DEVELOPMENT OF NEW COLD BITUMEN EMULSION MIXTURES AND FINITE ELEMENT MODELLING OF PREDICTING PERMANENT DEFORMATION

HAYDER KAMIL SHANBARA

A thesis submitted in partial fulfilment of the

requirements of Liverpool John Moores University

for the degree of Doctor of Philosophy

September 2018

DECLARATION

The research reported in this thesis was conducted at Liverpool John Moores University, Faculty of Engineering and Technology, Department of Civil Engineering between November 2014 and September 2018. I hereby declare this thesis is the result of my own work and any quotation from, or description of the work of others is acknowledged herein by reference to the sources. This thesis has not been submitted for any degree at another university.

Hayder Kamil Shanbara

Liverpool John Moores University

September 2018

DEDICATION

To the pure soul of my father who had dreamt to witness these moments and who has been the source of inspiration to me throughout my life …

To my kind-hearted mother for her unlimited love, inspiration, sacrifices and prayers for me during my life;

To my uncles, brothers and sisters for their help, support and encouragement …

To my sweetheart and beloved wife for her endless love, great patience, encouragement and personal support …

To my beloved children, Maryam, Noor, Sarah and Renad for their smiles and love that give me energy to work …

I dedicate this work hoping that I made all of them proud …

Hayder Kamil Shanbara

Liverpool John Moores University

September 2018

ACKNOWLEDGEMENTS

First and foremost, I would like to express my deepest gratitude to my director of study, Mrs Felicite Ruddock for her excellent guidance, continuous enthusiasm, generous support and encouragement over the years.

Sincere thanks are due to my second supervisor, Dr William Atherton, who helped me to overcome difficulties and provided me with valuable advice for this study.

I am also deeply indebted to my dear friend Dr Anmar Dulaimi for his helpful advice during the period of this study. I would also like to thank all my colleagues and friends for their help and suggestions during my study and for the pleasant time we spent together.

In addition, I would like to acknowledge the financial support provided by the Ministry of Higher Education & Scientific Research, Iraq and Al Muthanna University, Iraq.

I would like to thank my family for their constant encouragement and endless love.

Last but not least, I would like to thank all those working in the Department of Civil Engineering, Faculty of Engineering and Technology, Liverpool John Moores University for their valuable help and cooperation over the long period of testing, especially Mr Mal Feegan.

Hayder Kamil Shanbara

Liverpool John Moores University

September 2018

LIST OF PUBLICATIONS

A. List of book chapters

1. Hayder Kamil Shanbara, Felicite Ruddock & William Atherton (2018), Stresses and strains distribution of a developed cold bituminous emulsion mixture using finite element analysis. **Book title: Science and Technology Behind Nanoemulsions.** Publisher: IntechOpen. http://dx.doi.org/10.5772/intechopen.74221.

B. List of peer reviewed published journal papers:

1. Hayder Kamil Shanbara, Felicite Ruddock & William Atherton (2018), Predicting the rutting behaviour of natural fibre-reinforced cold mix asphalt using the finite element method. **Construction and Building Materials**, 167, 907-917. doi.org/10.1016/j.conbuildmat.2018.02.072.
2. Hayder Kamil Shanbara, Felicite Ruddock & William Atherton (2018), A laboratory study of high-performance cold mix asphalt mixtures reinforced with natural and synthetic fibres. **Construction and Building Materials**, 172, 166-175. doi.org/10.1016/j.conbuildmat.2018.03.252.
3. Hayder Kamil Shanbara, Felicite Ruddock & William Atherton (2018), A viscoplastic model for permanent deformation prediction of reinforced cold mix asphalt. **Construction and Building Materials**, 186, 287-302. doi.org/10.1016/j.conbuildmat.2018.07.127.
4. Hayder Kamil Shanbara, Felicite Ruddock & William Atherton (2018), Mechanical Properties of Ordinary Portland Cement Modified Cold Bitumen Emulsion Mixture. **International Journal of Civil and Environmental Engineering**, 12 (5), 567-572. http://scholar.waset.org/1307-6892/10009286.

5. Hayder Kamil Shanbara, Felicite Ruddock & William Atherton (2016), Rutting Prediction of a Reinforced Cold Bituminous Emulsion Mixture Using Finite Element Modelling. **Procedia Engineering**, 164, 222-229. doi.org/10.1016/j.proeng.2016.11.613.

