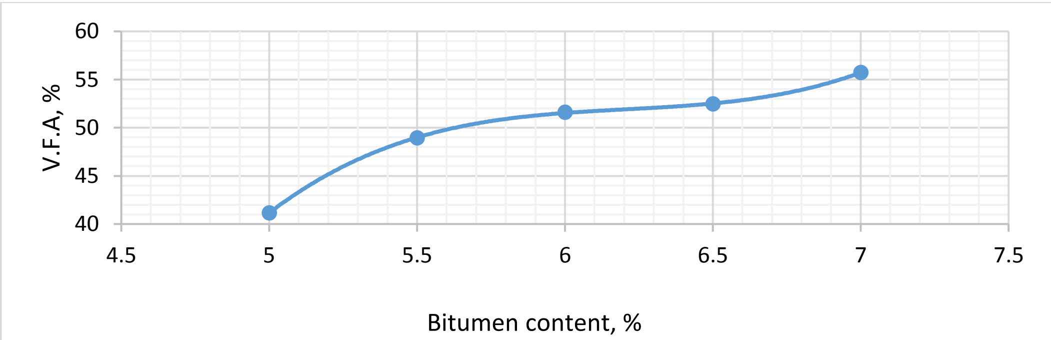


Figure 4-15 V.F.A vs asphalt emulsion content of CCM

4.3.3 Mechanical properties

4.3.3.1 Marshall test

Marshall test includes more than one indicators as follows:

- Marshall stability: the results of Marshall stability of mixtures as shown in Figure (4-16).

  Initially the stability was low relatively, After that with increase in bitumen content high bonding gained which led to higher values. Then the curve descended again due to high bitumen that prevention interlock between aggregates. Also, the particles of CMF is thin as observed from SEM analysis as shown in Figure (3-2, a), that may be resulted lower strength for mixture. In general, stability value of CCM is 4.9 kN as illustrated in Figure (4-16), which is very low when compared with HMA-CMF' value 11.5 kN from Figure (4-1) , where the value of stability is decreased about 57%. The reason may be return to low viscosity of binder according to process of preparation of asphalt emulsion, where stability is a function of the binder properties in an asphalt mixture, this value can be increased with a stiffer binder.

- Marshal Flow: Figure (4-17) illustrates flow of specimens of CBEMs comprising CMF. The flow value of CCM is high relatively (6 mm) as illustrated in Figure (4-17) when compared with flow of HMA-CMF' value 3.7 mm from Figure (4-2), that means the increasing in flow value obtained about 62%. Because of no efficient strength of CCM during early time due to exist water, further to binder that represented the emulsion which is softer.

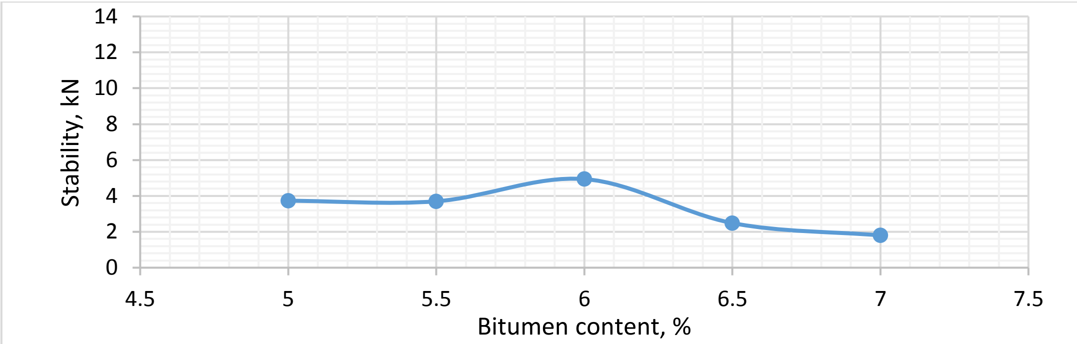


Figure 4-16 Stability vs bitumen content of CCM

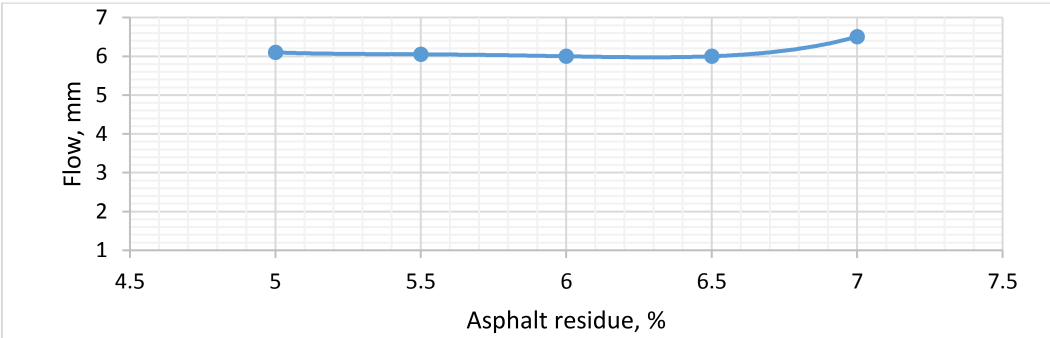


Figure 4-17 Flow vs bitumen content of CCM

4.3.3.2 Indirect Tensile Strength (ITS)

ITS specimens were prepared in the same procedure described for the Marshall test. The only main differences are in the curing protocols, which were left for 24 hours at lab temperature (25 ºC), then subjected to the second stage curing; i.e., 24 hours at 40 ºC and then left the specimen at 25 ºC for 2 hrs. before testing. Test setup was described in section 3.5.2.2.; ITS test was conducted according to ASTM D6931(ASTM, 2012b).

In fact, ITS test was conducted only to optimum result value that obtained from Marshall test -because the Marshall stability test is an indication of the deformation resistance of the mixture, and additionally, it shows the capacity of the mixture for flow- which represents 3% pre-mixing with 6% - asphalt residue or asphalt emulsion content of 11.2 % - of aggregate weight. The average result of specimens described in Figure (4-18).

In contrast to HMA, ITS for CCM is low due to inert action of CMF, which expected low strength of CCM during early time; similar explanations for Marshall stability can adopted here. ITS increased with increasing CMA viscosity. The decreasing of ITS is get about 64% when comparative between HMA-CMF and conventional CBEM.

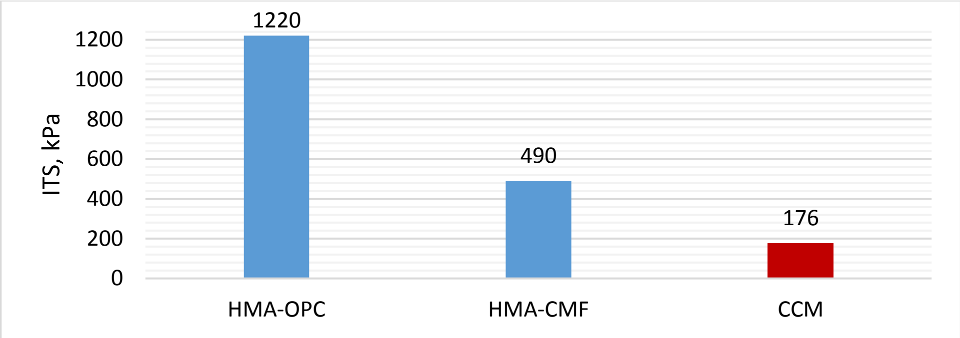


Figure 4-18 ITS test for HMA and CBEMs comprising OPC and CMF

4.3.3.3 Wheel Track Test

Mixtures were prepared as the same procedure followed in pervious sections. Specimens that have optimum value obtained from Marshall test were selected for this test. The mixture was compacted using 133 bowls on each face, and then the specimen was left for 24 hours at lab temperature (25 ºC) for curing. The following day, the specimen was extruded from the mold after gaining some strength and subjected to 40 ºC oven curing for 14 days to ensure full curing according to Thanaya recommendation (Thanaya, 2003). Nevertheless, test setup was described in section 3.5.2.3.Wheel Track test was conducted according to AASHTO T324 (AASHTO, 2004). The results of wheel track test can be shown in Figure (4-19).

CCM has inferior fatigue characteristics comparatively to HMA, because such mixture has high air void and less bitumen cohesion comparative to HMA. It is necessary to accentuate that the CCM mixture is failed at 4500 cycles, therefore the creep stiffness measured at 4500 cycles while HMA creep stiffness measured at 5000 cycles as illustrated in Figure (4-20), and the creep stiffness of CCM is less than HMA-OPC as 45%.

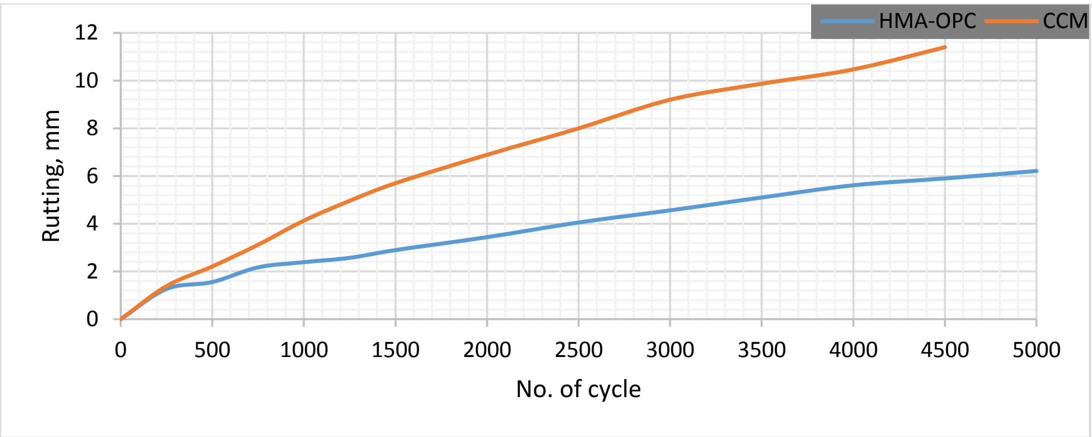


Figure 4-19 WTT for CCM and HMA

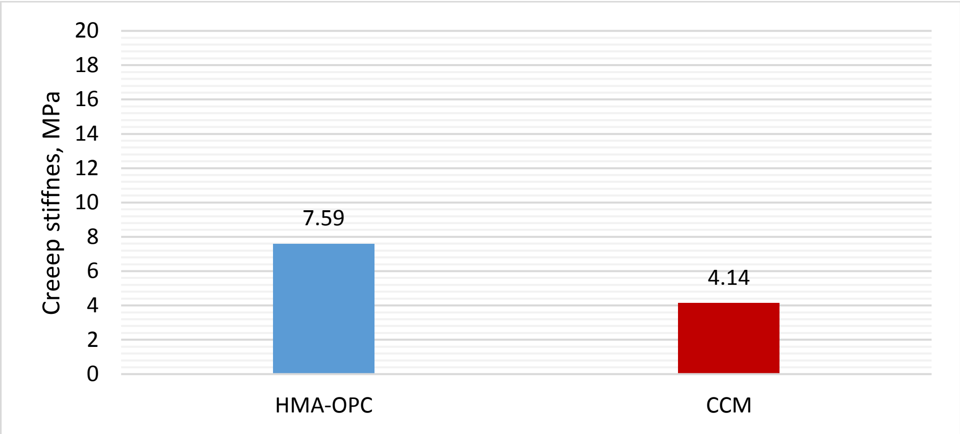


Figure 4-20 Creep stiffness for CCM and HMA

4.3.4 Durability tests

The durability test specimens were prepared in the same manner which was described for the Marshall test. The only main difference is in the curing protocol. Results of such testing are demonstrated below:

4.3.4.1 Water Sensitivity test

The water sensitivity test preparation includes two sets which were prepared for each single mix; the first set was cured for 24 hrs. at 25 ºC then cured at an oven 24 hr. at 40 ºC, while the second set was cured in addition to the first cured with vacuumed for 30 min and un-vacuumed for an extra 30 min, then immersed in water for 1 day at 60ºC. After applying the curing protocol, test was conducted according to ASTM D6931, D4867/D4867M (ASTM, 2012b, ASTM, 2014a). Results for specimens of CCM content the optimum asphalt emulsion value and other HMA are shown in Figure (4-21).

Because of high air void content and no anti-stripping additive, the mixture was no resistant the water damage for CCM.

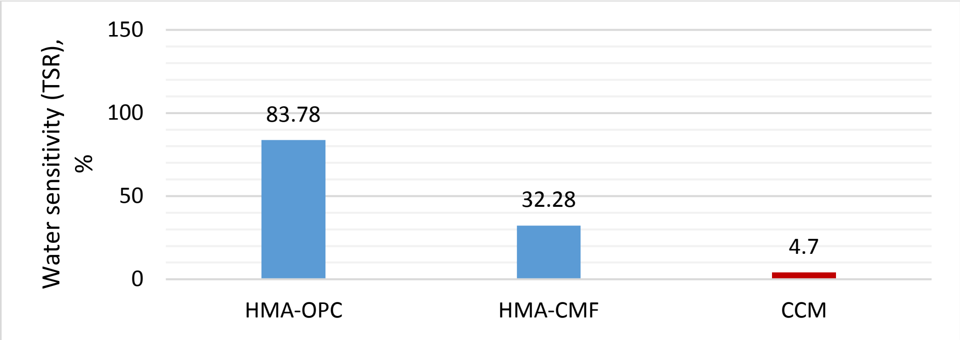


Figure 4-21 Water sensitivity CCM compared with HMA

4.3.4.2 Ageing test

Two sets of specimens were prepared for ageing test, the first cured for 14 days at 40 ºC, and the second set subjected to the same curing plus 5 days in an oven at 85 ºC according to Bell et al. recommendation to represent the long term ageing (1994). The results for the optimum emulsion value with other HMA are shown in Figure (4-22). The ageing test result of CCM is acceptable value when compared with HMA mixtures.

For comparative between HMA mixtures, OPC mixtures more affected both mixtures became deterioration, where OPC is more ageing and CMF is decline its properties, the reason may be became more brittle according continuous chemical reaction of cement, and for CMF as simply inert filler not resistance hard conditions of environmental. Where comparative between HMA mixtures and CMA, the ageing of HMA is less than CMA, it may be according to less air void.

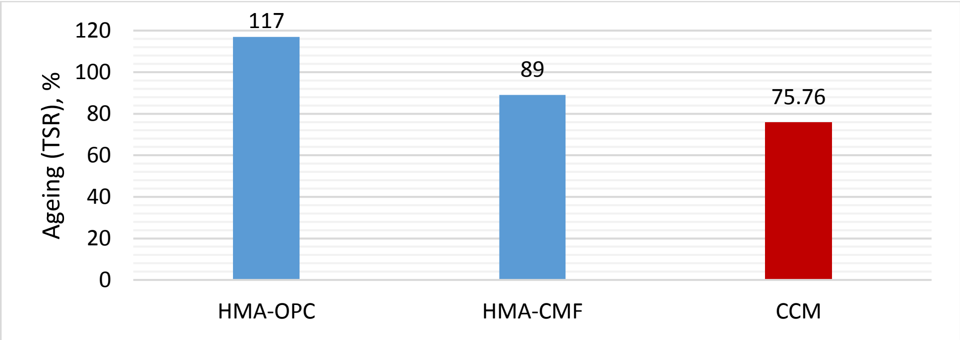


Figure 4-22 Results of ageing test of CCM

The results indicated that using conventional mineral filler with CBEMs are inappropriate. Also many researchers were pointed an agreement with this indication. García et al. reported that conventional CBEMs has low strength with reference to Marshall stability tests than HMA (García et al., 2013). Chávez-Valencia et al. stated that the compressive strength of conventional CBEMs is low without modifications (Chávez-Valencia et al., 2007). Al Nageim et al. apparent that the conventional CBEMs early age strength is low and failed in testing of creep stiffness before complete the testing (Al Nageim et al., 2012). Al-Busaltan et al. explained that the conventional CBEMs have poor resistance to permanent deformation (Oruc et al., 2007). About the durability test, the conventional CBEMs is low resistance to durability, also other researchers agree with this plaint as Al-Hdabi et al.(Al-Hdabi et al., 2013) and Al-Busaltan et al. (Al-Busaltan et al., 2012b).

4.4 Improving CMA by OPC

Attempt to improve the performance of CBEM by replacing conventional mineral filler by ordinary Portland cement was conducted. All CMF was replaced by OPC. OPC properties as described in section 3.2.2.2.

4.4.1 Mixtures' preparation

The preparation of mixture was the same procedure as followed in CCM, but the different from CCM is the following:

- Optimum Pre-Wetting Water Content (OPWwc)

Different five percent was used of pre-wetting water content to find the optimum pre-wetting, i.e., 3, 3.5, 4, 4.5, and 5 %, respectively. Approximately 3.5 % was found to be the optimum pre-wetting as shown in Figure (4-23).

- Optimum Asphalt Emulsion Content (OAEC)

  Repeated the same procedure as followed in CCM, also obtained 6 % as optimum value.

- Total liquid content (TLC= 3.5 + 11.2 = 14.7 %) of aggregate weight.

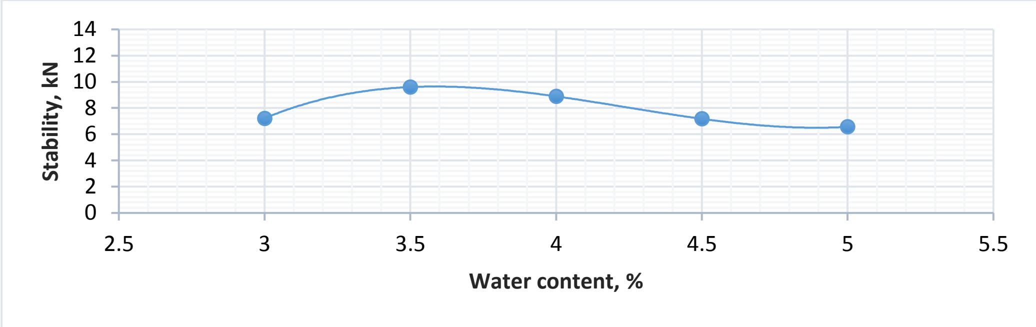


Figure 4-23 Water content vs stability of CBEM content OPC

4.4.2 Volumetric properties

Procedure used in CCM was followed with OPC, results of volumetric properties of the developed mixture as follows:

- Density as shows in Figure (4-24). The density decreased with continuance increasing bitumen content because the water of bitumen materials is left the mixture matrix with extra void after curing, and this minimize the density.
- Air void , Figure (4-25). It is clear from previous section the air void increase with increasing emulsion content.
- Void in mineral aggregate (V.M.A), Figure (4-26). VMA is increased with increased air void as described in section 4.3.2.
- Voids filled with binder (V.F.A), Figure (4-27). The same reason as described in section 4.3.2 is applied here.

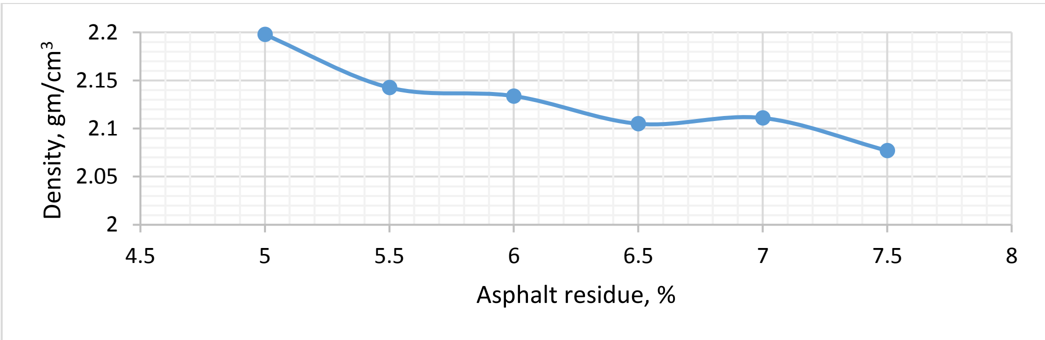


Figure 4-24 Density vs bitumen of CBEM content OPC

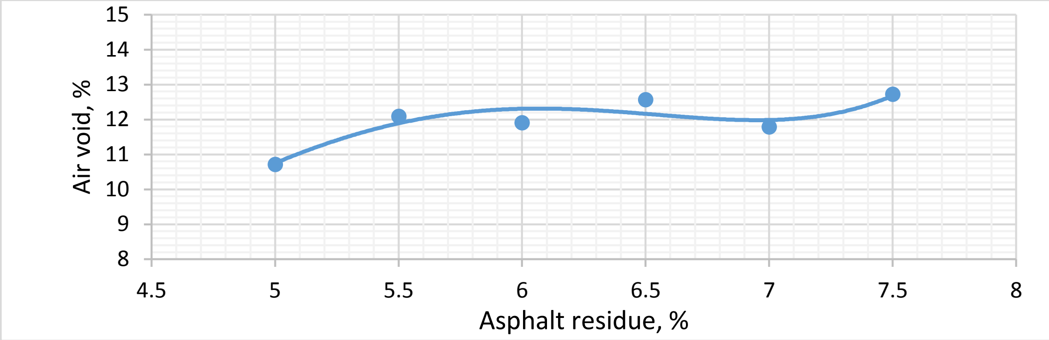


Figure 4-25 Air void vs bitumen of CBEM content OPC

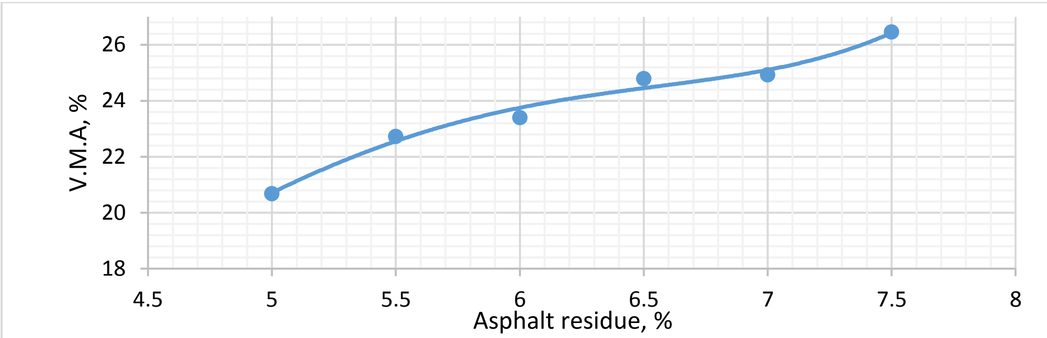


Figure 4-26 VMA vs bitumen of CBEM content OPC

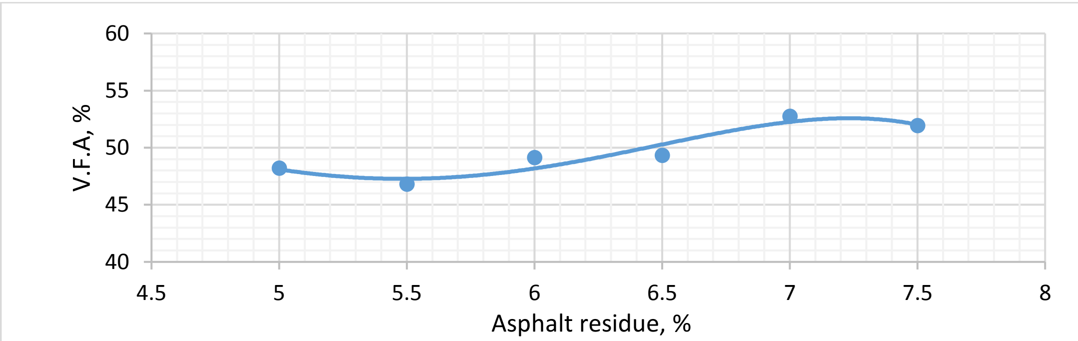


Figure 4-27 VFA vs bitumen of CBEM content OPC

4.4.3 Mechanical properties

In this section the results was set directly, while the details of tests as same as CCM.

4.4.3.1 Marshall test

- Marshall stability: the results of Marshall stability of mixtures as shown in Figure (4-28). The result is accepted according to GSRB. High value of stability depends to high interlock between particles of mixture, especially OPC particles are irregular and angular shapes and evenly distributed as shown Figure (3-2, b). Also, using OPC cured the mixture faster. OPC may act as a secondary binder in CBEMs that may be overcome to low strength at early time by hydration. The hydration process needs water to start and continue, so trapped water between aggregates and bitumen films is the source for that. Additionally, the viscosity of binder increased due to decreasing water content by OPC chemical reaction. The strength of mixture was clearly decreased when increased emulsion content, as a result of making thick film about aggregates, therefore decrease the friction between them. The percentage of enhancing of CMA-OPC when compared with CCM is 95% , also CMA-OPC stability value is slightly higher than HMA-OPC and the enhancing is 2%, it can be said that these values are equal.

- Marshal Flow: Figure (4-29) illustrates flow of specimens mixtures. As the same reason as described in previous section, recorded Marshall flows are started low and gradually increased with increase in emulsion content. Also the flow value of CMA-OPC is less than CCM, according to percentage the CMA-OPC is better than CCM by 35%, but when compared with HMA-OPC, the CMA-OPC flow is slightly more than HMA-OPC as 5% and can be say equally.

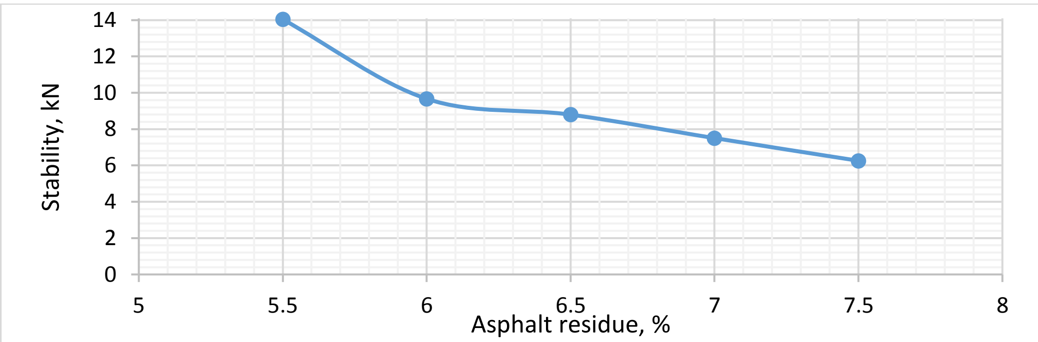


Figure 4-28 stability vs bitumen of CBEM content OPC

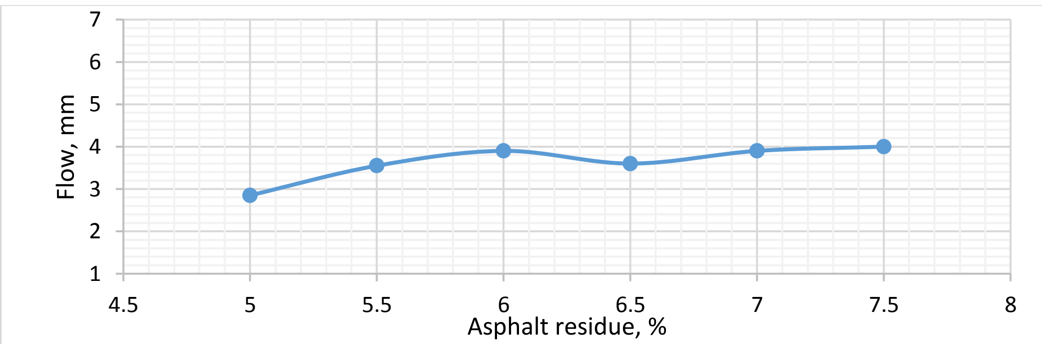


Figure 4-29 Flow vs bitumen of CBEM content OPC

4.4.3.2 Indirect Tensile Strength (ITS)

The results of ITS are low when compared with HMA, according to high water content at early life of mixture, therefore its strength for cracking is low. While when compared with CCM a significant improvement recorded, because OPC acts to produce a secondary binding from the hydration process. The natural of CBEMs is brittle or not flexible, therefore its strength for fatigue cracking is low due to brittle characteristics. Figure (4-30) illustrates the results. The percentage improvement of ITS when compare CMA-OPC with CCM is 80%.

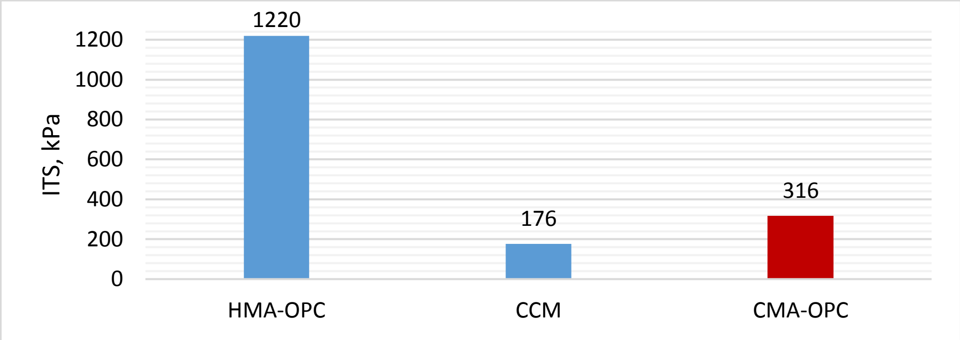


Figure 4-30 ITS test of CBEM content OPC

4.4.3.3 Wheel track test

The resistance of compacted asphalt mixtures to rutting was evaluated by using WTT. The results are presented in Figure (4-31), CBEM comprising OPC showed lower rutting from CCM and HMA, because the addition OPC to CBEMs produced a secondary binder. Creep stiffness results of mentioned mixture confirm the superiority of CBEM comprising OPC in resisting permanent deformation as shown in Figure (4-32). When compare CBEMs creep stiffness of CMA-OPC and CCM is observed, CMA-OPC better than CCM by 314%, also creep stiffness of CMA-OPC is better than HMA-OPC by 126%, therefore, CMA-OPC is less affected permanent deformation than other mixtures.

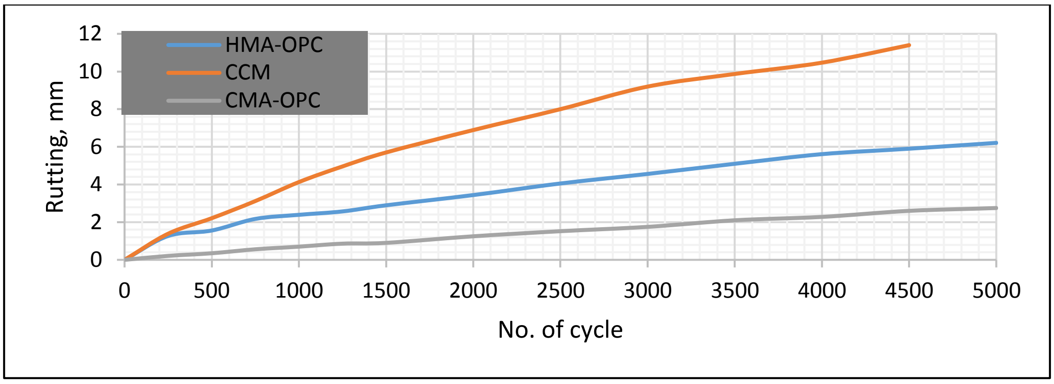


Figure 4-31 WTT for CMA with OPC

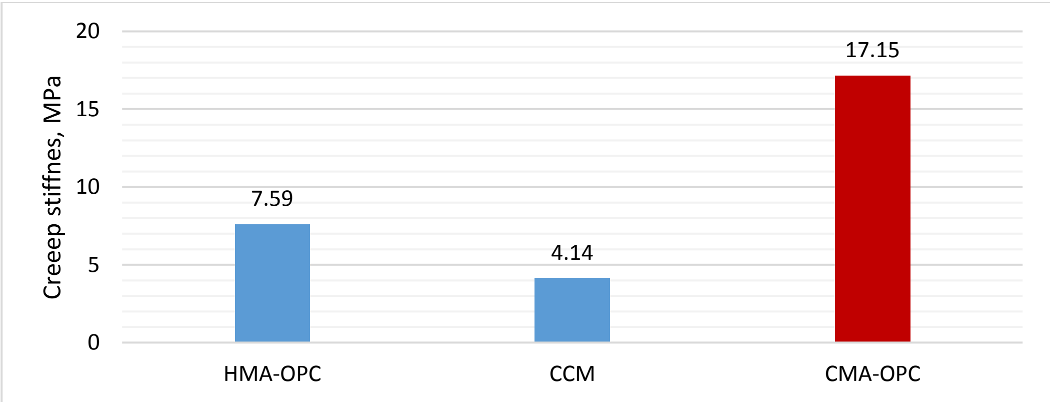


Figure 4-32 Creep stiffness of CBEM content OPC

4.4.4 Durability tests

Durability is related to air voids content and the asphalt binder film thickness around each aggregate particle. Tests details described in section 3.5.3, water sensitivity and ageing tests, conducted on CBEM comprising OPC. Result of such test explore in Figures (4-33) and (4-34), respectively. The air void of CBEM comprising OPC showed high resistance to water damage, as OPC acts anti-stripping binder from aggregate by chemical reaction with water, therefore materials became more cohesive and raised from viscosity of binder.

The ageing is more affected by bitumen and filler because of their primary importance in asphalt mixtures. Bitumen is the binder in the asphalt pavement, and filler because of its relatively large surface area compared to the rest of the aggregate and air void.

Although the air void of HMA is less than CMA, HMA-OPC is more affected to ageing from CMA-OPC. it may be returned to no temperature used for production of CMA which allows for less aging of the mixture. Also high air void of CMA at the same time associated with high VMA and VFA as described in volumetric properties; this caused thick film of bitumen about aggregates. CMA-OPC better than CCM according to high surface area of OPC when compared with CMF, where high surface area and particles' irregular shape of OPC that hamper the workability and lead to increase thickness of binder films by creating adsorbed layer of bitumen and increased resistance to age hardening. where specific surface area increase, it can contribute in increased adsorption. Also OPC improved bonding of the bitumen and aggregate, fracture toughening and reduction in the effects of ageing. When comparative this mixtures as a percentage value, the enhancing get when using OPC with CBEMs than CCM for both water sensitivity and ageing tests. From Figure (4-33) CMA-OPC get better than CCM as 2222%, also when compared CMA-OPC with HMA-OPC, the CBEMs with OPC is better than HMA with same filler as 30%.

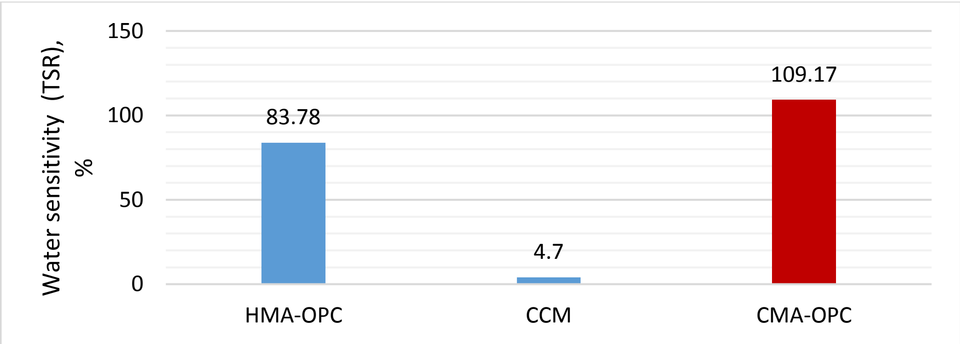


Figure 4-33 Water sensitivity test for CBEM content OPC

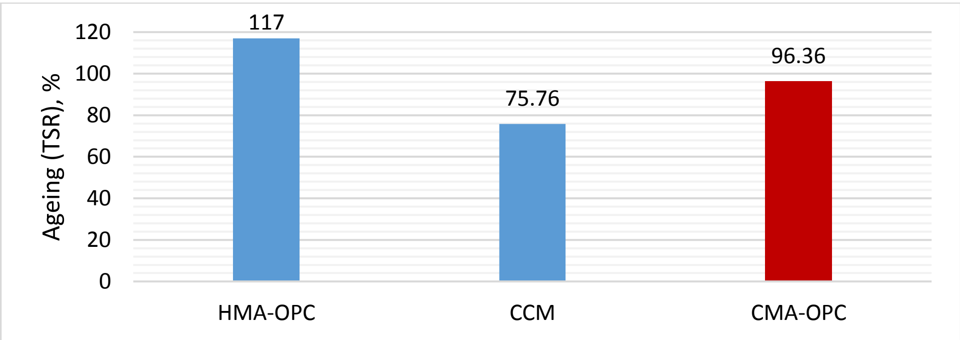


Figure 4-34 Ageing test for CBEM content OPC

It is concluded that using OPC as a filler instead of CMF in CBEMs gets very good mechanical, durability and volumetric properties of mixtures, it may be better until than HMA in more tests. It have high strength and resistance to deformation, water damage and ageing. Other researchers are agreement with these. Addition Portland cement to CBEMs increased the stability value and tensile strength (Issa et al., 2001, Niazi and Jalili, 2009). Creep stiffness increased with adding OPC to CBEMs (Dulaimi et al., 2015b, Al Nageim et al., 2012, Al-Hdabi et al., 2013). Water sensitivity of CBEMs with OPC is higher than until over HMA (Al-Hdabi et al., 2013, Dulaimi et al., 2015b, Al Nageim et al., 2012, Choudhary et al., 2012). Permanent deformation resistance were by addition of OPC (Choudhary et al., 2012, Xiao and Yu, 2011, Niazi and Jalili, 2009). Portland cement is effective adhesive agents for emulsion mixtures (Niazi and Jalili, 2009, Oruc et al., 2007). Brown and Needham reported that hydration of the cement, increasing the rate of coalescence and increasing the binder viscosity (Brown and Needham, 2000a).

4.5 CBEM with blend of CKD – OPC

CKD is known as cement by-pass dust, which is generated during production of Portland cement. OPC have explored a good contribution in improving CBEMs, but for economically and environmentally purposes, other alternatives have to use as supplementary Cement Materials; CKD and PLA are nominated in this research for such purpose.

4.5.1 Mixtures' preparation

There were different percentages of supplementary replacement of OPC by CKD have been used in order to achieve the mechanical properties stated by Iraqi specification for HMA; and adopted here for CBEM as a target properties. The following statement were tracked for preparation CBEMs comprising CKD:

- The percentages of supplementary fillers replacement of OPC are 25, 50, 75 and 100% CKD.
- The same value of residual bitumen content was used ; i.e., 6 %.
- The same pre-wetting water content as for CBEM comprising OPC (i.e., 3.5%) was adopted for using blend OPC with CKD, but when using CKD only the water content adopted 2.5 % as the value of using only PLA in mixtures, where experiments providing OPWwc for PLA is 2.5 %.
- Total liquid content results as (14.7 %).

4.5.2 Volumetric properties

- Density, illustrates as shown in Figure (4-35).
- Air void, as shown in Figure (4-36).

- Void in mineral aggregate (V.M.A), Figure (4-37).
- Voids filled with binder (V.F.A), Figure (4-38).

All volumetric properties for different percentages of OPC and CKD are near with them because of properties of OPC and CKD is close.

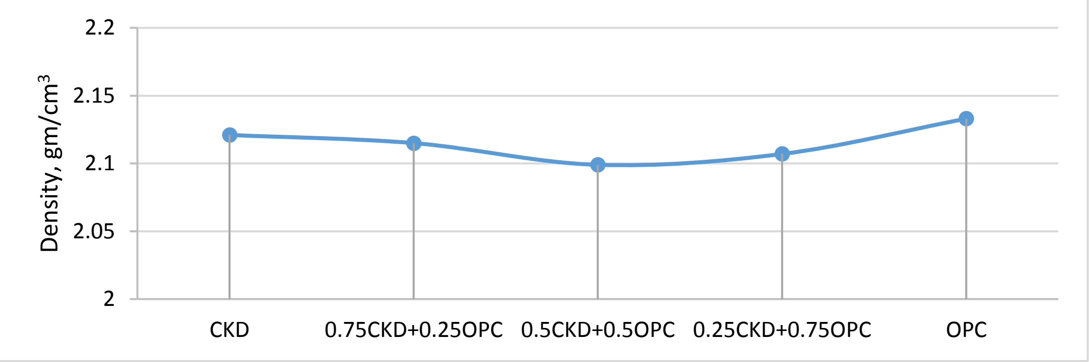


Figure 4-35 Density vs different percentages filler for CBEMs content(CKD+OPC)

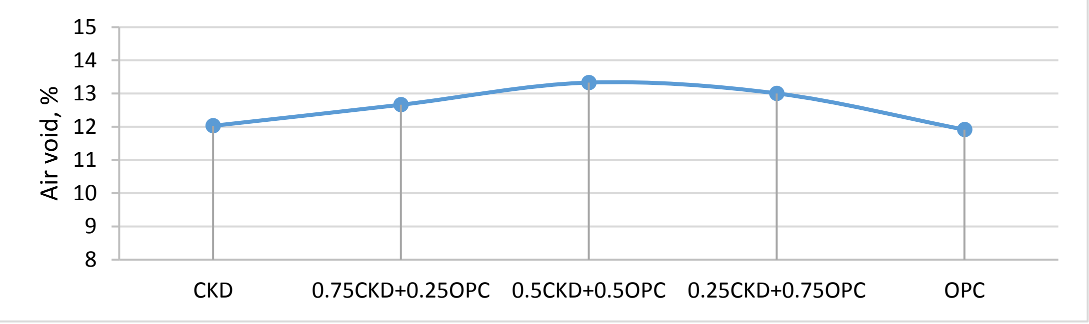


Figure 4-36 Air void vs different percentages filler for CBEMs content (CKD+OPC)

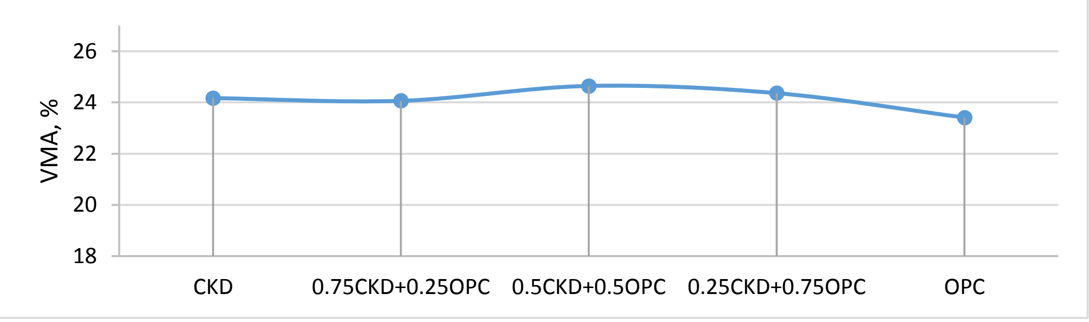


Figure 4-37 VMA vs different percentages filler for CBEMs content (CKD+OPC)

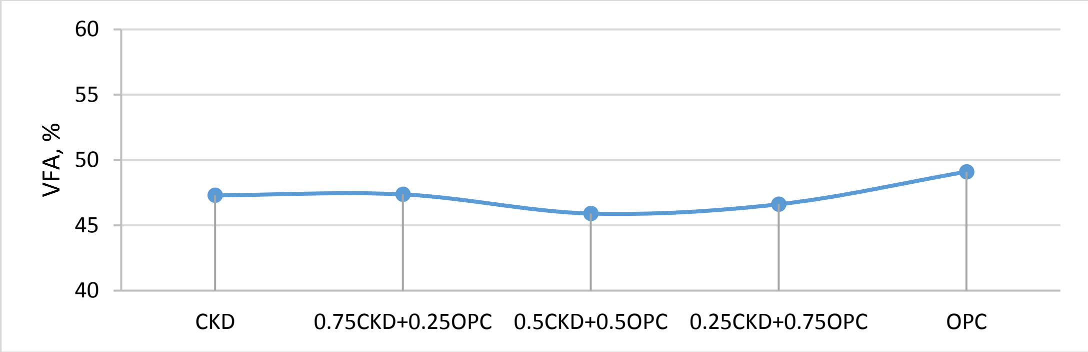


Figure 4-38 VFA vs different percentages filler for CBEMs content (CKD+OPC)

4.5.3 Mechanical properties

4.5.3.1 Marshall test

- Stability as shown in Figure (4-39). It is clear from the results that CKD negatively influenced to the mixture stability, whereas the stability of CBEMs decreased from containing CCM when used CKD as a filler alone by 95%, the stability increased with adding OPC until indicated the lower limit of GSRB at using (0.75OPC+0.25CKD). thereupon the enhancing percentage when comparative with CCM is 64%, but still lower than stability of mixtures containing OPC alone as 19%. The reason may be according to low hydraulic activity of CKD compared with OPC.
- Flow illustrates in Figure (4-40), the same reason can said here where initially high flow recorded with high CKD, then gradually decreased with increasing OPC. The value of flow when using CKD with CBEMs is better than using CCM' flow by a percentage of 25%, but be left higher from upper limit of GSBR, as stability with increasing OPC decreased flow value, until reached to optimum value when used (0.75OPC+0.25CKD) in CBEMs. Thus the enhancing in flow when comparative this mixtures with CCM is 40%. While when comparative with CBEMs containing OPC, (0.75OPC+0.25CKD) is very slightly enhanced flow as 7%.