C. List of peer reviewed published conference papers:

1. Hayder Kamil Shanbara, Ali Shubbar, Felicite Ruddock & William Atherton (2018), Characterizing the Rutting Behaviour of Reinforced Cold Mix Asphalt with Natural and Synthetic Fibres using Finite Element Analysis. **International Conference Trends and Recent Advances in Civil Engineering TRACE-2018, Department of Civil Engineering, ASET Amity University Uttar Pradesh, Noida, India**, August 23rd & 24th, 2018.
2. Hayder Kamil Shanbara, Felicite Ruddock & William Atherton (2017), Improving the Mechanical Properties of Cold Mix Asphalt Mixtures Reinforced by Natural and Synthetic Fibers. **International Conference on Highway Pavements and Airfield Technology, The American Society of Civil Engineers (ASCE),** August 27–30, 2017 Philadelphia, USA. doi/10.1061/9780784480946.010.
3. H.K. Shanbara, F. Ruddock, W. Atherton, & G. Rothwell (2017), Evaluation of rutting potential in cold bituminous emulsion mixture using finite element analysis. **The 10th International Conference on the Bearing Capacity of Roads, Railways and Airfields (BCRRA 2017),** June 28-30, 2017, Athens, Greece.
4. H.K. Shanbara, F. Ruddock, W. Atherton, & G. Rothwell (2017), Cold and hot asphalt pavements modelling. **The 10th International Conference on**

the Bearing Capacity of Roads, Railways and Airfields (BCRRA 2017), June 28-30, 2017, Athens, Greece.

5. Hayder K Shanbara, F Ruddock, & W Atherton (2017), Modelling of permanent deformation in reinforced cold flexible pavements using three dimensional simulations. **Post Graduate Research Conference, Faculty of Technology and Environment Liverpool John Moores University**, 22-26 May 2017, Liverpool, UK.
6. Hayder K. Shanbara, Anmar Dulaimi, Felicite Ruddock & William Atherton (2016), The Linear Elastic Analysis of Cold Mix Asphalt by Using Finite Element Modelling. **The 2nd BUiD Doctoral Research Conference,** the British University in Dubai, UAE, 14th–15th May 2016.
7. Hayder K Shanbara, F Ruddock, & W Atherton (2015), Improve performance and damage prediction of cold bitumen emulsion mixtures using finite element modelling. **Post Graduate Research Conference, Faculty of Technology and Environment Liverpool John Moores University**, 15-19 June 2015, Liverpool, UK.

Abstract

The increase of road infrastructure around the world involving the traditional hot mix asphalt (HMA) technology and its effects on the environment and health means that serious attention needs to be paid to building more sustainable flexible pavements. Cold bitumen emulsion mixture (CBEM) as an increasingly attractive cold asphalt mixture is therefore becoming an important subject area for study. Despite the efforts applied during the last few decades to enhance and develop CBEM application, certain issues still exist that make it inferior to HMA, resulting in limiting or minimizing its use. However, the enhancement of CBEM for flexible pavements construction, rehabilitation and maintenance is increasingly gaining interest in both pavement engineering industrial and research sectors. Therefore, the main aim of this study is to gain a deep insight and understanding into the impact response of using natural and synthetic fibres as reinforcing materials, on the mechanical properties and water susceptibility of CBEM including indirect tensile stiffness and resistance to rutting, cracking and moisture damage. Four different types of fibres were used: glass as a synthetic fibre, and hemp, jute and coir as natural fibres. Various samples of CBEM, with and without fibres, were fabricated and tested. Traditional hot mix asphalt mixture was also used for comparison. By achieving this aim it is expected that the use of CBEM would increase, allowing such mixtures to be used as structural pavement materials with some confidence.

In spite of the quality of an asphalt mix being one of the most important and significant factors that affect the performance of both hot and cold mix flexible pavements, and the high quality mixes are often cost effective as these mixes require less maintenance and increase the service life of the pavements, it is also cost efficient to replace the semi-experimental flexible pavement design methods with fast and powerful software that includes finite element analysis. Several finite element models (FEM) have been developed to simulate the behaviour of hot mix asphalt, but none exists for cold mix asphalt reinforced by natural and synthetic fibres. This study also describes the development of a three-dimensional (3-D), finite element model of flexible pavements made with CBEMs, which has itself been reinforced with natural and synthetic fibres. The 3-D finite element model was employed to predict the viscoelastic and viscoplastic responses of flexible pavements based on CBEM when subjected to different multiple axle loads, bituminous material properties, tyre speeds and temperatures. The pavements were subject to moving and static loading conditions to test for permanent deformation (rutting).