But it can said that Iraqi specification requirements can be achieved with (0.75OPC+0.25CKD).

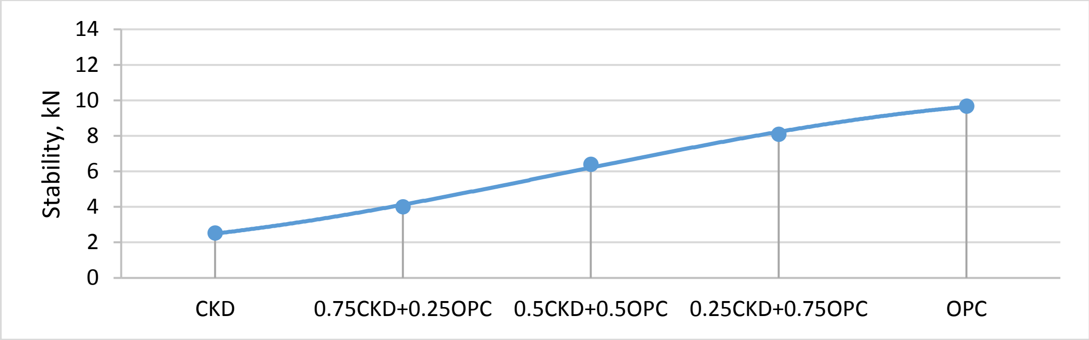


Figure 4-39 Marshall stability vs different percentages filler for CBEMs content (CKD+OPC)

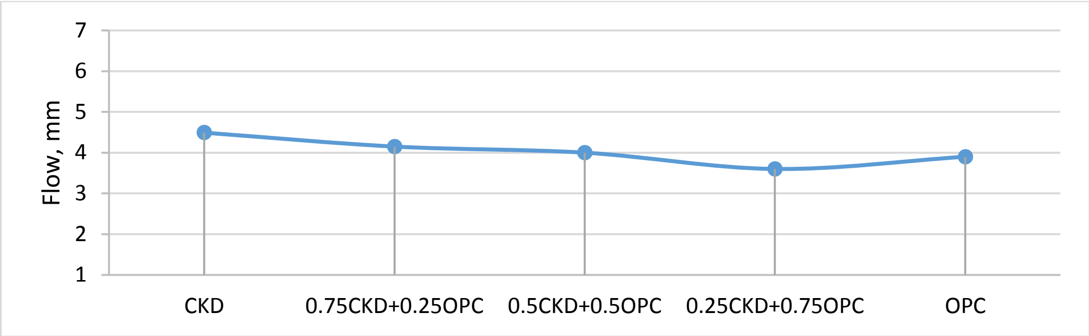


Figure 4-40 Flow vs different percentages filler for CBEMs content (CKD+OPC)

4.5.3.2 Indirect tensile strength ITS

ITS is applied only for the mixture that success the specification according to Marshall test. This mixture represented CBEM have fillers of (0.75OPC+0.25CKD). Figure (4-41) illustrates the result of such mixture. The same discussion as described in 4.4.3.2 can applied here in this section. ITS of CBEMs is enhanced by using (0.75OPC+0.25CKD) when comparative with CCM by 76%. While when comparative this mixtures with other containing OPC alone, there is no clear different can be seen between them as shown in Figure (4-41).

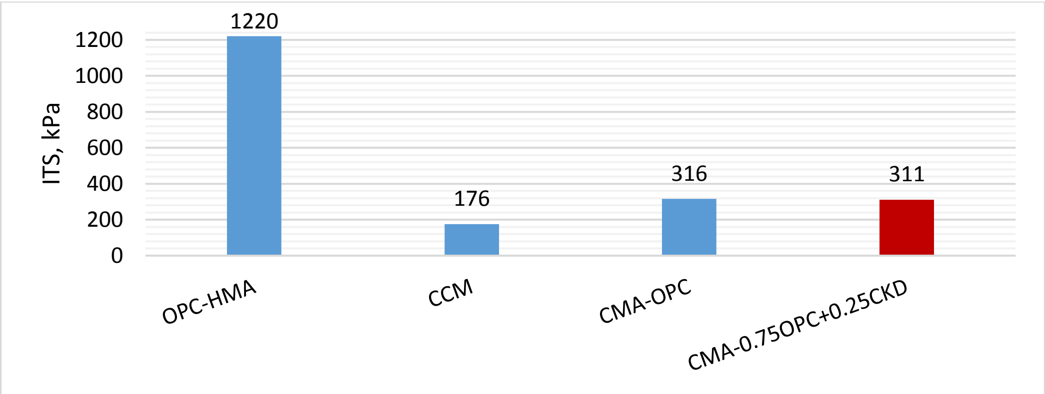


Figure 4-41 ITS test for OPC+CKD

4.5.3.3 Wheel track test

As the same for ITS, wheel track was applied only on the mixture that pass the Marshall test according to Iraqi specification. Figure (4-42) illustrates the wheel track test. Because of high content of OPC, mixture is behaved as same as when contain only OPC. Creep stiffness confirm the same results as can be seen in Figure (4-43), from the same figure it can be concluded that the creep stiffness of CBEMs containing (0.25OPC+0.75CKD) is higher than CCM by 242%, but it is less than CBEMs contained OPC alone by 17%.

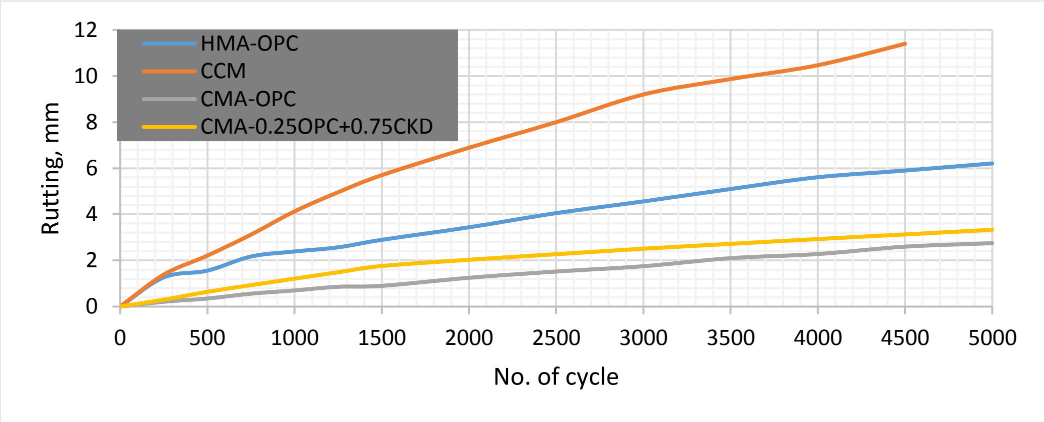


Figure 4-42 Wheel track test for mixture having fillers (CKD+OPC)

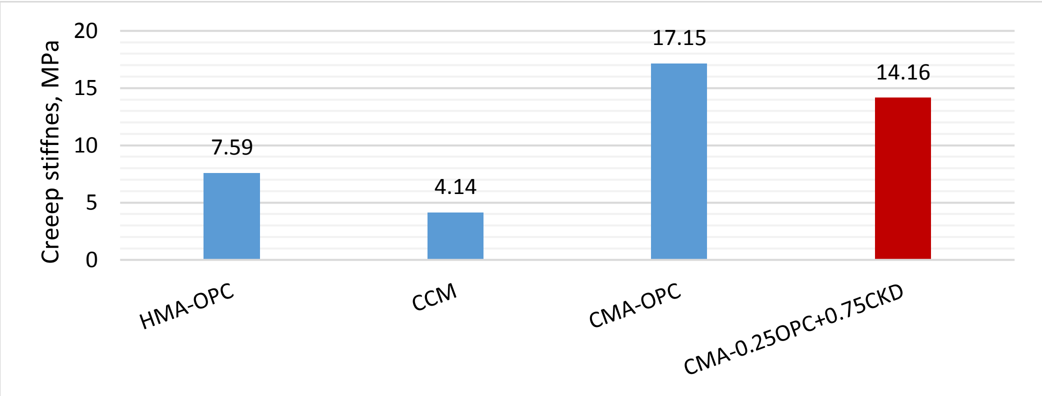


Figure 4-43 Creep stiffness of CBEM content blend of (CKD+OPC)

4.5.4 Durability test

The water sensitivity and ageing test as shown in Figures (4-44) and (4-45), respectively for the mixtures that having fillers (0.75CKD+0.25OPC). The durability test of CBEM comprising blending of CKD with OPC is behavior such as when mixture contain only OPC, but because of less hydraulic activity, furthermore high surface area of CKD may be enhanced the water sensitivity of CBEMs. When comparative the water sensitivity of CBEMs, the using (0.75CKD+0.25OPC) is highly better than CCM by 2427%, and slightly better than using OPC in mixtures as 8%. In addition the discussion about ageing in section 4.4.4, Indeed no high variation in ageing properties for mixes containing different types of fillers (CMA-OPC and CMA-0.75OPC+0.25CKD) can be seen, the little depression in ageing about CBEMs containing (0.75OPC+0.25CKD) according to CKD' particles shape is not angularity as OPC' particles, this may be lead to not restricted bituminous materials and thus lead to continuously and melt in heating.

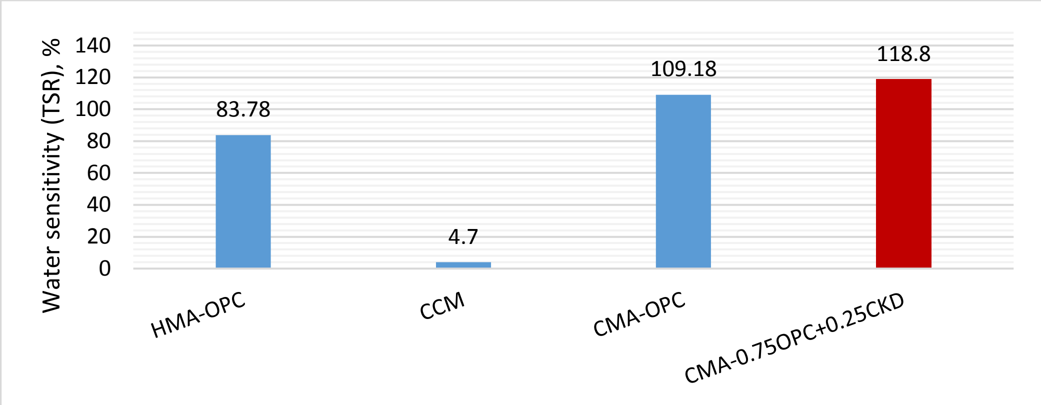


Figure 4-44 Water sensitivity test for mixture having fillers (CKD+OPC)

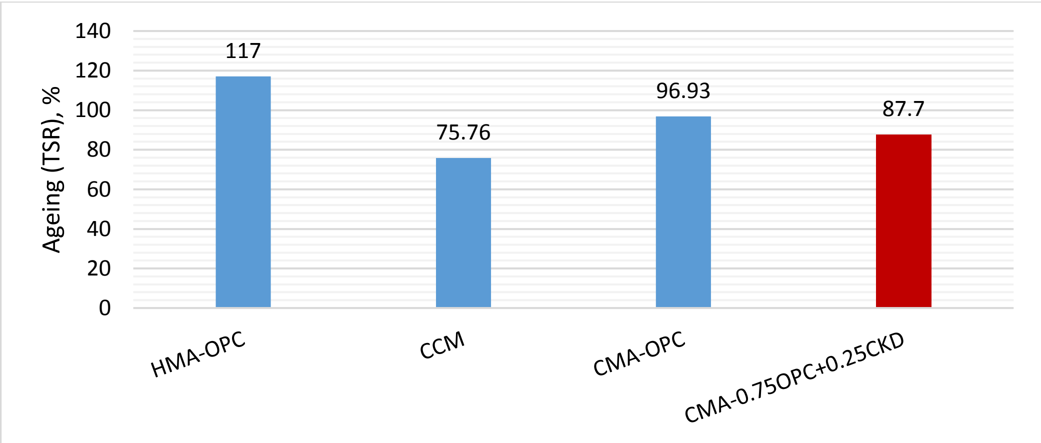


Figure 4-45 Ageing test for mixture having fillers (CKD+OPC)

CKD could be tested for the first time as a filler in the CMA in this research work. As previously described, CKD is a by-product generated during manufacturing of Portland cement. But researchers used CKD in other civil engineering applications and there results could be reached to support this research work. Hydraulic binder such as CKD, possibly use as replacement for Portland cement, CKD increased the viscosity of binder, thus increased the stiffness (Ekblad et al., 2015), therefore more negative affects to ageing was recognized when adding CKD to mixture. The tensile strength increased by the CKD content (Modarres et al., 2015). CKD fillers is fine particles, according this specific surface area increased, also the tensile strength increased by the CKD content (Modarres et al., 2015). CKD increased the viscosity of asphalt and a positive effect on the bond strength of the mastic (Wahhab and Dalhat). Active fillers in foamed asphalt mixes were added to modify the fine fraction of aggregate gradation or to reduce the moisture sensitivity of the mix. The addition of CKD increased the strengths in foamed CMA (Halles and Thenoux, 2009). Cement kiln dust Hardens when exposed to moisture (Goel and Das, 2004), therefore CKD have high resistance to water damage. To resistance moisture damage can be used hydraulically active fillers; Portland cement or cement kiln dust (Ekblad et al., 2015).

4.6 CBEM with blend of PLA – OPC

The effect of waste materials as PLA on CBEM properties was investigated by partial replacement of OPC by PLA. The same procedure of section 4.5 was followed in this section. Mixture preparation is carried out as the same manner of (CKD – OPC).

4.6.1 Volumetric properties

- Density , illustrates as shown in Figure (4-46).
- Air void, as shown in Figure (4-47).
- Void in mineral aggregate (V.M.A), Figure (4-48).
- Voids filled with binder (V.F.A), Figure (4-49).

No clear variation in density for mixes containing different types and percentages of OPC and PLA fillers can be seen, this may be attributed to similarity about angularity particles shapes. Low air void and VMA, and high VFA of PLA filler is according to high surface area, where increasing specific surface area can contribute to increased adsorption of bitumen.

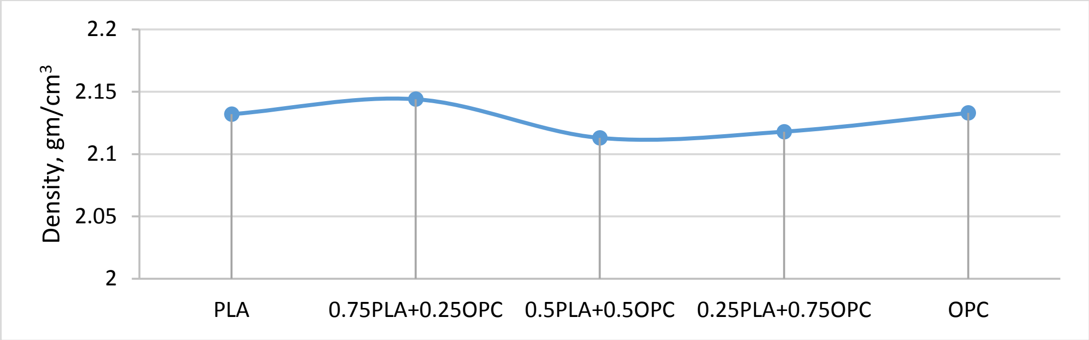


Figure 4-46 Density vs different percentages filler for CBEM comprising (PLA+OPC)

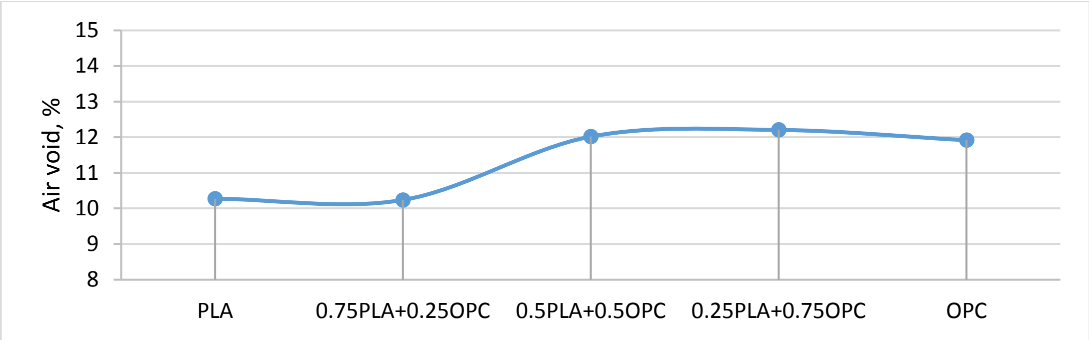


Figure 4-47 Air void vs different percentages filler for CBEM comprising (PLA+OPC)

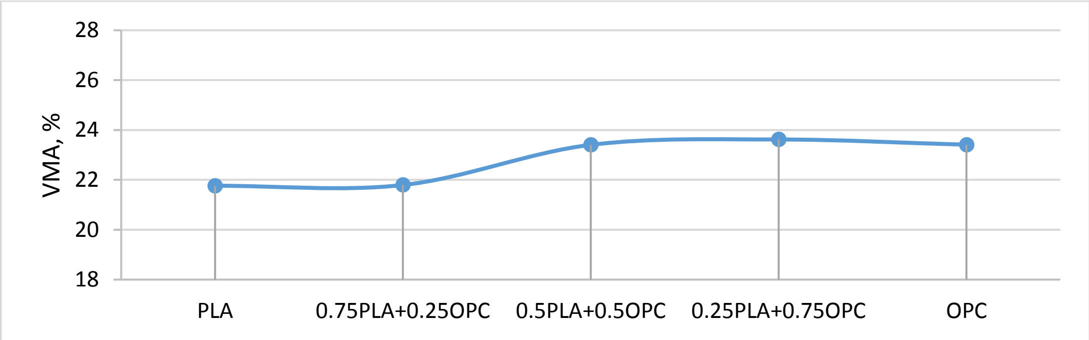


Figure 4-48 VMA vs different percentages filler for CBEM comprising (PLA+OPC)

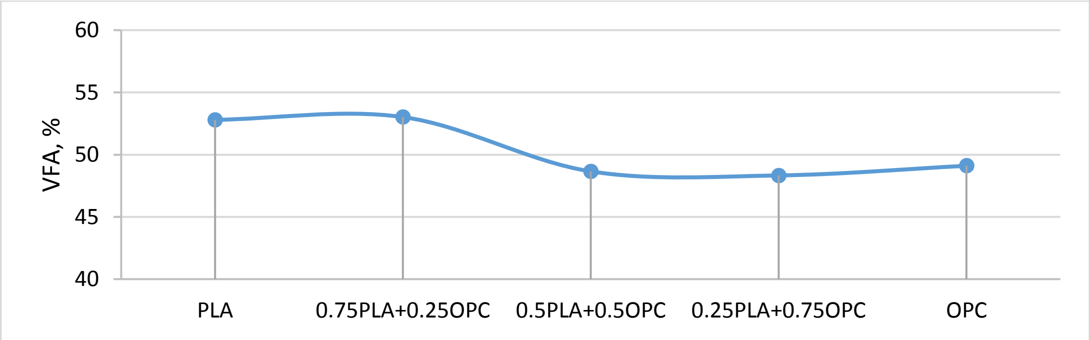


Figure 4-49 VFA vs different percentages filler for CBEM comprising (PLA+OPC)

4.6.2 Mechanical properties

4.6.2.1 Marshall test

- Stability, Figure (4-50) illustrates the results. The stability of CBEM comprising PLA alone is close to CCM when its used as 100% CMF. it may return to low hydraulic characteristics and particles shape angularity of CMF and PLA.

  It is observed from Figure (4-50) that the stability increased with increase the replacing percent of PLA by OPC, relatively, until reach optimum value with 0.25PLA+0.75OPC, even better than OPC alone by 12%. Also, when the mixtures having 0.75PLA+0.25OPC was satisfied the Iraqi specification and better than CCM by 52%. High strength of mixtures may be returned to pozzlanic effect and high surface area of PLA when compared with other fillers. In addition, angularity shape of particles, this may be all increased viscosity of mastic, thus high cohesive between component of mixture. Also it may be retain to the ability of PLA to absorbed water of mixture.

- Flow, illustrated in Figure (4-51). As the same reasons as described in stability, flow initially high and decreased gradually with increasing OPC percentage.

  Flow value of CBEMs containing PLA is better than flow value of CCM, but still higher than upper limit of GSRB. When partially replacement PLA by OPC in CBEMs, the flow values of mixtures enhanced and agreed with limits of GSRB. The enhanced percentage when comparative CCM with CBEMs containing (0.75PLA+0.25OPC) and (0.25PLA+0.75OPC) is 48% and 38% respectively, and when comparative the same two mixtures with CBEMs including OPC is enhanced as 20% and 4% ,respectively.

From figures blow chose the minimum percentage value of OPC that achieve the Iraqi specification. It was represented by (0.75PLA+0.25OPC).

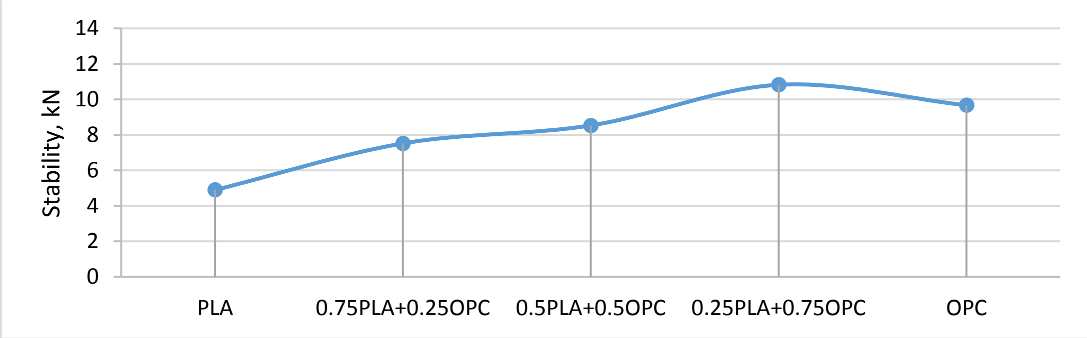


Figure 4-50 Marshall stability vs different percentages filler for CBEM comprising (PLA+OPC)

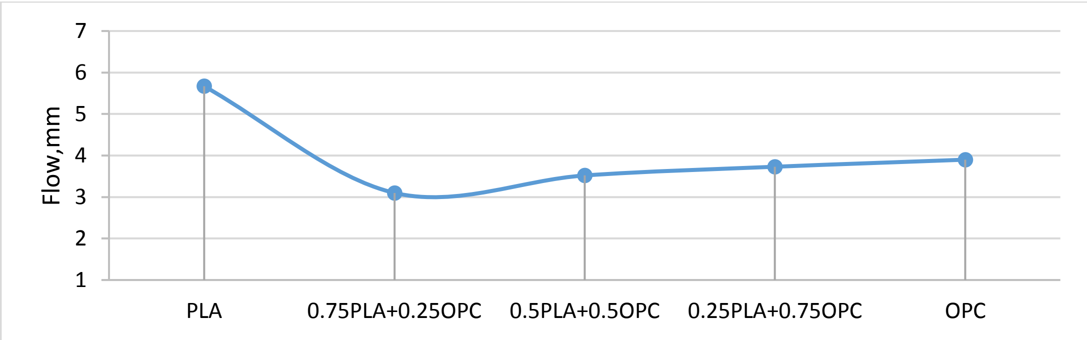


Figure 4-51 Flow vs different percentages filler for CBEM comprising (PLA+OPC)

4.6.2.2 Indirect tensile strength, ITS

ITS was applied only for the mixture have fillers (0.75PLA+0.25OPC). ITS for this mixture is good when compared when CCM as shown in Figure (4-52). The high result is according to improvement that added by PLA which work as pozzlanic material. CBEMs with fillers (0.75PLA+0.25OPC) have ITS higher than CCM by 53%, but less than CBEMs with OPC by 14%.

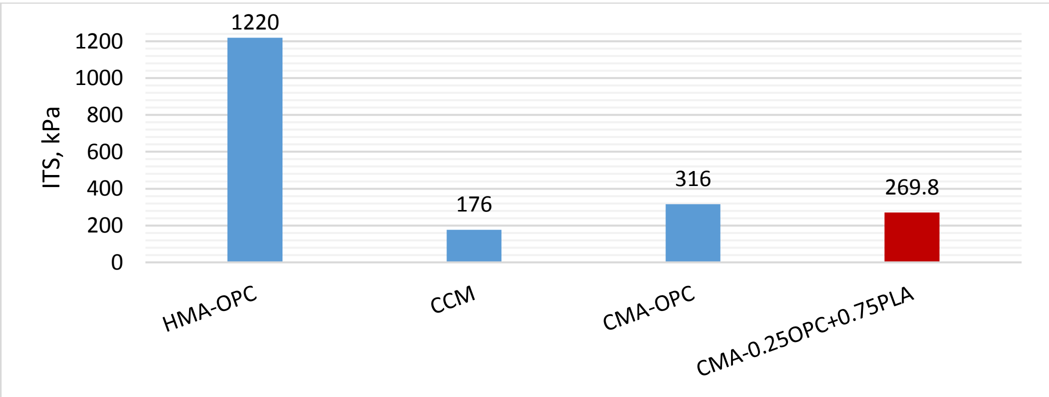


Figure 4-52 ITS test

4.6.2.3 Wheel track test

Also, wheel track test applied only for specimens that chose with fillers of (0.75PLA+0.25OPC). Figure (4-53) illustrates the result. WTT for PLA is good when compared when CCM and HMA. Creep stiffness confirm the results as illustrated in Figure (4-54). The same discussed in Marshall and ITS test is applied here about low permanent deformation for this mixtures. From Figure (4-54) it can be expression that the enhanced in permanent deformation when compare CBEMs contained fillers (0.25OPC+0.75PLA) with CCM by 184%, this mixture is lower than CBEMs contained OPC by 31%.

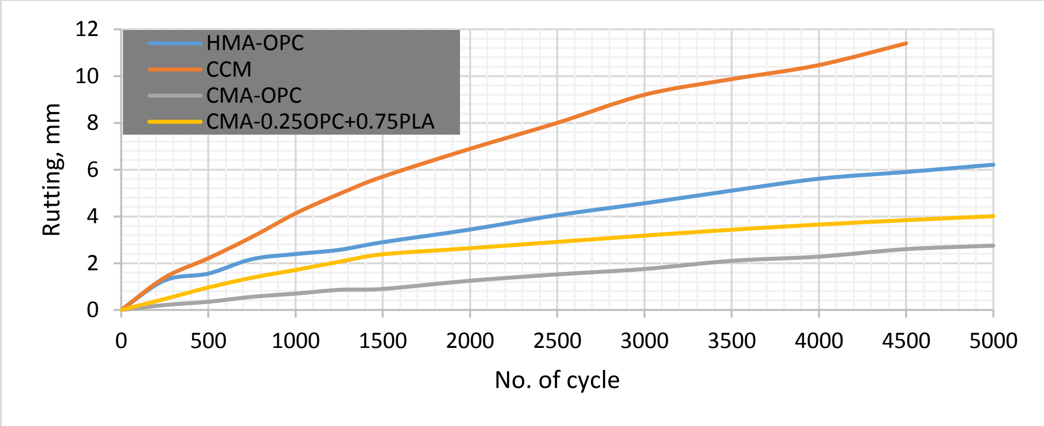


Figure 4-53 WTT for mixture having fillers (PLA+OPC)

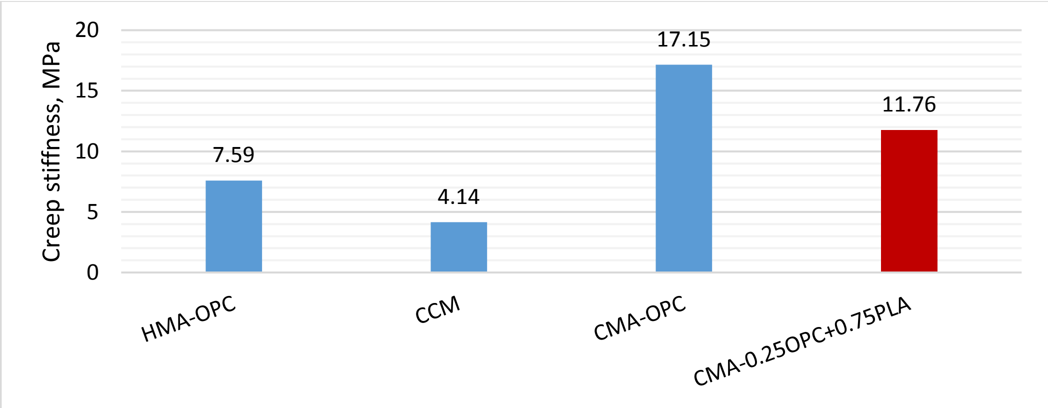


Figure 4-54 Creep stiffness of CBEM comprising blend PLA+OPC

4.6.3 Durability test

The water sensitivity and ageing test as shown in Figures (4-55) and (4-56), respectively, for the mixtures that having fillers (0.75OPC+0.25PLA). PLA pozzlanic characteristics may after the improvement in water damage resistance, therefore this mixture have high resistance of deterioration. Also PLA when added to mixtures, decreased air void that may be decreased permeability of mixture, thus high durability. In addition discussion as described in sections 4.4.4 and 4.5.4 for ageing are applied here. It is noteworthy, PLA have very high surface area. From Figure (4-55), CBEMs with fillers (0.25OPC+0.75PLA) are highly resistance of water damage by 3065% and 36% higher than CBEMs contained CMF and OPC, respectively. From Figure (4-56) this mixtures (CMA-0.25OPC+0.75PLA) is close to CBEMs having OPC alone.

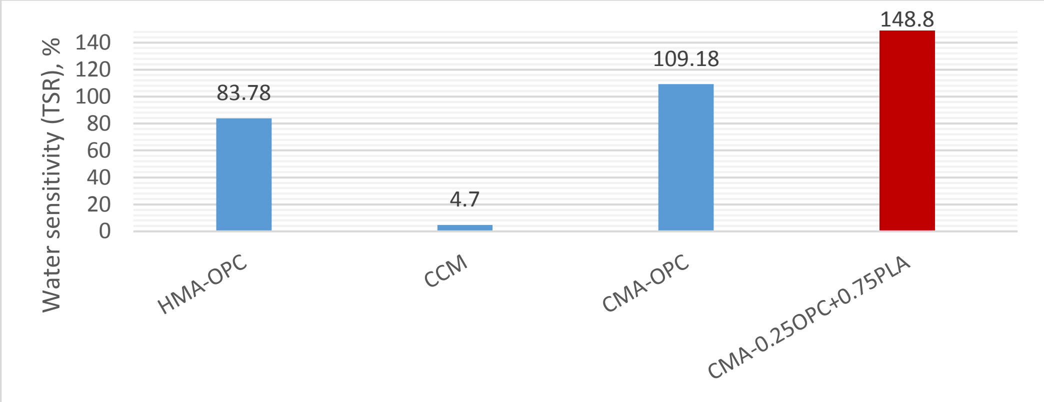


Figure 4-55 Water sensitivity test for mixture having fillers (PLA+OPC)

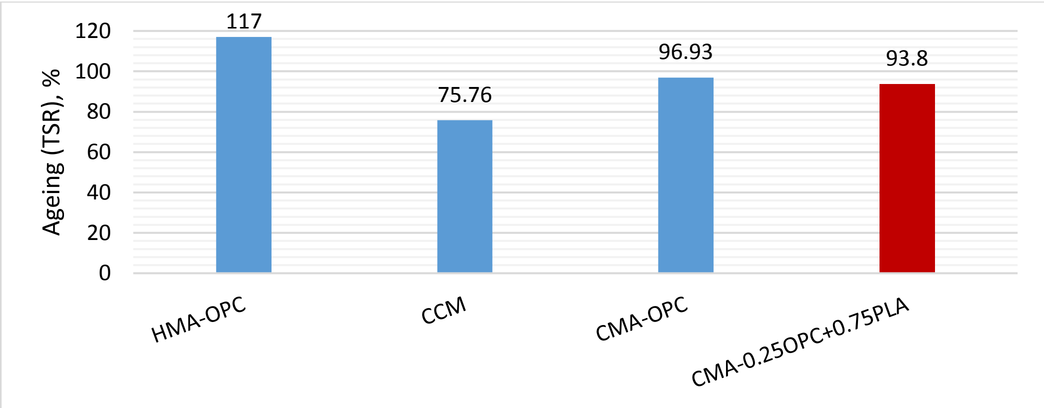


Figure 4-56 Ageing test for mixture having fillers (PLA+OPC)

There are many benefits of using pozzolanic materials in road construction, especially in CBEMs, many researchers agreed with this hypothesis as next. Thanaya reported that Pozzolanic harden in the presence of water and/or cement (Thanaya et al., 2009), enhancement of ultimate strength due to the cementitious effect (Thanaya, 2003). Modarres claimed that this materials increased the Marshall stability, ITS and the moisture resistance was acceptable (Modarres and Ayar, 2016). Al-Hdabi claimed that improving the mechanical properties due to the cementitious properties of waste and by-product materials (Al-Hdabi et al., 2014). While Al-Busaltan said that pozzolanic improved of permanent deformation resistance and water sensitivity when compared with CCM (Al-Busaltan et al., 2012b). Al Nageim said that some of fillers as fly ash superiority to OPC in enhancing the mechanical and durability properties due to its high water absorbability of CBEM's, until over than CBEMs contained only OPC (Al Nageim et al., 2012), Al-Busaltan agree whit him and added, it is due to the hydration process (Al-Busaltan, 2012), and Dulaimi (Dulaimi et al., 2015a). Some of the pozzolanic use as secondary binders (Nunes, 1997). Hesami said that biomass filler increased the viscosity of mastic, moisture and aging had significant effects on the viscosity of mastics according to particle shape, size distribution (Hesami et al., 2013). Roger et al. claimed interestingly enough that highest reactivity to emulsions consisted of material with high surface (Lundberg et al., 2016).

4.7 CMA with blend of CKD – PLA

Attempt was conducted for further improvement of CBEM by blending by-product material and waste material by replacing all OPC to CKD and PLA. This is on the base of chemical composition of the both filler when compared with OPC.

4.7.1 Mixtures' preparation

There were different percentage of supplementary blending for CKD and PLA. The different percentage used in order to get optimum blending percentage that may be used.

- The percentages of supplementary fillers was achieved when replaced CKD by 25, 50, 75 % of PLA.
- The same value of residual bitumen content was used for CKD and PLA; i.e., 6 %.
- The same value of pre-wetting water content for PLA (i.e., 2.5 %) was adopted.
- Total liquid content results as 13.7 %.

4.7.2 Volumetric properties

- Density , illustrates as shown in Figure (4-57).
- Air void, as shown in Figure (4-58).
- Void in mineral aggregate (V.M.A), Figure (4-59).
- Voids filled with binder (V.F.A), Figure (4-60).

The behaviors of volumetric properties about adding PLA and CKD fillers to mixtures are the same manner as described in section 4.6.1.

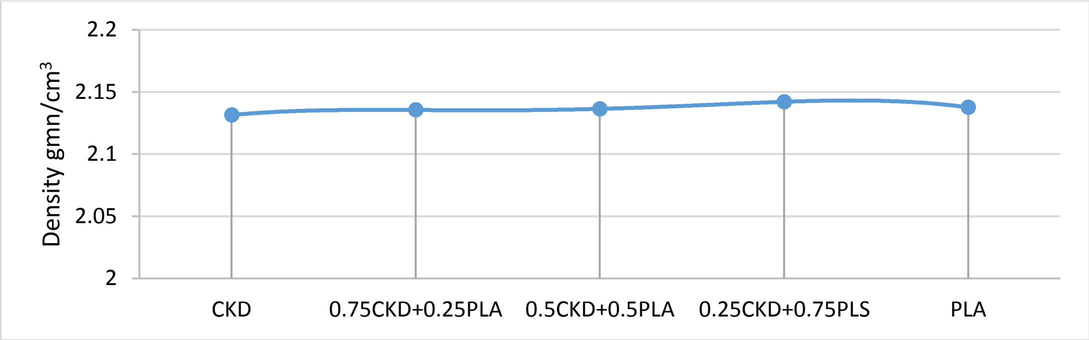


Figure 4-57 Density vs different percentages filler for CBEM comprising (CKD+PLA)

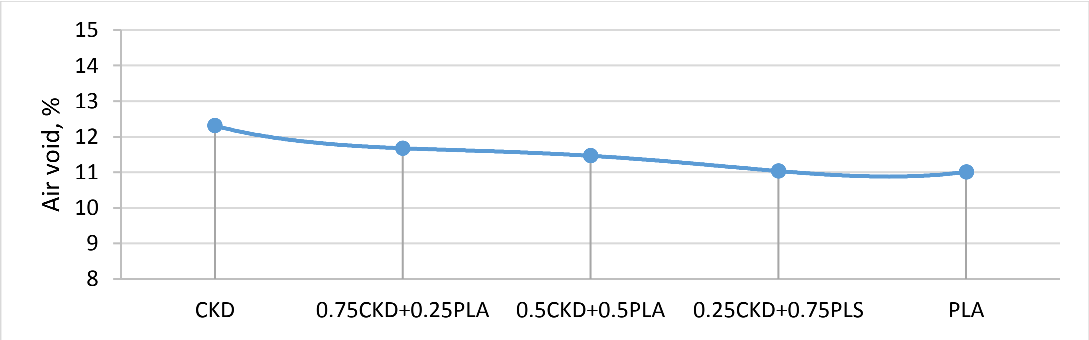


Figure 4-58 Air void vs different percentages filler for CBEM comprising (CKD+PLA)

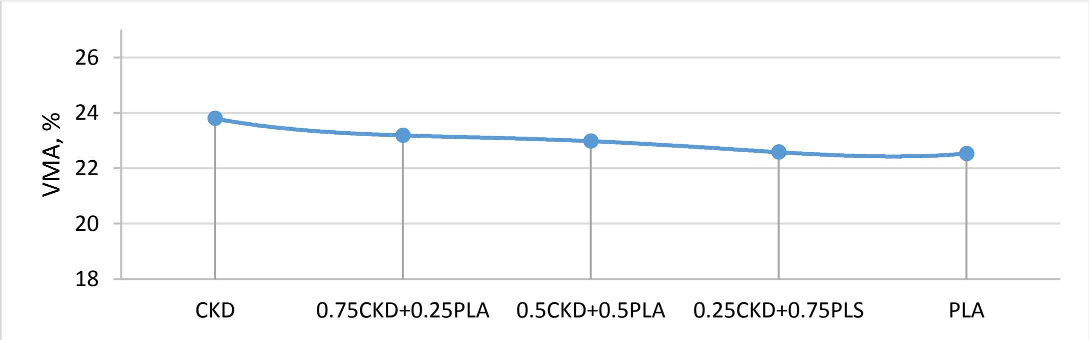


Figure 4-59 VMA vs different percentages filler for CBEM comprising (CKD+PLA)

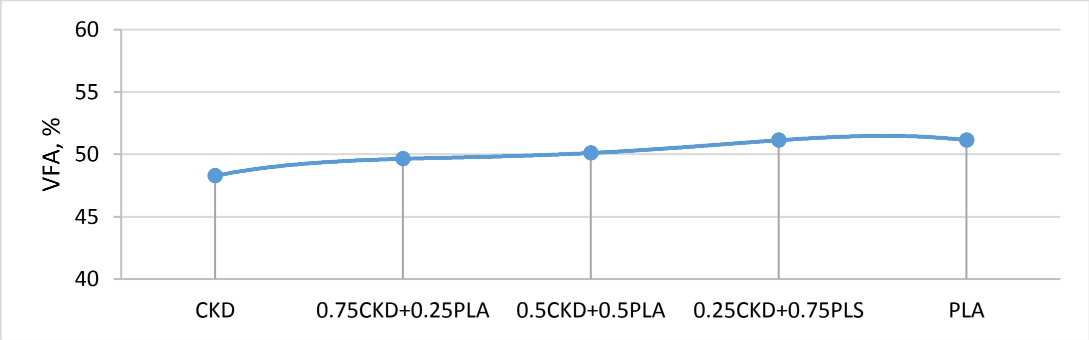


Figure 4-60 VFA vs different percentages filler for CBEM comprising (CKD+PLA)

4.7.3 Mechanical properties

4.7.3.1 Marshall test

Marshall stability for CBEM comprising (CKD+PLA) is shown in Figure (4-61), while Marshall flow is illustrated in Figure (4-62). From this figures the optimum percentage of blending can be nominated as (0.25CKD+0.75PLA), although maximum Marshall stability is obtained with 100% PLA, but Marshall flow govern the nominated value. However, the low hydraulic activity of CKD with pozzolanic effect of PLA are after such results. Also, it has to say that none of blend percentage facilitated to reach the Iraqi specification requirements. The decreasing percentage of stability for this mixture (0.25CKD+0.75PLA) when compare with CCM is 23%, but flow enhanced by 27%.