The results indicate a significant improvement in the indirect tensile stiffness modulus, for all fibre-reinforced CBEMs, over different curing times. The improved tensile behaviour represents a substantial contribution towards slowing crack propagation in bituminous mixtures, while scanning electron microscopy analysis confirmed the fibre shape and surface roughness characteristics. The improved performance of the reinforced mixtures with both natural and synthetic fibres facilitated a substantially lower permanent deformation than traditional hot and cold mixtures at two different temperatures (45 °C and 60 °C). When using glass and hemp fibres as reinforcing materials, there was a significant improvement in CBEM in terms of water sensitivity. These reinforcing materials can extend the service life of flexible pavements. Finally, the results show that the finite element model can successfully predict rutting of flexible pavements under different temperatures and wheel loading conditions.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

2-D	Two-dimensional
3-D	Three-dimensional
AASHTO	American Association of State Highway and Transportation Officials
ABBCF	Activated binary blended cementitious filler
AC	Asphalt Concrete
AEMA	Asphalt Emulsion Manufacturers Association
BBF	Binary blended filler
CBEM	Cold bitumen emulsion mixture
CBEMs	Cold bitumen emulsion mixtures
CMA	Cold mix asphalt
CRA	Cold-rolled asphalt
EPA	Environmental Protection Agency
EVA	Ethylene Vinyl Acetate
FEM	Finite element model
GGBS	Ground Granulated Blastfurnace Slag
HMA	Hot mix asphalt
HRA	Hot Rolled Asphalt
IEC	Initial emulsion content
ITSM	Indirect tensile stiffness modulus
ITSR	Indirect tensile stiffness ratio
MS	Medium-setting
OPC	Ordinary Portland Cement

OPWwc	Optimum pre-wetting water content
OREC	Optimum residual emulsion content
OTLC	Optimum total liquid content
QS	Quick-setting
RAP	Reclaimed asphalt pavement
RH	Relative humidity
RLAT	Repeated Load Axial Test
RS	Rapid-setting
RSC	Rapid Setting Cement
SBS	Styrene-Butadiene-Styrene
SCB	Semi-circular bending
SEM	Scanning electron microscopy
SF	Silica fume
SMA	Stone Mastic Asphalt
SMR	Stiffness modulus ratio
SS	Slow-setting
TBF	Ternary blended filler
WFA	Waste Fly Ash
WMA	Warm mix asphalt

Nomenclature

°C	Celsius
a	Regression parameter (time development coefficient)
A	Power law multiplier
B	% of aggregate passing sieve 2.36 mm and retained on sieve 0.075 mm
b	Regression parameter (constant represent the initial ITSM)
C	% of aggregate passing sieve 0.063 mm
C3D8	Eight-node brick element
C3D8R	Eight-node brick element with reduced integration
C50B3	Cationic slow setting bituminous emulsion with 50% bitumen content
Ca^{2+}	Calcium ion
CAB 50	Cold Asphalt Binder based on 40/60 penetration grade
CO	Carbon monoxide
CO_2	Carbon dioxide
COI	Coir fibre-reinforced cold mix
CON	Conventional cold mix
D	Compliance of elasticity
E	Young’s modulus
Ei	Elastic modulus at any time
E_o	Initial elastic modulus
F	% of aggregate retained on sieve 2.36 mm
FC3R	Fluid catalytic cracking catalyst residue

F_{max}	Maximum force of specimen
GLS	Glass fibre-reinforced cold mix
h	The mean thickness of the test specimen
HEM	Hemp fibre-reinforced cold mix
HYD	Hydraulic Universal Testing Machine
JUT	Jute fibre-reinforced cold mix
K	Stiffness matrix of elasticity
K_{IC}	Fracture toughness
L	The peak level of the applied vertical load
M	Loading cycles number
m	Time order
MS-14	Asphalt Institute Manual Series No.14
MS-19	The Basic Asphalt Emulsion Manual Series No.19
N	Number of Kelvin models
n	Equation stress order
NaOH	Sodium hydroxide
P	% of initial residual bitumen content
pH	A scale of acidity from 0 to 14
R	The diameter of specimen
R^2	Correlation coefficient squared
t	Time
T	Temperature
T_i	Retardation time
$\mathrm{T_L}$	Loading time
T_o	Relaxation time

T_R	Relaxation time
X	Bitumen content of the emulsion
y	the peak horizontal diametric deformation resulting from the applied load
z	Notch depth of specimen
ε	Strain
ε_e	Elastic strain
ε_p	Plastic strain
ε_t	Total strain
ε_{ve}	Viscoelastic strain
ε_{vp}	Viscoplastic strain
η	Viscosity
v	Poisson’s ratio
σ	Stress

Glossary

Amidoamine	A class of chemical compounds.
Diamine	An organic compound.
Imidazoline	A class of heterocycles formally derived from imidazoles by the reduction of one of the two double bonds.
Lignin	One of the most predominant biopolymers present in plants.
Rosin	A solid form of resin obtained from pines and some other plants, mostly conifers, produced by heating fresh liquid resin to vaporise the volatile liquid terpene components.
Saponification	The name of the chemical reaction that takes place when oil and water mix with lye (a strong alkali - sodium hydroxide) under heat.
Tall oil	A viscous yellow-black odorous liquid obtained as a by-product of the Kraft process of wood pulp manufacture when pulping mainly coniferous trees.

Chapter 1

Introduction

1.1 Overview

An effective transport system is essential for the economic and social development of any country. Roads are one of the most popular elements of a transportation system. In recent years, demand on road transport networks around the world has developed increasingly in terms of traffic volume and axle loads. Subsequently, road pavement structures are deteriorating due to structural failure leading to a need to construct new roads or overlay the old ones. These include the use of hot mix asphalt (HMA) technologies for manufacturing, laying down and compacting the asphalt mixtures at high temperatures. At the same time, it is associated with high-energy consumption, greenhouse gas emission and health impacts in both construction and maintenance of the road network (Miljković, 2014). In addition, asphalt pavements are considered as a factor in the global heating and air pollution (European Environment Agency, 2013). Therefore, there is a significant need to enhance the asphalt pavement technology by enabling the production at lower temperatures (Bonaquist, 2011; Prowell, Hurley and Frank, 2011). The construction of road pavements industry has paid increasing attention to using cold mix asphalt (CMA), which uses bitumen emulsion instead of hot bitumen. Cold bitumen emulsion mixture (CBEM) is the most common type of CMA, which comprises bitumen emulsion as a binder. However, current technology only allows such a mixture to be used for particular applications in certain situations. To date, it has been considered as an inferior mixture, in comparison to HMA, because of low early stiffness, a long curing time needed to reach its final strength and high air void content. This cold process has been extensively used for many years in several countries such as the United States of America, Australia, France, Belgium, Brazil and those in Scandinavia. In the United Kingdom, the development of CMA technology is only recently being brought forward (Thanaya, 2003).

1.2 Problem Statement

Hot and cold asphalt mixes are composite materials that mainly consist of bitumen as a binder, aggregate and voids. They have generally been used as a material for constructing flexible road pavements because of the good adhesion that exists between binder and aggregates (Wu, Ye and Li, 2008). However, due to some certain factors that can negatively affect the performance of CBEM such as weak early strength, long curing time, traffic and environment, poor mechanical properties, high air voids and construction quality control, various types of distress or damage can appear on the surface of such pavements. Rutting (permanent deformation) development is one of the major distresses that occurs frequently in flexible pavements due to the non-linear, viscous and plastic behaviours of asphalt mixes. It can be defined as the irrecoverable vertical deformation of pavement under the vehicle wheel path (as shown in Figure 1.1) caused by high temperature and load repetitions. It might be limited to the asphalt surface layers that comprises the viscoelastic and viscoplastic properties of asphalt and the plastic characteristics of aggregates. During rainy weather, rutting prevents water drainage away of the pavement surface making it accumulate in the ruts that increases the probability of car accidents related to hydroplaning as shown in Figure 1.2. Mallick and El-Korchi (2013) considered a 12.5 mm rut depth as rutting failure, although, this value is dependent on the type of road and design speed. Therefore, each country or

Figure 1.1: Rutting of bituminous pavements (Pavement Interactive, 2012)

Figure 1.2: Hydroplaning issues in bituminous pavements (Roadex Network, 2018)

specifications may have their own judgement, not following to a specific failure value. In addition, deep rutting causes difficulties in steering for vehicles. This may cause loss of car control which then leads to an accident (Khanzada, 2000). In hot weather, asphalt pavements can rut after about one year following construction due to high temperature (e.g. pavement temperature over 50 °C) and heavy axle loads.

One of the main factors that affects rutting in CBEM is mixture properties. There is a lack of knowledge on how mixture properties affects the rutting of CBEM and how the improvements in the mixture properties cause a change in the performance of the CBEM.