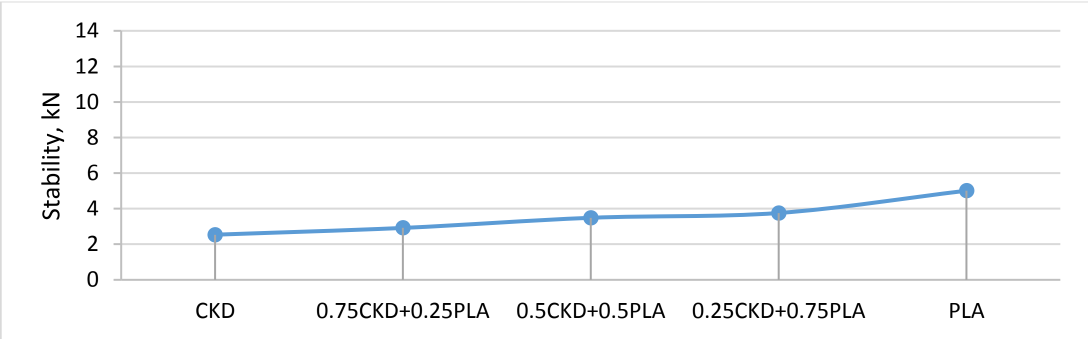


Figure 4-61 Marshall stability vs different percentages filler for CBEM comprising (CKD+PLA)

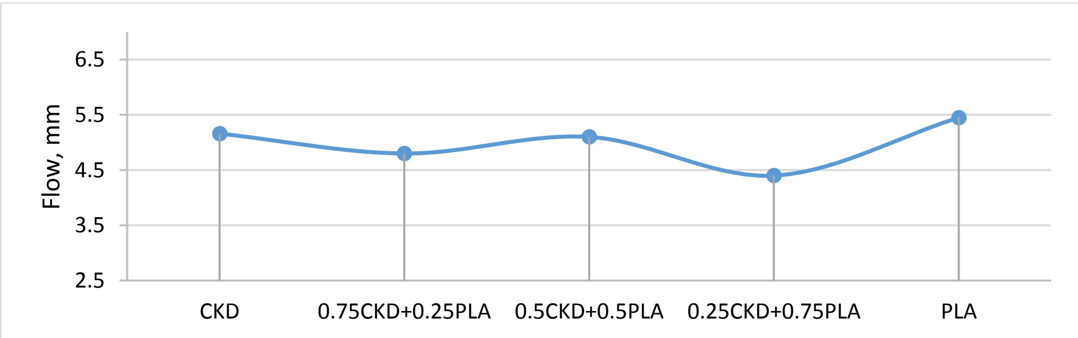


Figure 4-62 flow vs different percentages filler for CBEM comprising (CKD+PLA)

4.7.3.2 Indirect tensile strength ITS

ITS test applied only to the optimum value as previous. The results are shown in Figure (4-63). It is observed from this figure that the value of CBEMs comprising blending of (0.25CKD+0.75PLA) is low when compared with CCM, the reason may be related to low activity of CKD to PLA, where the particle shape plays the role in gain the cracking resistance. The decreasing percentage of ITS for this mixture (0.25CKD+0.75PLA) when comparative with CCM is 20%, while when compare with CBEMs containing OPC, the decreasing is 55%.

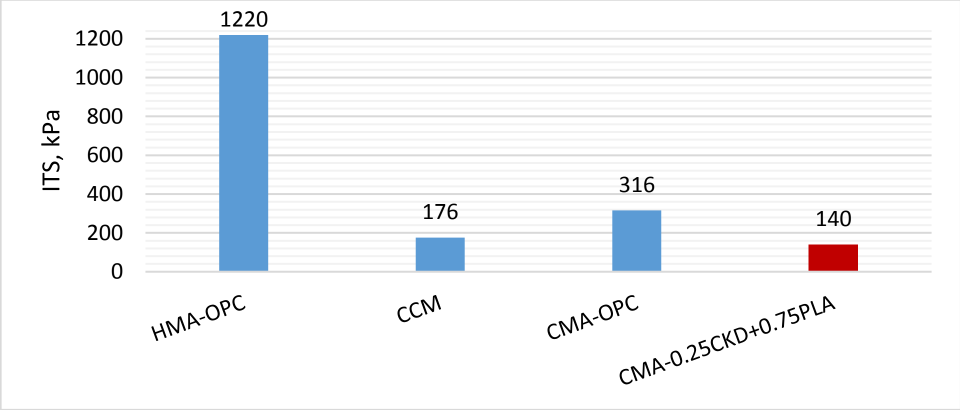


Figure 4-63 ITS test for CBEM comprising (CKD+PLA)

4.7.3.3 Wheel track test

Also, Wheel track test was applied only to the optimum value. Figure (4-64) illustrates the test value. Rutting resistance is good for this mixture when compared with CCM and HMA. Creep stiffness confirm the result as shown in Figure (4-65). Although CBEMs with fillers (0.25CKD+0.75PLA) are failed in Marshall test and ITS' value is low, but from Figure (4-65) notices this mixture have good creep stiffness and higher than CCM as 181%.

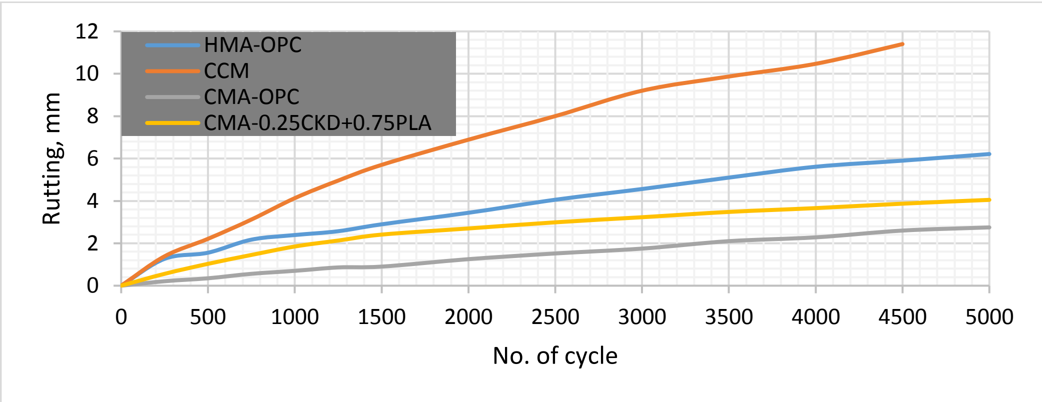


Figure 4-64 WTT for mixture having fillers CBEM comprising (CKD+PLA)

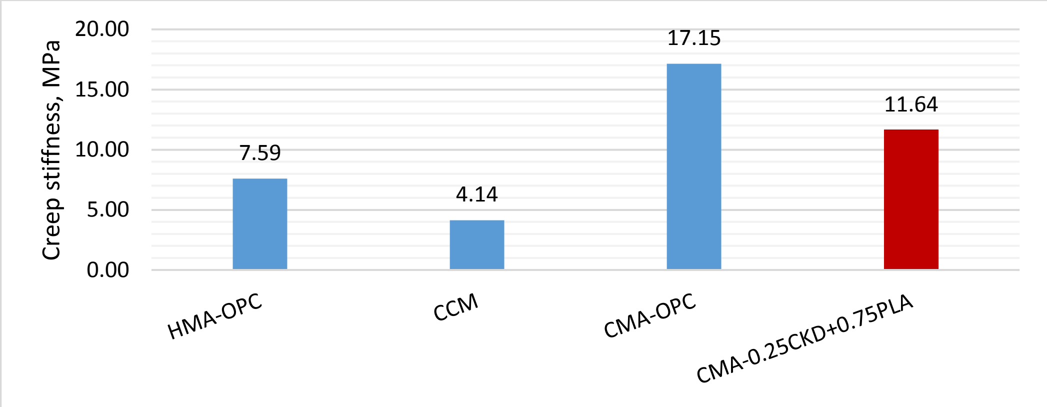


Figure 4-65 Creep stiffness of CBEM comprising blend CKD+PLA

4.7.4 Durability tests

Also, in these tests that used CBEMs comprising (0.25CKD+0.75PLA) water sensitivity and ageing tests were achieved, where their results illustrated in Figures (4-66) and (4-67), respectively. Water damage resistance is good when compared CCM with CBEM comprising (0.25CKD+0.75PLA), it is higher as 1953% than CCM. It appears that the low activity of CKD with the pozzlanic effect of PLA is enough to resist the stripping. About ageing resistance may be return to high surface area of PLA that leads to increasing thick film, therefore it is better than CCM.

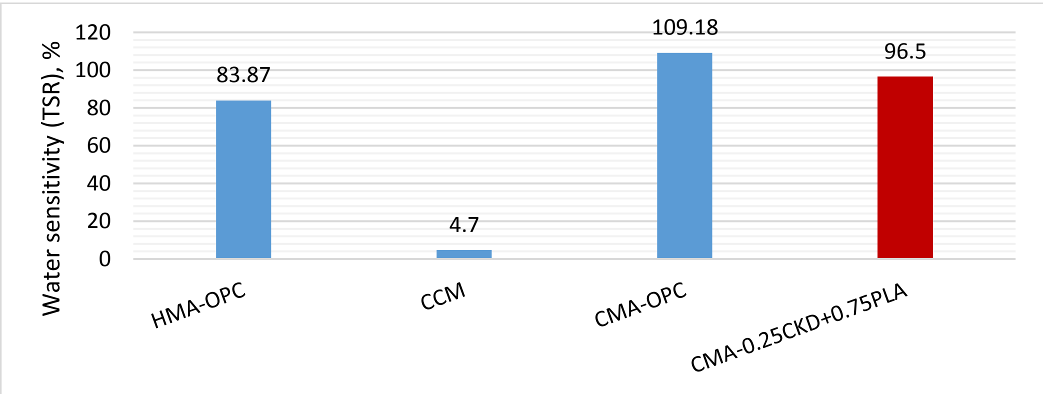


Figure 4-66 Water sensitivity test for mixture having fillers (CKD+PLA)

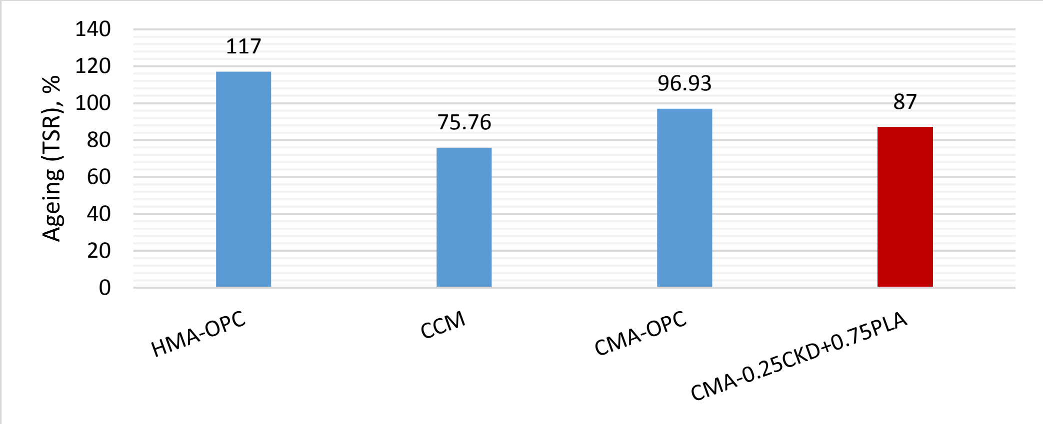


Figure 4-67 ageing test for mixture having fillers (CKD+PLA)

The pozzolanic and hydraulic materials needed an agent to active, therefore pozzolanic as alone is not enough to give acceptable strength, thus it is not using in binder layer of road without adding an activators as OPC. CKD is not acted active filler as OPC. Al-Nageim said that the pozzolanic reaction must be generated when mixed with cold mixture components (Al Nageim et al., 2012). Pozzolanic materials that gain no strength when blended alone with water (Al-Busaltan, 2012). It has to be mixed either with lime or with Portland cement to develop cementing action (Thanaya, 2003). Sin said that OPC acts as a binding agent on hydraulic as CKD or pozzolanic materials (Sin, 2001). Nunes claimed that pozzolanic materials need to activators in order to development binding properties, for example, cement, also CKD must be combined with another binder to achieve better results (Nunes, 1997).

4.8 CMA with blend of CKD - PLA – OPC

After failure in achieving the minimum level of standard specification requirement by comprising fillers of CKD and PLA to the CBEM instead of CMF, this section deals the attempt to improving CBEM by partially replacement of OPC with CKD and PLA as a certain percent.

4.8.1 Mixtures' preparation

- The percentages of supplementary fillers fixed the percentage of CKD by 25 % of total filler, according to the tests presented in section 4.5. Then applied the same procedure followed by previous section 4.6 by replacing OPC with different percentage of PLA. The replacing of OPC by PLA occurred within the part of 75% of total filler.

- The same value of residual bitumen content obtained from CCM and OPC was adopted (i.e., 6 %).
- The same value of the pre-wetting water content as came out of OPC (i.e., 3.5%) was used.
- Total liquid content results as (14.7 %).

4.8.2 Volumetric properties

- Density, illustrates as shown in Figure (4-68).
- Air void, as shown in Figure (4-69).
- Void in mineral aggregate (V.M.A), Figure (4-70).
- Voids filled with binder (V.F.A), Figure (4-71).

No highly different in volumetric properties about using different percentage fillers, the discussion in sections 4.5.2 and 4.6.1 are applied here too.

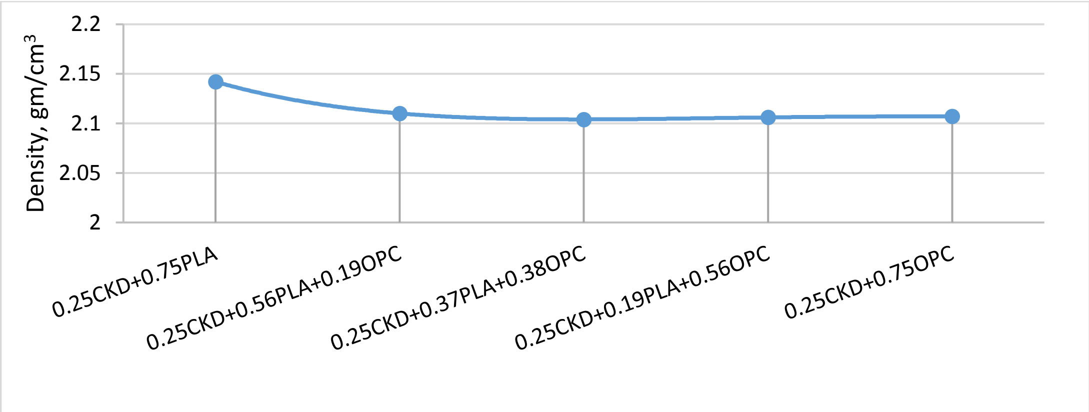


Figure 4-68 density vs different percentages filler for CBEM comprising (CKD+PLA+OPC)

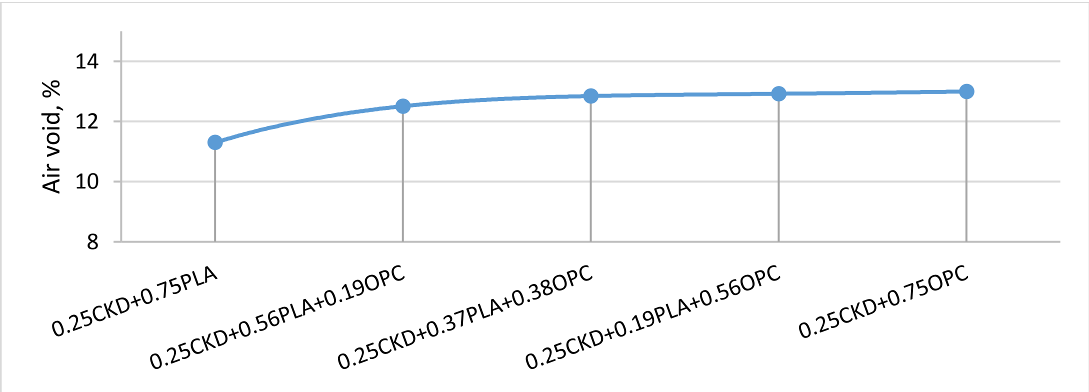


Figure 4-69 air void vs different percentages filler for CBEM comprising (CKD+PLA+OPC)

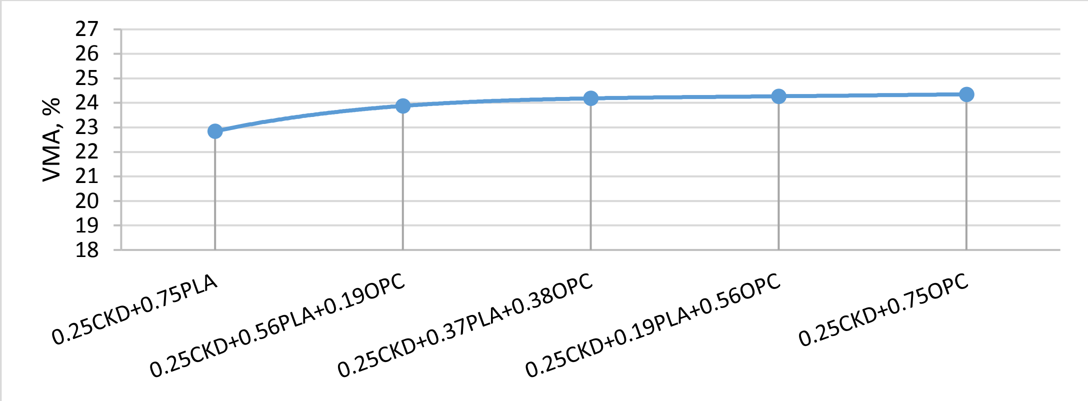


Figure 4-70 VMA vs different percentages filler for CBEM comprising (CKD+PLA+OPC)

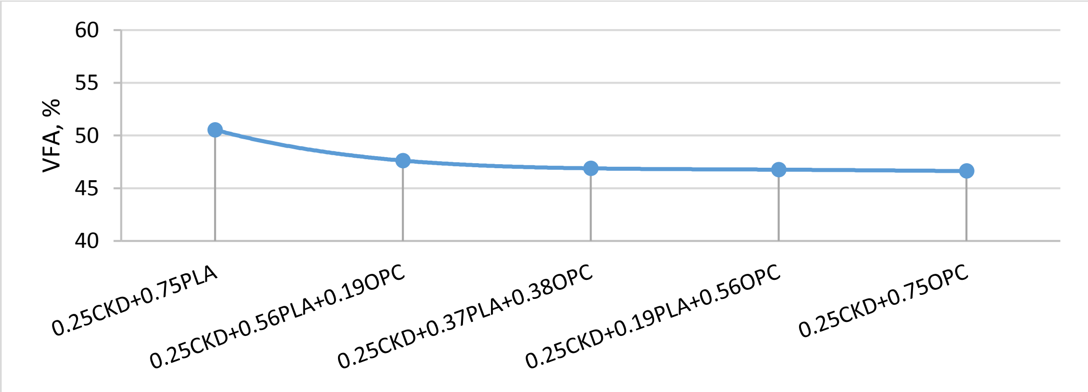


Figure 4-71 VFA vs different percentages filler for CBEM comprising (CKD+PLA+OPC)

4.8.3 Mechanical properties

4.8.3.1 Marshall test

Marshall Stability and Flow results are illustrated in Figures (4-72) and (4-73), respectively. From this figures the best alternative that achieved the lower limits of Iraqi specification with minimum OPC was (0.25CKD+0.37PLA+0.38OPC). However, significant achievement obtained by minimizing the OPC content to 38%; this is might be a result of the full potential of the hydraulic activity and pozzolanic effect of the CKD and PLA. When compared this mixture with CCM, the stability is enhanced by 42%, but lower than CBEMs contained only OPC by 27%. When comparative the same mixtures about flow, CBEMs contained filler (0.25CKD+0.37PLA+0.38OPC) are better than CCM and CBEMs contained only OPC by 46% and 18%, respectively. Whereas using (0.25CKD+0.19PLA+0.56OPC) gave high stability than (0.25CKD+0.37PLA+0.38OPC).

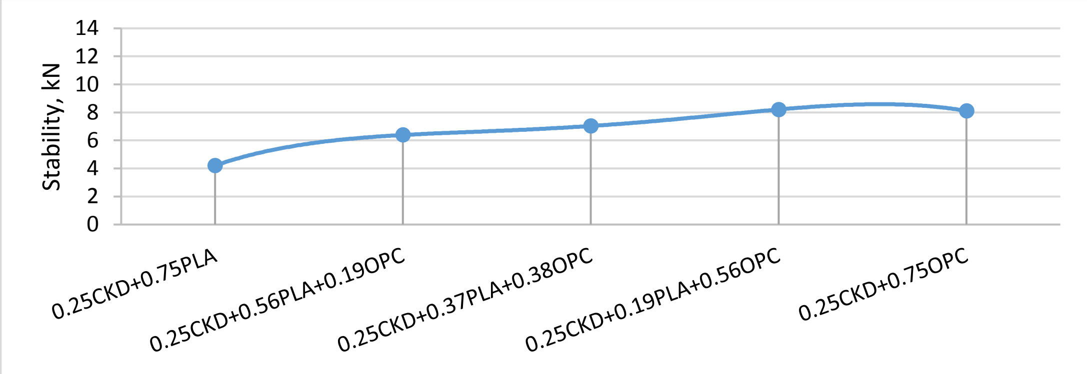


Figure 4-72 stability vs different percentages filler for CBEM comprising (CKD+PLA+OPC)

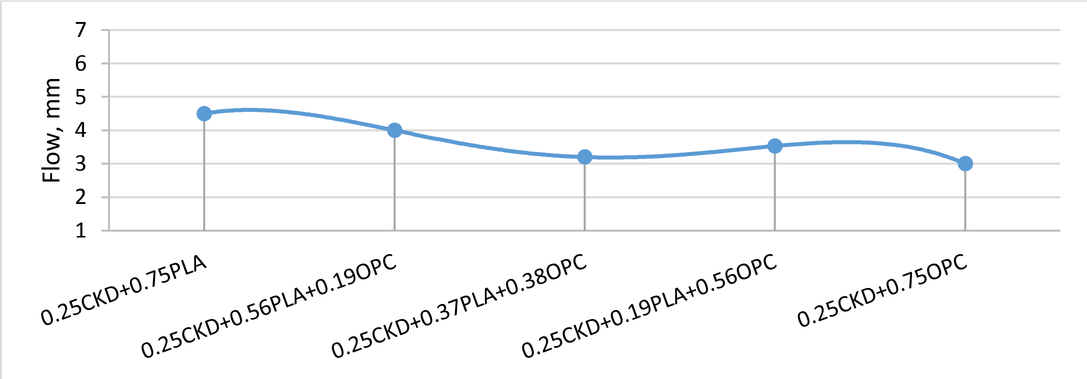


Figure 4-73 flow vs different percentages filler for CBEM comprising (CKD+PLA+OPC)

4.8.3.2 Indirect tensile strength

ITS was applied only for the mixture that chosen as an optimum, i.e., (0.25CKD+0.37PLA+0.38OPC). ITS results as shown in Figure (4-74) demonstrate that ITS for CBEM with blending (0.25CKD+0.37PLA+0.38OPC) has lower value than from mixtures having only OPC by 30%, (0.75PLA+0.25OPC) by 18% and (0.25CKD+0.75OPC) as 29%. That means ITS decreased with decreasing OPC or PLA, and concluded PLA is good filler that having characteristic to give high ITS when used as supplementary OPC with (0.75PLA+0.25OPC) .

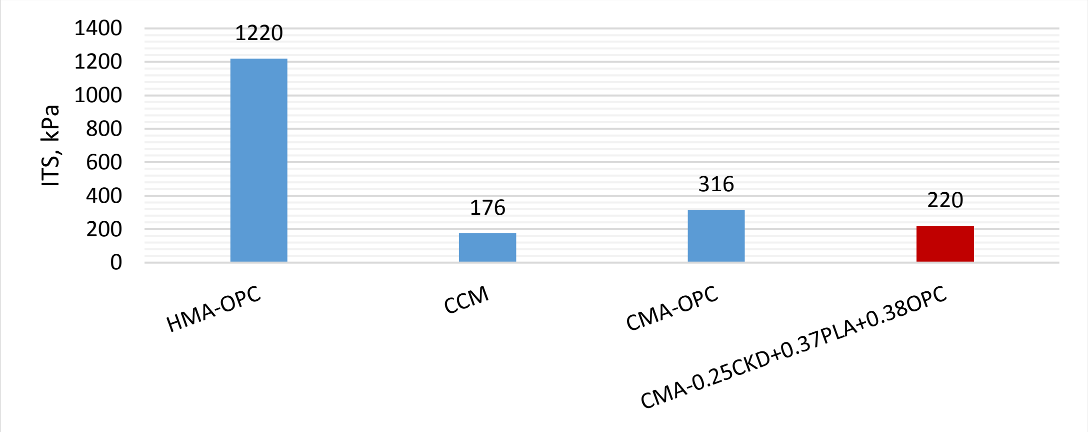


Figure 4-74 ITS test for CBEM comprising (CKD+PLA+OPC)

4.8.3.3 Wheel track test

Wheel track test was applied only for specimens that chosen, i.e., CBEM of blend of (0.25CKD+0.37PLA+0.38OPC). Figure (4-75) illustrates the wheel track test for this mixture. WTT for this mixture is good when compared with CCM and HMA. As the same reasons as described previously, the good results according to OPC acts a secondary binder, anti-stripping and an active filler to activity pozzolanic PLA, of which increased the strength of mixture. Creep stiffness confirm the results as shown in Figure (4-76), from this figure can be expressed that CBEMs with (0.25CKD+0.37PLA+0.38OPC) fillers are higher than CCM creep stiffness by 200%, whereas this mixtures creep stiffness are lower than mixtures with OPC by 27%.

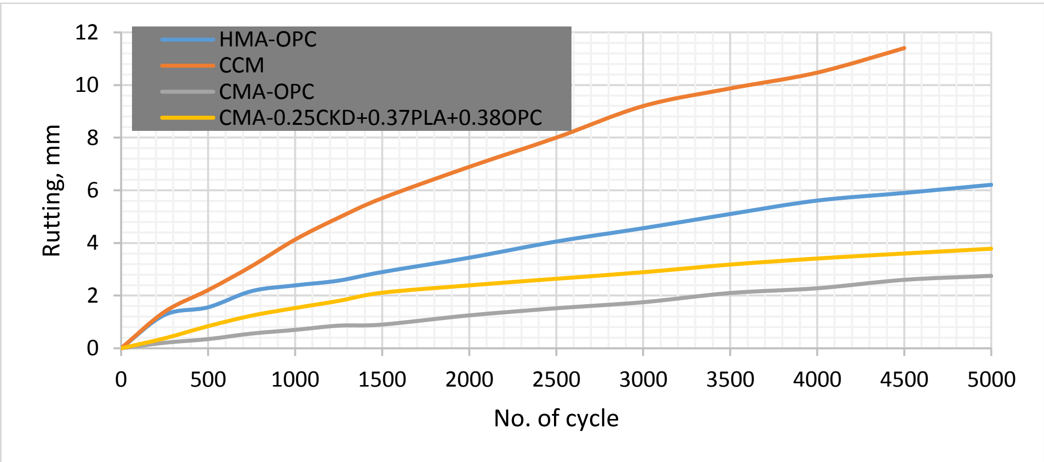


Figure 4-75 wheel track test for mixture having fillers (CKD+PLA+OPC)

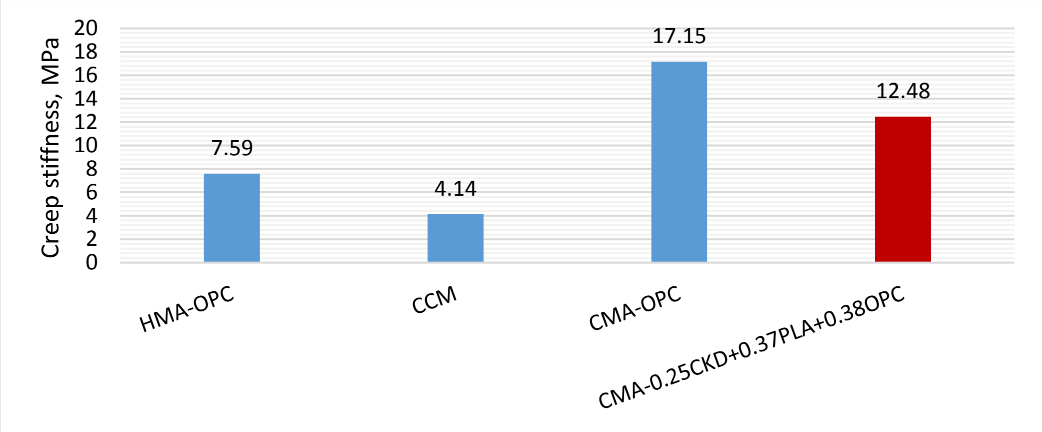


Figure 4-76 Creep stiffness of CBEM comprising blend of CKD+PLA+OPC

4.8.4 Durability test

The water sensitivity and ageing test results as shown in Figures (4-77) and (4-78), respectively, for the mixtures that having fillers (0.25CKD+0.37PLA+0.38OPC). Durability tests for this mixtures is acceptable when compared with CCM and HMA. The good results of durability are returned to OPC and PLA as described previously. From Figure (4-77) can be concluded that CBEMs containing (0.25CKD+0.37PLA+0.38OPC) is higher than CCM to resistance water damage by 2125% and lower than CBEMs with only OPC as just 4%.

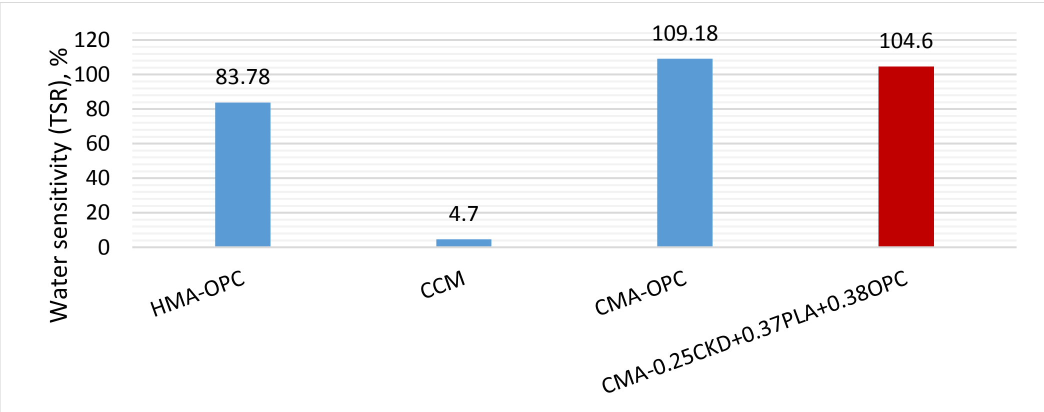


Figure 4-77 water sensitivity test for mixture having fillers (CKD+PLA+OPC)

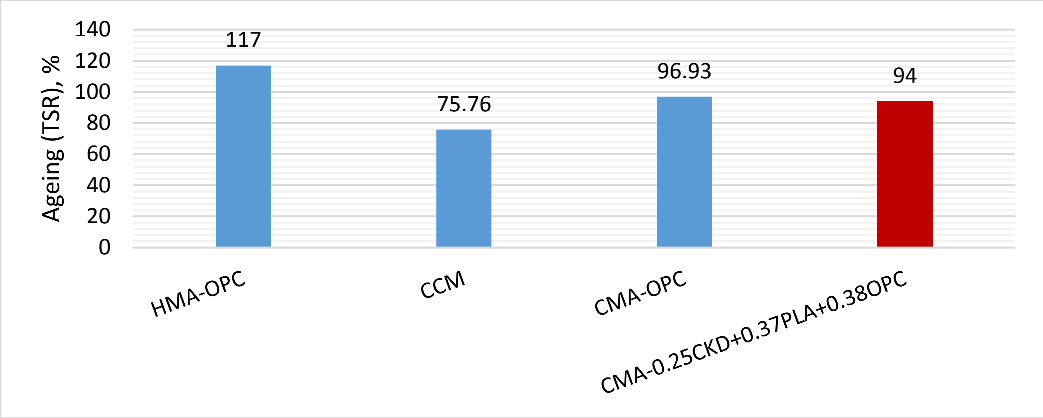


Figure 4-78 ageing test for mixture having fillers (CKD+PLA+OPC)

Previously argumentation in section 4.7 that the pozzolanic and hydraulic materials needed an agent to active, such as OPC to give acceptable strength. Therefore in this section added OPC, thus adding 38% OPC to (25%CKD+37%PLA) gave acceptable mechanical and durability properties of CBEMs, despite adding 56%OPC to (25%CKD+19%PLA) are higher strength than above mentioned mixtures. Overview must me adding active filler to pozzolanic and/or hydraulic materials either individually or collectively, also previous in sections 4.5, 4.6 and 4.7 proven that. Many studied are reaching an agreement with this provability, also as described in the sections aforementioned.

4.9 The overview of results

To facilitate the summary of the results obtained in this research work, below are the overview of the test results that make the comparison process is more easier.

4.9.1 Volumetric properties

The volumetric properties of all alterative mixtures as shown in figures below

- Density, Figure (4-79)
- Air void, Figure (4-80)
- Void in mineral aggregate, Figure (4-81)
- Void filled with bitumen, Figure (4-82)

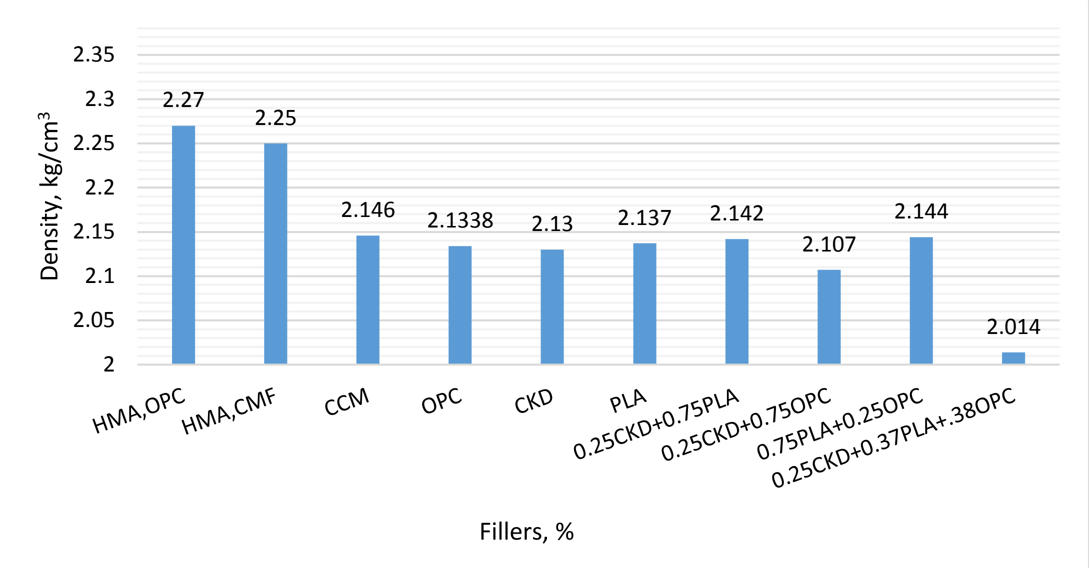


Figure 4-79 density of mixtures for different type fillers

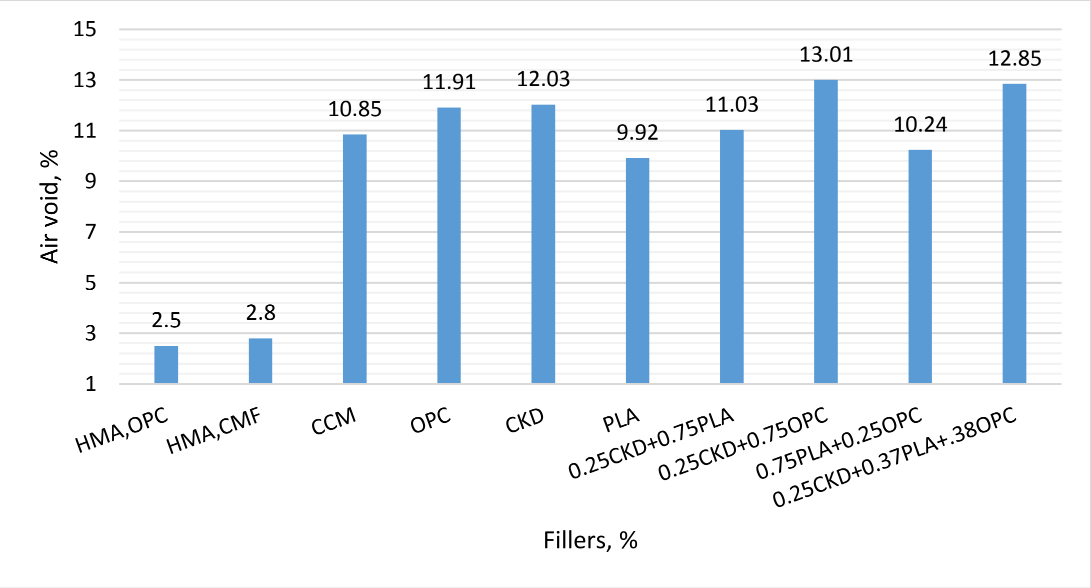


Figure 4-80 air void of mixtures for different type fillers

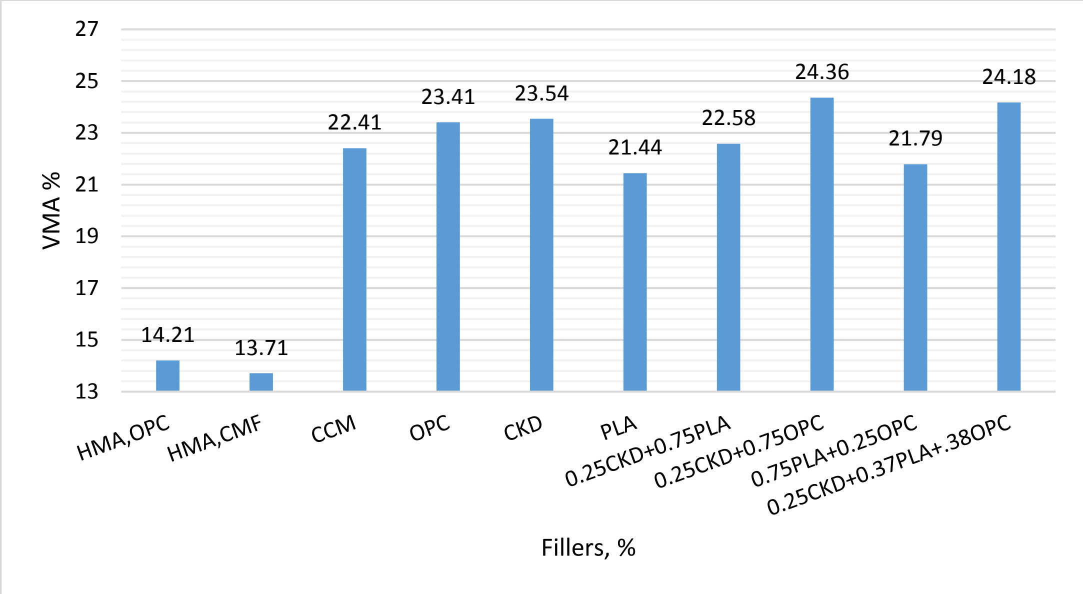


Figure 4-81 VMA of mixtures for different type fillers

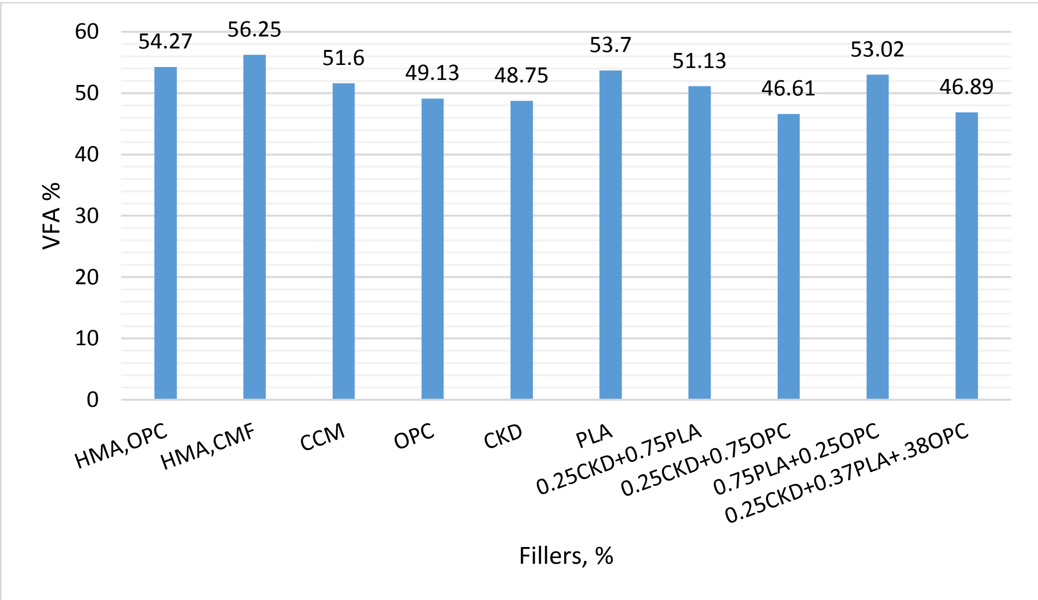


Figure 4-82 VFA of mixtures for different type fillers

4.9.2 Mechanical tests

Tests of materials as mechanical test including several category

4.9.2.1 Marshall test

The results of all mixtures for different type fillers as shown in Figure (4-83) and (4-84) for Marshall stability and flow respectively.

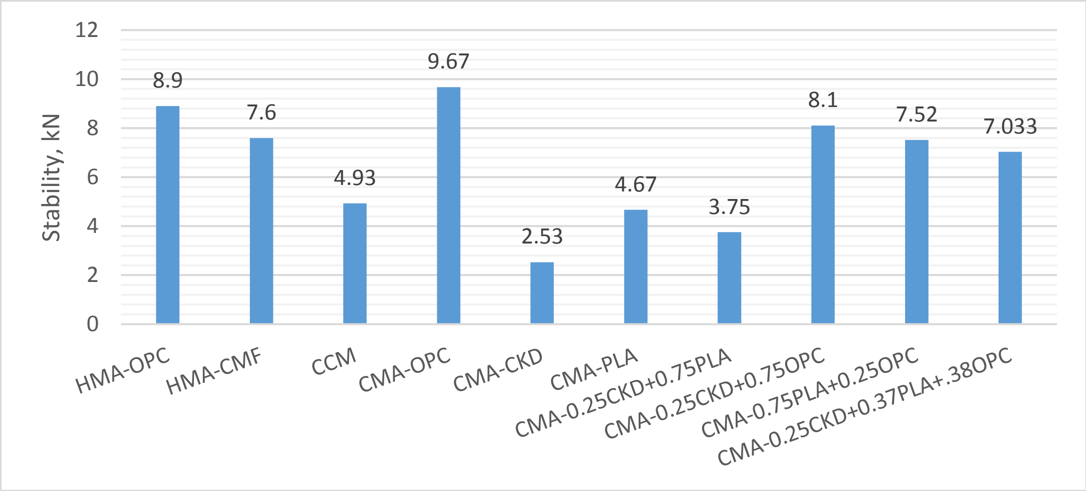


Figure 4-83 Stability for mixtures of different type fillers

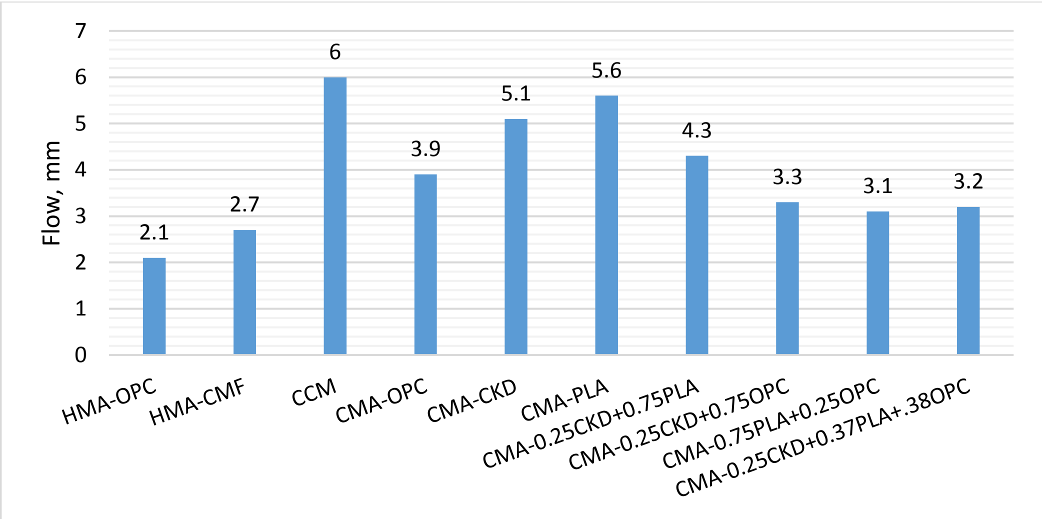


Figure 4-84 Flow for mixtures of different type fillers

4.9.2.2 Indirect tensile strength ITS

The results as shown in Figure (4-85).