1.3 Why Cold Mix Asphalt (CMA)?

Cold mix asphalt (CMA) is defined as bituminous materials which are prepared at ambient temperature by emulsifying the asphalt in water before blending with the aggregates. It has been considered an inferior mixture compared to hot mix asphalt for the last several years, mainly in terms of its mechanical properties, the extended curing period required to achieve an optimal performance and its weak early life strength (Thanaya, Forth and Zoorob, 2009). CMA has a number of benefits over HMA, but the main difference lies in the fact that CMA does not require any heating as it can be manufactured, laid and compacted without heating. In addition, CMA can offer the following advantages:

- Bitumen emulsion does not require a petroleum solvent to make it liquid. Bitumen emulsions can also be used in most cases without additional heat. Both of these factors contribute to energy savings (Asphalt Institute, 2008).

- CMA is not dependent upon warm weather. It is a flexible material that could be strong enough to withstand temperature fluctuations. It can be used in all weather.
- It can be mixed on site or off site and then transported to location where other mixtures need special equipment to control the temperature before laying.
- Eco-friendly option during all production processes made from water-based materials at ambient temperatures, which reduces emissions, energy consumption and toxic fumes (Bouteiller, 2010). There are little or no hydrocarbon emissions from asphalt emulsions (Asphalt Institute, 2008).
- Cost-effective solution for paving or repairing rural roads that are nowhere near a hot mix plant, as minimal material and transportation costs required where CMA used in remote areas (Al-Hdabi, 2014).
- 2-3 times faster progress than other types of mixtures using existing facilities at site without any extra investment in capacity building or equipment.
- Ageing of the binder does not occur during storage and construction stages as no heat is required (Al-Busaltan, 2012).
- Recycled and virgin aggregate can be used to produce CMA (Al-Busaltan, 2012).
- No waste is expected during construction stage of CMA in comparison to HMA when its temperature reaches a certain unacceptable rate (Al-Busaltan, 2012).

1.4 Aim and Objectives

Asphalt mix quality is one of the most important and significant factors that affects the hot and cold flexible pavements performance. The high quality mix is often economic, sustainable and safe during pavement performance enhancements and this constitutes the main driving forces affecting the incentives to further develop of CMA.

The aim of this study is to understand the behaviour of the conventional CBEM and to improve this behaviour using natural and synthetic fibres as reinforcing materials in CBEM.

This aim is achieved partially through experimental analysis of the behaviour of the conventional CBEM and improvement of this behaviour using natural and synthetic fibres as reinforcing materials. The purpose of this part of the work is to gain a thorough understanding on how the reinforced and unreinforced CBEMs respond in terms of different mechanical properties. The study also aims to numerically develop a three-dimensional (3-D) finite element model (FEM) to predict the rut depth caused by repeated wheel loading on reinforced and unreinforced CBEM, and HMA mixtures using viscoelastic and viscoplastic analysis.

Even though extensive experimental and numerical work has been carried out on natural and synthetic fibres-reinforced HMA, very limited research work has been undertaken to investigate the effect of natural fibre on the mechanical response of CBEMs under different loading and environmental conditions. The research work proposed in this project provides a better understanding of the mechanical behaviour of CBEM reinforced with natural and synthetic fibres under different loading conditions.

The novelty of these aims lies in the fact that CBEM has been used only for specific environments and road types and is currently considered inferior to hot mix asphalt because of the low structural competence of the material in early life, adhesion properties, long curing time and moisture damage resistance compared with hot mix.

Natural fibre reinforcement of CBEM has not previously been investigated at different temperatures and environmental conditions. Therefore, using natural and synthetic fibres in CBEMs is to achieve the optimum properties for replacing HMA. In addition, based on the engineering properties of CBEMs, a finite element model has been developed as a first model simulating the permanent deformation of such mixtures.

In order to achieve these aims the following objectives are required:

- Conduct a detailed literature review on asphalt pavements in general and the technology of CBEM in order to optimise the mix design, fibre's length and content, and to determine the experiments and parameters that are needed to evaluate the CBEMs and build up the analytical model. The literature review focuses on the properties, testing and design procedures associated with the current use of CBEM, and also focuses on the techniques that are used to improve CBEM by adding OPC, waste materials and by-products as a replacement to the filler. In addition, using natural and synthetic fibres as reinforcing materials in asphalt mixtures has been reviewed.
- Select the candidate natural and synthetic fibres as reinforcing materials in CBEM. These fibres considered are hemp, jute and coir as natural fibres, and glass as a synthetic fibre.
- Test the reinforced and unreinforced CBEMs and also HMA mixture (for comparison) in the laboratory to determine and evaluate the properties of such mixtures. To achieve this goal, analyse the performance of these mixtures based on the results from different tests such as indirect tensile stiffness modulus (ITSM), wheel tracking, uniaxial compressive cyclic (creep), water sensitivity and semi-circular bending monotonic tests.

- Use the scanning electron microscope (SEM) to show the microstructure of the fibres and their surface area to help the understanding of mixture-fibre interlock.
- Develop a 3-D finite element model for predicting permanent deformation in reinforced and unreinforced CBEM and HMA mixtures under static and moving wheel loads. A particular focus of the calibration is the viscoelastic and viscoplastic model components, which are the most relevant for the rutting problem. ABAQUS software is selected for this task.
- Use the developed model to calculate the rutting of the reinforced and unreinforced mixtures and compare with measured rut depth from the wheel track testing.

1.5 Thesis Outline

This thesis presents an extensive literature review of the existing research related to this study. The experimental results of different tests are presented and discussed. The validation of numerical simulations, parametric studies and the simplified theoretical models are also explained and examined. The thesis consists of six chapters and is organised as follows:

Chapter 1: Presents an introduction of the CMA and the finite element analysis. In addition, the main aims and objectives of the research as well as the thesis outline are included.

Chapter 2: Reviews the previous research work relevant to the present investigation. The experimental investigations and developments of CBEM and HMA mixtures are presented and discussed. The finite element analysis investigations on the asphalt pavements are also included.

Chapter 3: Describes the experimental work which includes the materials characterisation, mix design, test methods, and the preparation of specimens. The fibre reinforcing CBEMs process is also presented.

Chapter 4: The experimental results obtained from different tests are presented and discussed. This chapter provides the detailed results of performance characterisation of CBEMs reinforced with different types of fibres.

Chapter 5: Presents the development of the finite element analysis to simulate the mechanical behaviour of the reinforced and unreinforced CBEM and HMA mixtures under different loading and environment conditions using the commercial code ABAQUS/Explicit. The chapter describes model geometry, materials properties, loading conditions, failure criteria, mesh sensitivity study, as well as the boundary conditions. All numerical models were validated against the experimental findings. Parametric studies using the validated numerical models developed in this chapter were carried out to investigate the effects of several parameters on the rutting response of the reinforced and unreinforced CBEMs. Here, the results obtained from these studies are compared and discussed.

Chapter 6: Draws the main conclusions of the research findings and gives suggestions for the future research work.

Chapter 2

Literature Review

2.1 Introduction

This chapter presents a comprehensive review of cold mix asphalt (CMA) mixtures associated with technologies in the asphalt pavement industry. The previous work relevant to the current research is reviewed in this chapter. The existing knowledge related to the studies on cold bitumen emulsion mixture (CBEM) under different loading and environmental conditions covers the experimental work and analytical research. It also includes a review of the previous studies on the structural behaviour of CBEMs. Furthermore, the results of research carried out on the structural behaviour of the CBEM improved by different techniques are presented, together with a review of the numerical analyses of bituminous pavements. Finally, the constitutive models used to perform bituminous mixtures behaviour are discussed and the related researches are reviewed.

2.2 Asphalt Mixtures

Asphalt mixtures are composite materials that mainly consist of, bitumen as a binder, graded mineral aggregate and voids. Depending on the types and proportions of these components as well as the aggregate grading and particle size distribution, different types of mixtures can be produced. Accordingly, asphalt mixtures are divided into two main types: continuous graded and gap graded mixtures. In the continuous graded mixture, there are different aggregate size fractions and the voids generated by the coarse aggregate are filled up by the fine aggregate, filler and bitumen (Roberts et al, 1991). The gap graded mixture produces a high air voids content to be filled with a mortar of sand, filler and bitumen. Hence, continuous graded mixtures perform better than the gap graded mixtures in terms of deformation resistance (Read, 1996). Different asphalt mixture types are used in the UK road pavements construction as is explained in the following sections.

2.2.1 Asphalt Concrete

Asphalt Concrete (AC), commonly called bitumen macadam, is a composite material in which the aggregate particles are continuously graded to form an interlocking structure. It gains its properties by the use of high quality stone, forming good aggregate skeletons. Its strength is derived from the interlock of coated aggregate. There are several types of AC ranging from 3 mm fine graded surface course to 40 mm Heavy Duty AC. The differences between these types are defined by varying the maximum nominal size of the aggregate, the bitumen grade and the filler content. AC is used for surface courses, binder courses, regulating courses and bases. The typical grading and an idealised section through this mixture are presented in Figure 2.1 according to the asphalt concrete specification (European Committee for Standardization - Part 1, 2006).