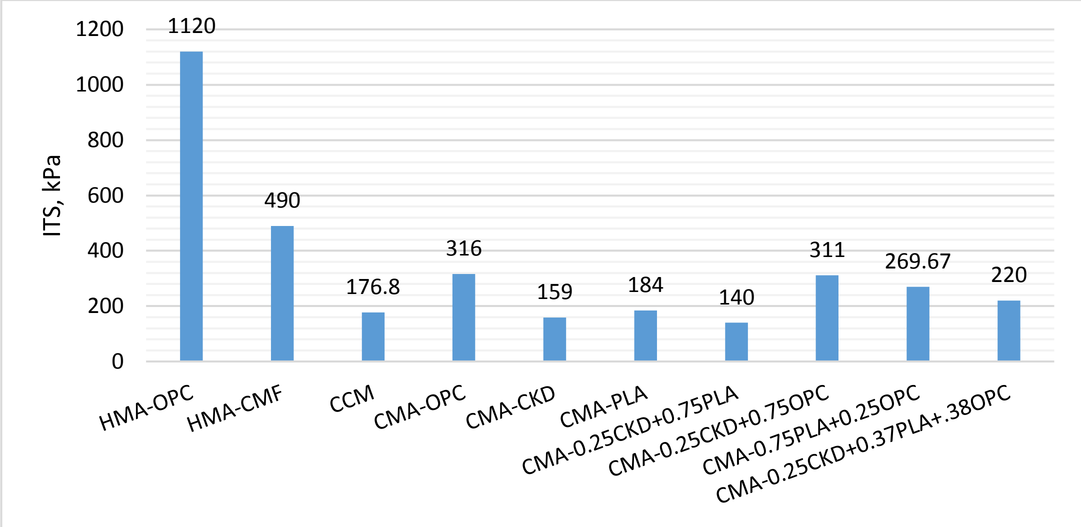


Figure 4-85 ITS test for mixtures of different type fillers

4.9.2.3 Wheel track test

The summery results of WTT illustrated in Figure (4-86). The creep stiffness as shown in Figure (4-87)

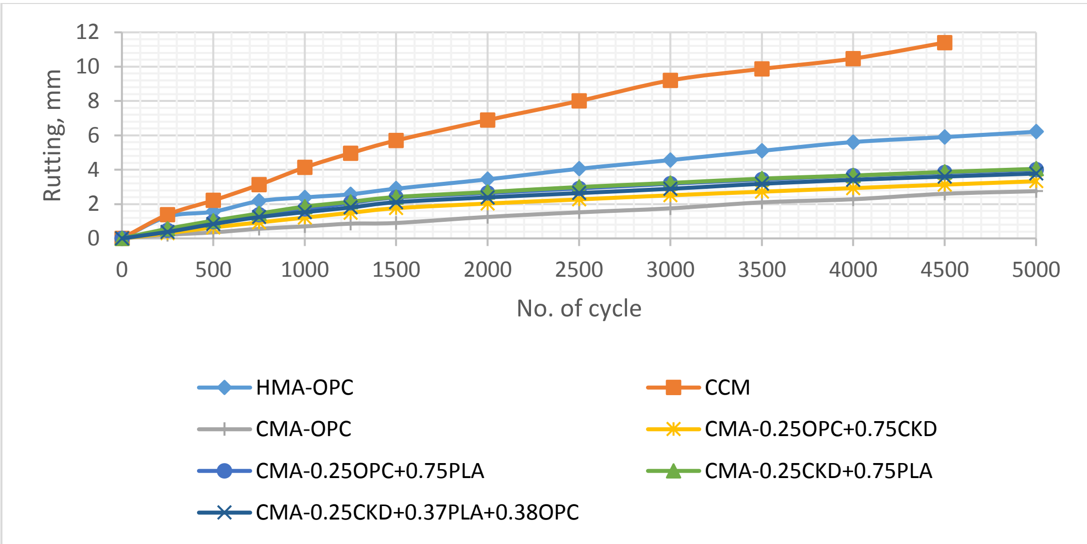


Figure 4-86 WTT for mixtures of different type fillers

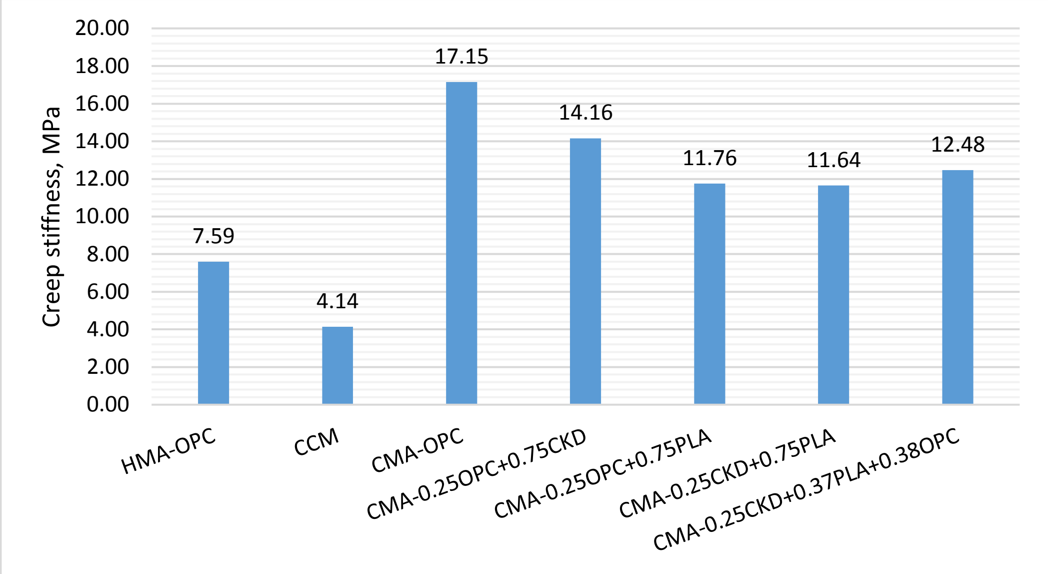


Figure 4-87 Creep stiffness test

4.9.3 Durability tests

The test of durability for water sensitivity and ageing test as follow

4.9.3.1 Water sensitivity test

The results as shown in Figure (4-88).

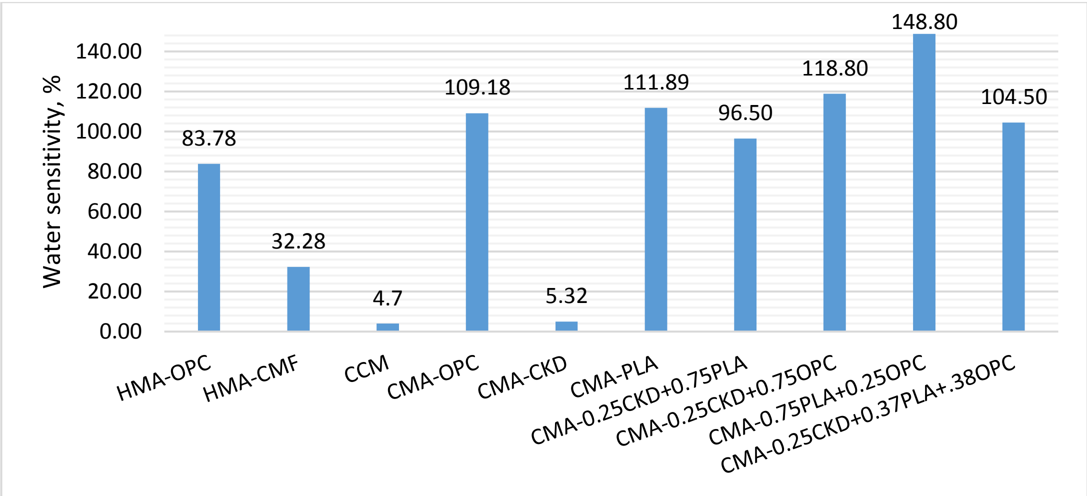


Figure 4-88 water sensitivity for mixtures of different type fillers

4.9.3.2 Ageing test

The results as shown in figure (4-89).

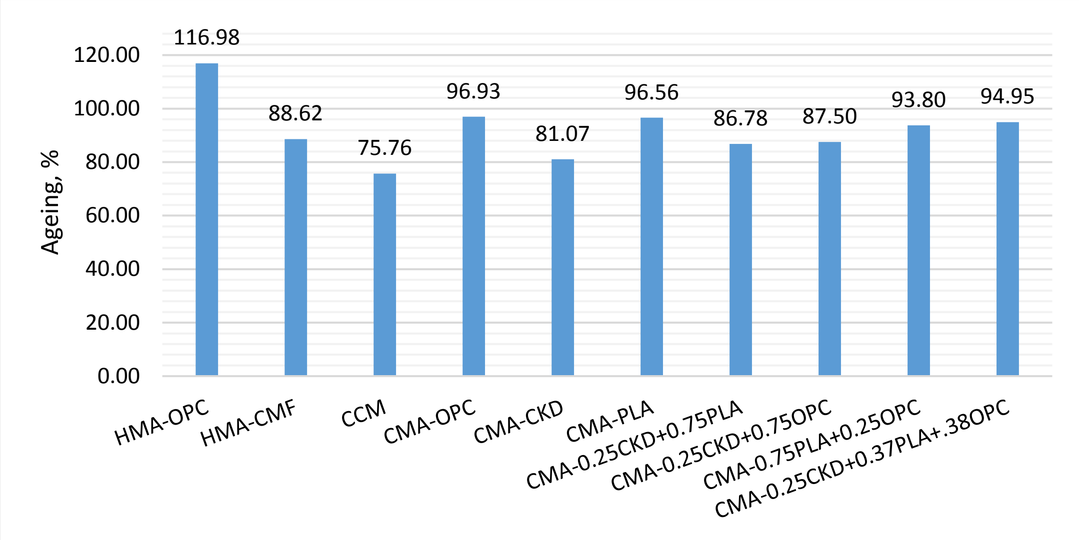


Figure 4-89 Ageing test for mixtures of different type fillers

4.10 Statistical Model Results

4.10.1 Identification of Dependent and Independent Variable

Program Testing needs to identify dependent and independent variables of the developed models to achieve the requirements built the models. These variables are listed as follows in Table (4-1).

Table 4-1 Dependent and independent variables considered in regression analysis

Dependent variable		
Abbreviation	Description	unit
MS	Marshall stability	KN
MF	Marshall flow	mm
ITS	Indirect tensile strength	KPa
CS	Creep stiffness	MPa
WS	Water sensitivity	%
AG	Ageing	%
Independent variable		
CMF	Conventional mineral filler	%
OPC	Ordinary Portland cement	%
CKD	Cement kiln dust	%
PLA	Palm leaf ash	%
CYCLE	NO. cycles of wheel	Cycles*
C	Constant	

* Equal or more than 1000 cycles

4.10.2 Prediction Models

All prediction models were nonlinear; trials for linear models were failed to represent the observations. SPSS software was carried out to achieve the analysis and build the required models.

4.10.2.1 Marshall models

- Marshall stability model

Modeling Marshall stability to filler type was conducted, the analysis results of such modeling as shown in Tables (4-2, 3 and 4). The analysis of the models includes the analysis of variance and goodness fitting between observed and predicted values. Figure (4-90) demonstrates the adequacy of model.

Table (4-3) states that the MS_E is very low, also from Table (4-4) the values of RMSE and MAE is low too. The high value of the R-Square and MAPE from Table (4-4) indicate a perfect prediction, thus from this values draw a conclusion the developed model for stability is very good. Also the Figure (4-90) illustrate majority observed values be located inside the two line of confidence interval.

Table 4-2 Marshall stability modeling

Developed model	$MS = C_1 * CMF + C_2 * OPC^{0.7} + C_3 * CKD^3 + C_4 * PLA$			
Parameter Estimates				
Parameters	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
C1	.049	.003	.042	.056
C2	.408	.007	.393	.422
C3	2.324E-6	.000	1.730E-6	2.919E-6
C4	.051	.002	.046	.055

Table 4-3 ANOVA for stability modeling

Source	Sum of Squares	Mean Squares
Regression	2112.113	528.028
Residual	15.711	.357
Uncorrected Total	2127.824	
Corrected Total	313.820	

Table 4-4 Goodness fit for stability modeling

Fit Statistic	Mean
R-squared	.961
RMSE	.514
MAPE	6.765
MAE	.375

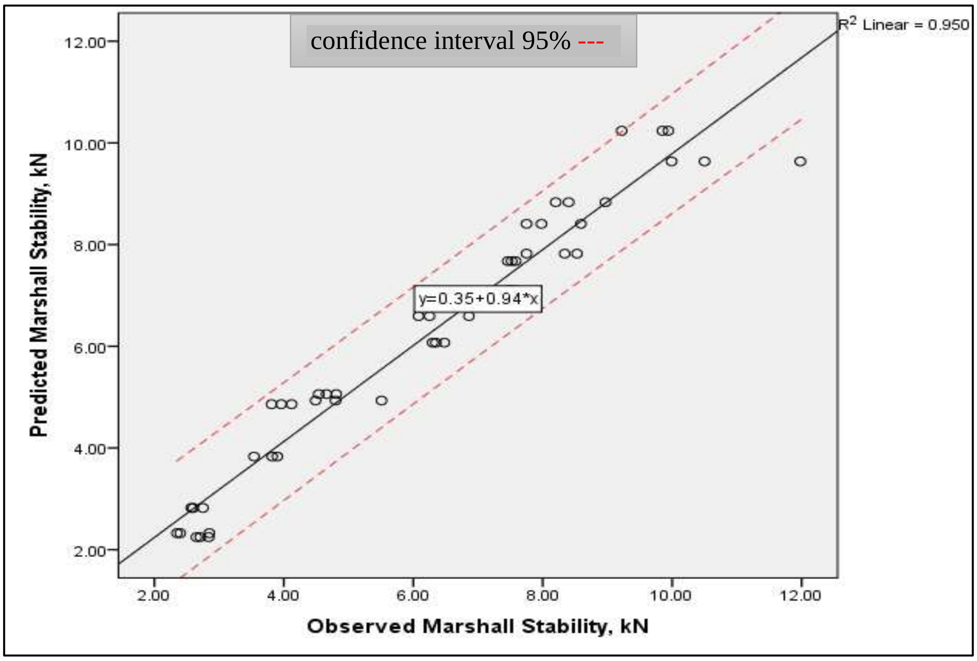


Figure 4-90 Marshall stability model checking

- Flow model

Tables (4-5, 6, and 7) illustrate the statistics model , variance of analysis and goodness fitting between observed and predicted values of Marshall flow. Figure (4-91) is checking the adequacy of model.

Similar to stability modeling, all parameters demonstrate the flow model is good such as MS_E as illustrated in Table (4-6), RMSE and MAE is very low, and MAPE is high as show in Table (4-7), in spite of slightly smaller R^2 from Table (4-7). In addition most points be situated inside of the lines of confidence interval as illustrated in Figure (4-91).

Table 4-5 flow modeling

Developed model	$MF = C_1 * CMF + C_2 * OPC + C_3 * OPC^2 + C_4 * \cos OPC + C_5 * CKD + C_6 * OPC * e^{CKD} + C_7 * CKD^3 + C_8 * PLA + C_9 * PLA^2 + C_{10} * PLA * \cos PLA$			
Parameter Estimates				
			95% Confidence Interval	
Parameter	Estimate	Std. Error	Lower Bound	Upper Bound
C1	.131	.037	.057	.206
C2	.054	.035	-.016	.124
C3	0.000483	.000	.000	.001
C4	-7.136	3.650	-14.524	.253
C5	.113	.036	.039	.186
C6	9.120E-35	.000	9.521E-37	1.814E-34
C7	4.905E-7	.000	-9.868E-7	1.968E-6
C8	.097	.054	-.013	.207
C9	0.000141	.000	-9.554E-5	.000
C10	.020	.040	-.062	.102

Table 4-6 ANOVA for flow modeling

ANOVA		
Source	Sum of Squares	Mean Squares
Regression	845.851	84.585
Residual	12.349	.325
Uncorrected Total	858.200	
Corrected Total	54.597	

Table 4-7 Goodness fit for flow modeling

Model Fit Statistics	
Fit Statistic	Mean
R-squared	.774
RMSE	.513
MAPE	10.883
MAE	.392

Note: cosine in radian

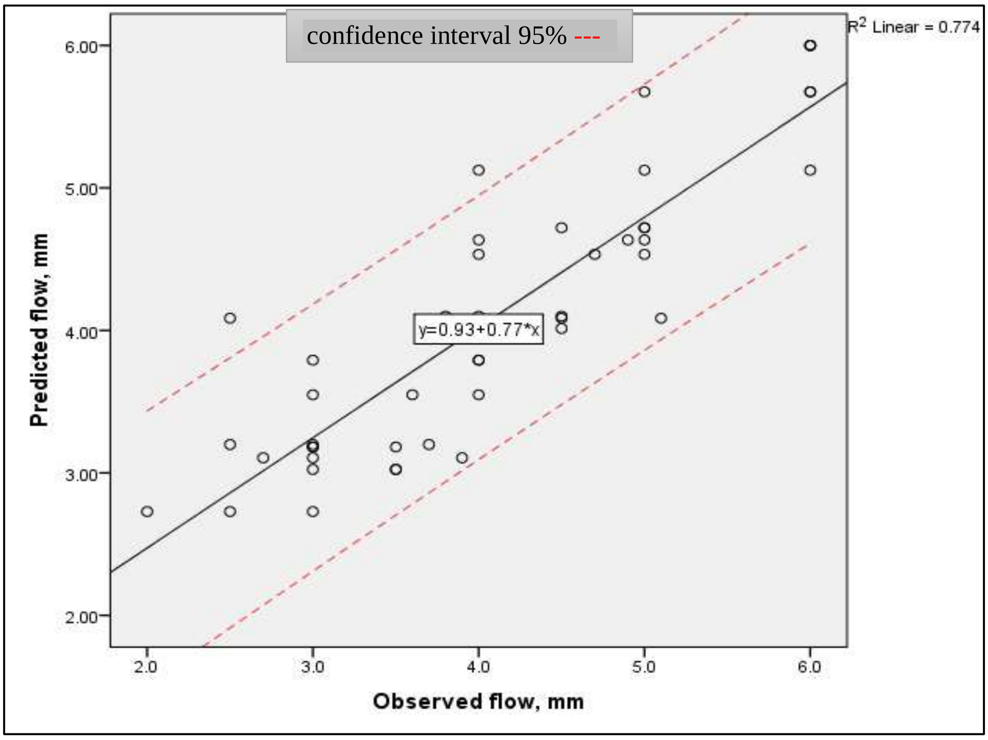


Figure 4-91 flow model checking

4.10.2.2 ITS model

The analysis results of modeling ITS as shown in Tables (4-8, 9, and 10). the modeling format, ANOVA and goodness fitting between observed and predicted values respectively, and Figure (4-92) for checking adequacy of model.

R^2 is very high, RMSE and MAE are low as illustrated in Table (4-10), and MS_E is low relatively as described in Table (4-9), MAPE is far of zero as shown from

Table (4-10) below, thus the modeling is very good, also all points that put inside of confidence interval as state in Figure (4-92).

Table 4-8 ITS modeling

Developed model	$ITS = C_0 + C_1 * CMF + C_2 * OPC^{0.5} + C_3 * CKD^2 + C_4 * PLA^2$			
Parameter Estimates				
Parameters	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
C0	43.790	23.741	-5.900	93.479
C1	1.331	.255	.798	1.865
C2	27.815	2.550	22.478	33.151
C3	.012	.003	.006	.017
C4	.014	.003	.009	.020

Table 4-9 ANOVA for ITS modeling

Source	Sum of Squares	Mean Squares
Regression	1283097.277	256619.455
Residual	4942.603	260.137
Uncorrected Total	1288039.880	
Corrected Total	101091.076	

Table 4-10 Goodness fit for ITS modeling

Fit Statistic	Mean
R-squared	.951
RMSE	14.662
MAPE	5.253
MAE	11.651

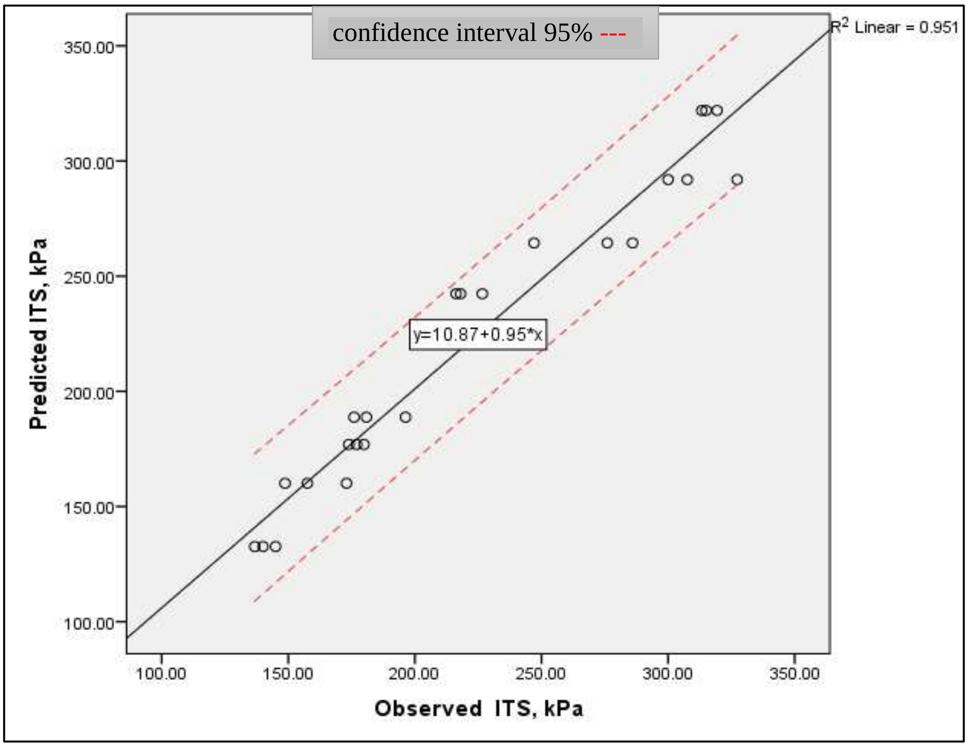


Figure 4-92 ITS model checking

4.10.2.3 Creep Stiffness model

The results of modeling of creep stiffness are shown in Table (4-11, 12, and 13), Figure (4-93) for checking the model.