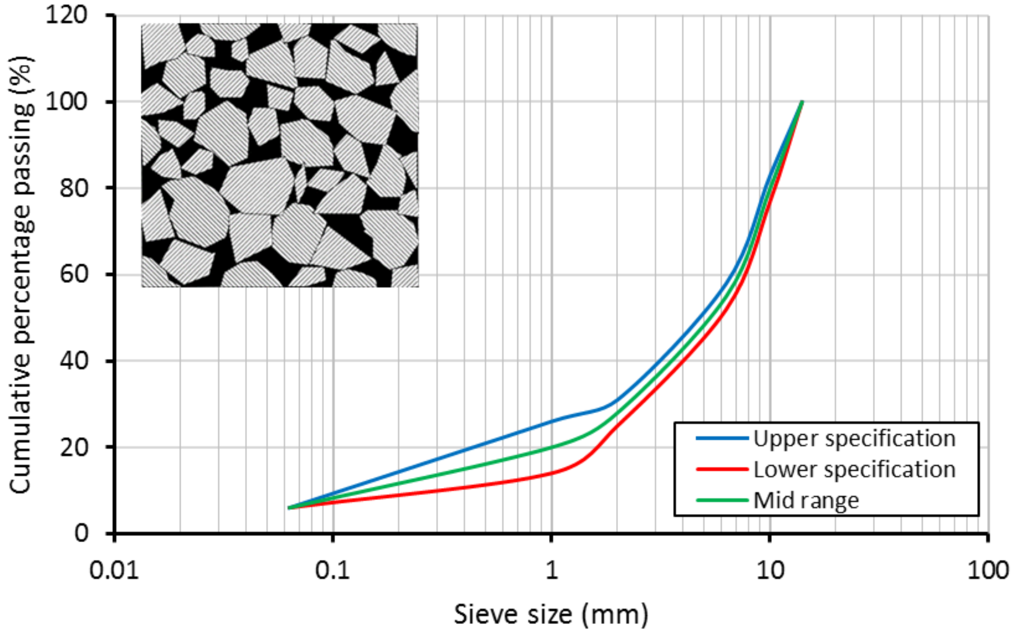


Figure 2.1: Typical 14 mm close graded surface course grading

2.2.2 Hot Rolled Asphalt

Hot Rolled Asphalt (HRA) is a dense, gap graded bituminous mixture in which the mortar of fine aggregate, filler and high viscosity binder are major contributors to the performance of the laid material. There is a high percentage of sand in the mixture resulting in a low percentage of air voids when it is compacted. Its strength is derived from the mortar of bitumen, sand and filler. Hot Rolled Asphalt is used for surface courses, binder courses, regulating courses and bases. The designation of HRA is in the form of two numbers, the first number indicates the nominal percentage of coarse aggregate in the mixture and the second number indicates the maximum nominal aggregate size in millimetres. The range of mixture types varies from a 0/3 sand sheet surface course to a 60/40 road base material. According to the HRA specification (European Committee for Standardization - Part 4, 2006), the most common material used in the UK is a 30/14 HRA surface course with pre-coated chippings rolled into the surface to provide skid resistance. This typically has a binder content of 6% to 8%, by mass of the total mixture, dependent upon the exact grading and mechanical properties required. Figure 2.2 shows a typical aggregate grading curve, and a cross section of the HRA mixture.