R^2 is high, RMSE and MAE are low from Table (4-13), MS_E is low from Table (4-12) and MAPE is high from Table (4-13). Thus the modeling is very good , especially most of points be situated interval confidence as illustrated in Figure (4-93).

Table 4-11 Creep Stiffness modeling

Developed model	$CS = C_0 + C_1 * CMF + C_2 * OPC + C_3 * CKD + C_4 * PLA * CKD + C_5 * OPC * \ln CYCLE^{0.05}$			
Parameter Estimates				
Parameters	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
C0	10.786	2.292	6.056	15.516
C1	-.049	.028	-.107	.010
C2	2.408	.176	2.044	2.772
C3	-.253	.078	-.415	-.091
C4	.006	.002	.002	.010
C5	-5.546	.441	-6.456	-4.636

Table 4-12 ANOVA for Creep Stiffness modeling

Source	Sum of Squares	Mean Squares
Regression	14594.731	2432.455
Residual	333.646	13.902

Uncorrected Total	14928.378	
Corrected Total	4553.297	

Table 4-13 Goodness fit for Creep Stiffness modeling

Fit Statistic	Mean
R-squared	.927
RMSE	3.323
MAPE	17.413
MAE	2.466

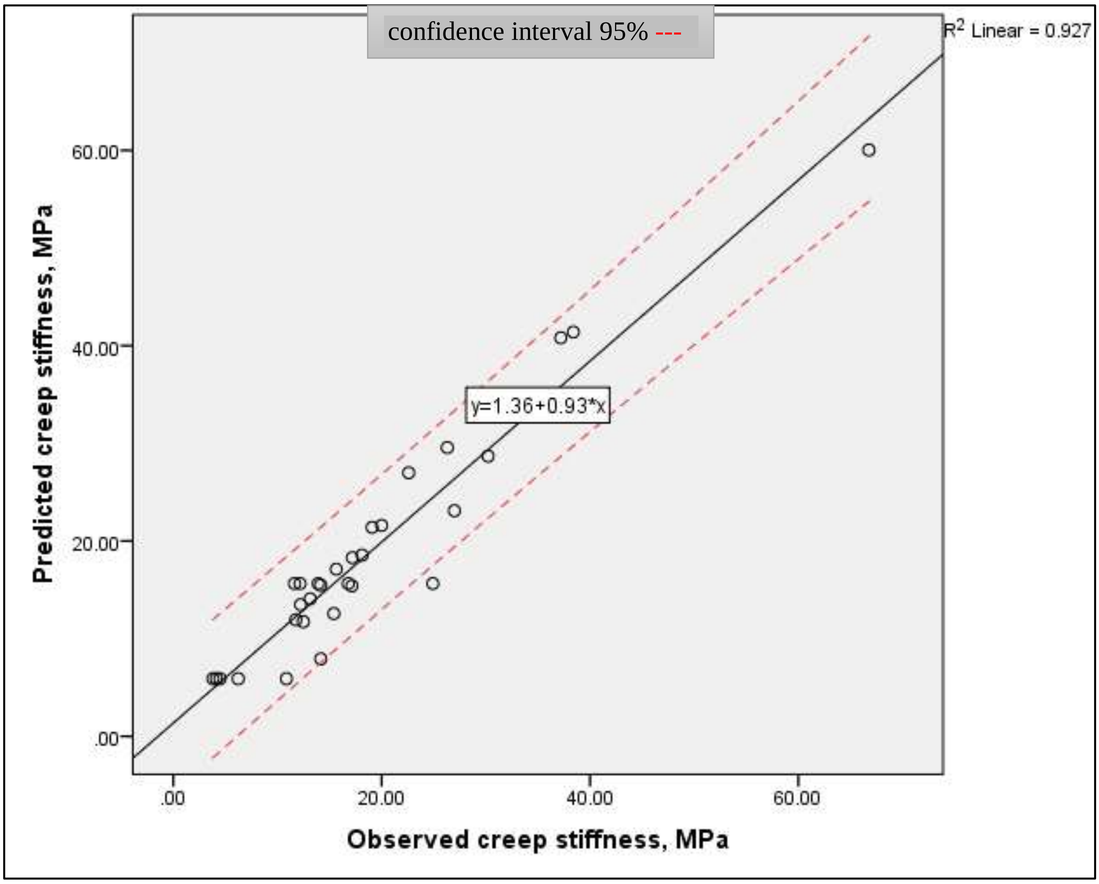


Figure 4-93 Creep stiffness model checking

4.10.2.4 Durability model

- Water sensitivity model

Modeling results of water sensitivity as shown in Tables (4-14, 15, and 16) and Figure (4-94). From Tables (4-15) and (4-16) state that the MS_E , and the values of RMSE and MAE are very low respectively. Also, the high value of the R^2 and MAPE values are very high, thus the conclusion from those values that the developed model for water sensitivity is very good. Also Figure (4-94) illustrates most observed values be located inside the two line of confidence interval.

Table 4-14 Water sensitivity modeling

Developed model	$WS = C_1 * OPC^{0.4} + C_2 * OPC * CKD + C_3 * PLA$			
Parameter Estimates				
Parameters	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
C1	.172	.010	.151	.193
C2	0.000139	.000	4.073E-5	.000
C3	.012	.001	.011	.013

Table 4-15 ANOVA for water sensitivity modeling

Source	Sum of Squares	Mean Squares
Regression	27.802	9.267
Residual	.324	.015
Uncorrected Total	28.126	
Corrected Total	7.494	

Table 4-16 Goodness fit for water sensitivity modeling

Fit Statistic	Mean
R-squared	.957
RMSE	.119
MAPE	9.088
MAE	.082

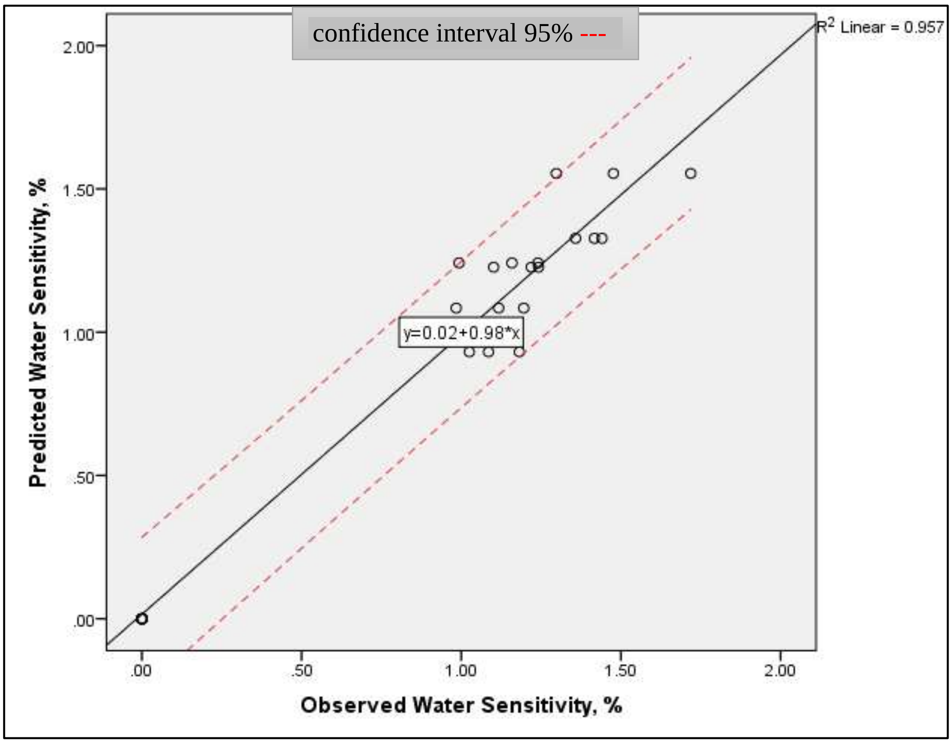


Figure 4-94 Water sensitivity model checking

- Ageing model

Modeling results as shown in Tables (4-17, 18, and 19) and Figure (4-95). From the results the modeling and by using the same parameters accredited of previously models, the model may be acceptable, but need more attempt with more samples to get better modeling.

Table 4-17 Ageing model

Developed model	$MS = C_0 + C_1 * CMF + C_2 * OPC + C_3 * CKD^{0.4} + C_4 * PLA^2 + C_5 * OPC * \sqrt{PLA} + C_6 * OPC^2$			
Parameter Estimates				
Parameters	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
C1	-.170	.045	-.265	-.076
C2	-.146	.221	-.614	.321
C3	-1.120	.729	-2.659	.418
C0	90.851	3.063	84.388	97.313
C4	.000	.000	.000	7.802E-6
C5	.072	.031	.007	.138
C6	.002	.002	-.003	.007

Table 4-18 ANOVA for ageing modeling

Source	Sum of Squares	Mean Squares
Regression	186707.289	26672.470
Residual	543.712	31.983
Uncorrected Total	187251.001	
Corrected Total	1630.766	

Table 4-19 Goodness fit for ageing modeling

Fit Statistic	Mean
R-squared	.667
RMSE	4.971
MAPE	4.403
MAE	3.865

Note: sine in radian

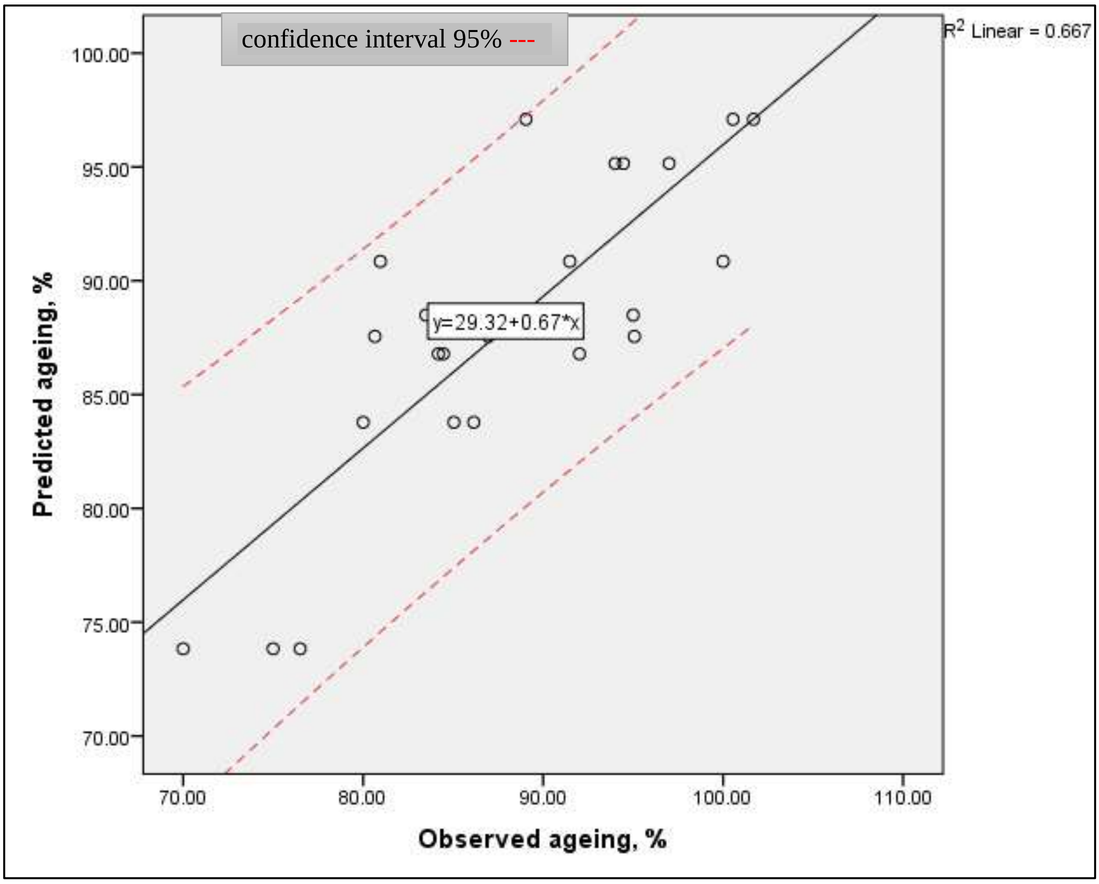


Figure 4-95 Ageing model checking

4.11 Summery

Previous studies assumed that the cementitious component is the main reason that lead further development for CBEM strength (Needham, 1996, Thanaya, 2003). However, this study proved that other characteristics could performance energetic roles in strength development by replacing a substantial part of OPC. Characteristics such as porous agglomerating morphology could absorb more trapped water. Other characteristics of filler such as high surface area could introduce wider active surface for the hydration process, while well graded particle size distribution provides sound microstructure.

The strength characteristics of CBEM with inert filler is dependent on the setting of asphalt emulsion to initiate the bounding, and this setting related to the rate of water evaporation. When active filler is incorporated, secondary binder initiates, because of the hydration process. Also, this hydration process consumes the trapped water. Durability tests for mixtures result have shown no significant effect due to high air void relatively.

Finally developed statistical model for laboratory tests by SPSS software, where by this analysis good relationship can be developed between mechanical or durability test, and type and/or percentage of fillers used.

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

This research is an attempted to develop CBEMs alternatives to compete conventional HMA. Although the great beneficial characteristics which can be achieved by using CBEMs in pavement industry which contains both environmental and safety issues, but CCM is accompanying mainly with high air void, long curing time, very low strength at early and highly sensitivity to water.

From this study, the development is based on adopting both sustainable and environmentally friendly approaches, where waste and by-product materials were used to reach the main research aim. However, the following conclusions are found based on performance of the developed cold mix:

1. OPC offers is help for good performance for mechanical and durability of CBEM, also it help in improving the volumetric characteristics, except the air void for the CBEM comprising OPC which still high. Cement is an effective adhesive and acts as a secondary binder in CBEMs.
2. The specific characteristics of waste or by-product materials that made them useful in upgrading conventional CBEMs may include; chemical compositions, surface area, and particle shape. Accordingly, waste or by-product material such as PLA and CKD.
3. CKD can be used as partially supplementary replacement filler of 25% OPC, this replacement provides acceptable level of mechanical and durability characteristics.
4. Strength of CCM is very sensitive to moisture conditions, also mixtures having only CKD too. But OPC and PLA help to reduce moisture sensitivity of these mixes and water sensitivity for OPC and PLA as 109% and 112%, respectively when using individually, when mixing (25%OPC+75%PLA) the result reaches up to 148%.
5. Although all CBEMs have high air void relatively, but this no significant to durability tests except CCM and mixtures having only CKD, this mixture high sensitive to water damage.

6. PLA showed significant improvement to the volumetric and mechanical properties of CBEMs' developed when used with scarce OPC and producing fast curing CBEMs and improving their durability properties. Also strength mixtures having (75%OPC+25%PLA) in certain percentage as described is better than using 100%OPC.
7. PLA have very high surface area that may be increased breaking rate of emulsions.
8. Pozzollanic PLA filler materials can absorb the trapped water between bitumen material and other compenents of mixture, provide secondary binder along with the primary bituminous binder.
9. Pozollanic PLA filler materials can be mighty absorbed the trapped water in CBEMs, therefore it is have very high resistance to water damage.
10. Replacement of the mineral filler of OPC by PLA can reach up to 75%, but CKD up to 25% without imparting the performance properties of the CBEMs, that means Pozzolanic materials have higher cementenious and resistance to water damage than hydraulic materials when mixing this materials with OPC.
11. When the main problem with the CBEMs is stripping, PLA can be used as a percentage up to 75% and give resistance up to or more than 100%, also without negatively effect to other mechanical properties.
12. Replacement OPC by 25% CKD and gave close results when using alone OPC in CBEMs ITS test.
13. Modeling for mechanically and durability tests by SPSS software proved good or acceptable models, especially for Marshall test, indirect tensile strength, water sensitivity test and creep stiffness that obtained very good model.

5.1 Recommendation

The development reached in this research study leads to a new generation of CBEMs which are comparable to HMA, in terms of environmental, economic, safety and mechanical and durability characteristics. So it is seriously recommended to use this mixtures for binder layer according to the benefits as mentioned above.

1. CKD may be used as inert filler to achieve purpose as described above, and getting rid of harm environmentally, which high amount of CKD disposed in wilderness.

2. Palm leaves can be used with production of Portland cement to enhanced cements' properties. Additionally dispose of palm leaves that may be effect negatively to farmland and productivity of fruits.
3. Waste and by-product materials are high recommended to use as supplementary with OPC individually or collectively in CBEMs.
4. Palm leaves can be burned to higher temperature 800 ℃ for more calcination, and then grinding to get more effective hydration.

5.2 Further works

Laboratory tests indicated that can be replaced OPC filler by CKD and PLA as 25% and 75%, respectively to give good mechanical and durability properties of CBEMs, and agreement with Iraqi specifications GSRB, furthermore these mixtures are friendly environmental, saving cost, safety and c to use. It is needed more information on this new CBEMs to accuracy on this matter, therefore further studies could include:

1. Applayed this mixtures in site in order to correlate the lab research sample characteristics with in-site samples, and check the accuracy of lab tests.
2. Some waste biomass and by-product materials may be checked to development CBEMs, where biomass materials may be supported to absorbed the tramped water between aggregates and bitumen materials.

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الخلاصة

زيادة عدد السيارات في كل سنة يؤدي الى زيادة الحاجة الى الطرق. وبذلك ازدادت اطوال الطرق حول العالم. أكثر من 90% من البنى التحتية المستخدمة للنقل هي بأستخدام الخلطة الأسفلتية، وبشكل رئيسي بأستخدام تقنية الخلطات الأسفلتية الحارة والباقي بواسطة الخلطات الدافئة والباردة. لكن تبقى الخلطات الاسفلتية الدافئة والباردة قيد التطوير ويحتاج الى تجارب كثيرة لاستخدامهما كبديل للخلطلت الاسفلتية الحارة. الخلطات الباردة مثل الخلطات الاسفلتية المستحلبة له فوائد كثيرة تفوق الخلطات التقليدية مثل: انها صديقة للبيئة ، حفظ للطاقة، اقل تكلفة و اكثر اماناً اثناء الإنتاج والتنفيذ؛ لذلك ازدادت استخدامها مؤخرا. لكن من جهة أخرى خواصها مقارنة بالخلطات الحارة اقل كونها مقاومتها اقل في بداية عمرها و اكثر تاثرا بالمياه.

حسب الدراسات السابقة اثبتت بأن الخواص الميكانيكية للخلطات المستحلبة تتأثر بعدة عوامل منها : المواد البتيومينية، المسامية، فترة الانظاج والمضافات مثل استعمال الاسمنت البورتلاندي الاعتيادي و مستحلب اسفاتي سريع التصلب. هذا البحث حاول استعمال نفايات عضوية ومواد ذات نواتج عرضية من المعامل كمواد مالئة لتحسين الخلطات المستحلبة التقليدية من جهتي تسريع مقاومة الخلطة وديمومتها إضافة الى استعمال الاسمنت البورتلاندي؛ لذلك تم استخدام رماد سعف النخيل و خبث افران الاسمنت الناتج من معامل الاسمنت لتحسين الخواص الميكانيكية وديمومة الخلطات المستحلبة.

تم استعمال الاسمنت البورتلاندي كبديل للمواد المالئة التقليدية – الناتجة من خلال تكسير الركام او موجودة كمواد ناعمة في الطبيعة – ثم استبدال الاسمنت بالرماد الناتج من حرق السعف او خبث افران الاسمنت بنسب مختلفة (0-100)%. خلال الدراسة اثبتت بأن استبدال الاسمنت بنسبة 25% الى رماد السعف يعطي خواص ميكاميكية اقوى حتى من استعمال الاسمنت وحدها بالخلطة الاسفلتية، وحتى استبدال الاسمنت بنسبة 75% الى الرماد يعطي خواص ميكانيكية و ديمومة مقبولة عندما تقارن مع غيرها من الخلطات الأسفلتية. كذلك خبث الافران ممكن استخدامها بنسبة 25% بدلا من الاسمنت ليعطي خواص هندسية مقبولة. أيضا من الممكن استعمال مادة مالئة مكون بنسب مختلفة من الاسمنت و خبث الافران والرماد.

النتائج المستوحاة من خلال البحث هو انتاج خلطة اسفلتية باردة جديدة، تمتلك خواص هندسية مقبولة وذات ديمومة جيدة. تمتلك مقومات كثيرة مما تجعلها تفوق ليس فقط الخلطات الحارة وانما الخلطات الاسفلتية التقليدية الباردة، منها التخلص من النفايات التي ربما تلوث البيئة مثل خبث الافران والسعف، اكثر اقتصادية و تحفظ الطاقة.

تم اعداد موديلات إحصائية للخلطات الاسفلتية الباردة لكل الفحوصات الميكانيكية والديمومة؛ وذلك لمعرف المادة المالئة الأكثر تأثيرا للفحص و تمكين الباحثين من استخدامها مستقبلا. في الموديلات الإحصائية كانت العامل المعتمد هو الفحص المطلوب إيجاد الموديل له و العامل غير المعتمد تمثلت بنسب المواد الفلر.

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

تحسين الخلطة الأسفلتية الباردة باستخدام النفايات للطبقة الرابطة في الطرق

رسالـــــــــة

مقدمة إلى كلية الهندسة في جامعة كربلاء

وهي جزء من متطلبات نيل درجة ماجستير في هندسة البنى التحتية

من قبل :

سجاد بهجت أحمد

(بكالوريوس علوم في الهندسة المدنية 2014)

بإشراف:

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