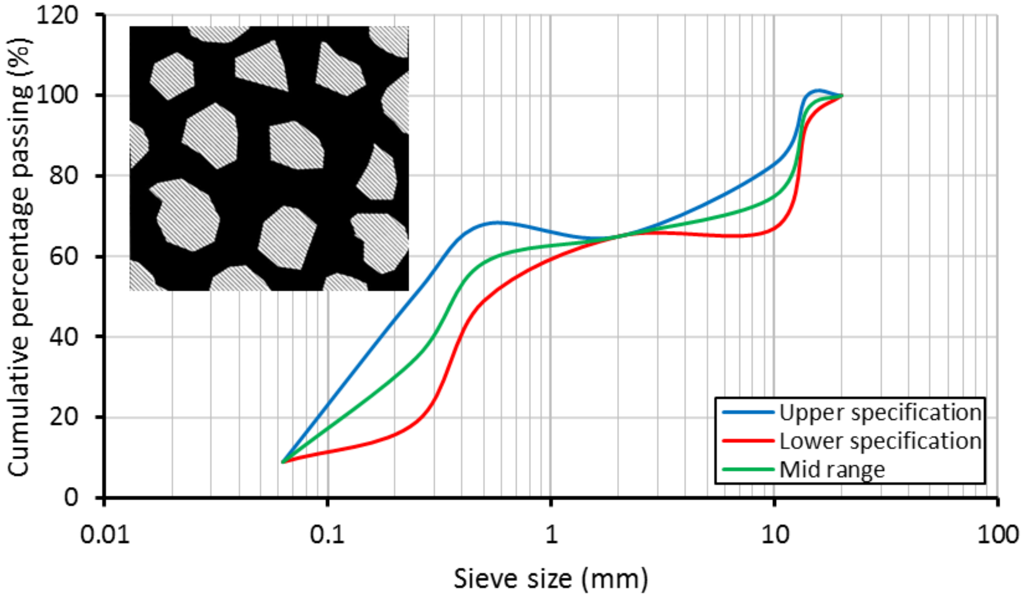


Figure 2.2: 30/14 Hot rolled asphalt

2.2.3 Stone Mastic Asphalt

Stone Mastic Asphalt (SMA) is a gap graded bituminous mixture with bitumen as a binder, composed of a high coarse crushed aggregate content that interlocks to form a stone skeleton bound with a mastic mortar. It provides a deformation-resistant, durable surfacing material, suitable for heavily trafficked roads. Stone Mastic Asphalt is mainly used for surface courses. A typical aggregate grading curve, and a cross section of the SMA mixture are shown in Figure 2.3 according to the SMA specification (European Committee for Standardization - Part 5, 2006).

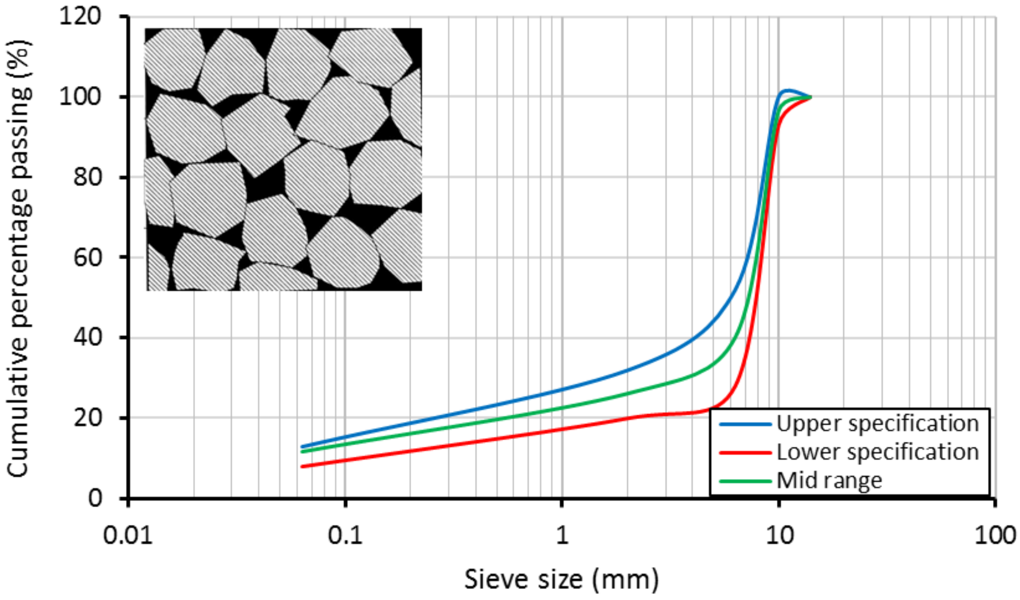


Figure 2.3: Typical stone mastic asphalt grading

2.3 Asphalt Mixtures Classification

Asphalt mixtures have generally been used as a material for constructing flexible road pavements because of the good adhesion that exists between bitumen and aggregates (Wu, Ye and Li, 2008). Bitumen plays an essential role in determining the properties of asphalt pavements, and it is responsible for the viscoelastic and viscoplastic behaviour characteristics of such pavements under different loading conditions (Thom, 2008). Depending on the mixing process and temperatures that are used, the asphalt mixtures are classified to the following types (Vaitkus et al, 2009):

2.3.1 Hot Mix Asphalt

Hot mix asphalt (HMA) is a combination of mineral aggregate uniformly mixed and coated with bitumen. To dry the aggregates and to achieve sufficient flexibility of bitumen for appropriate mixing and workability, both the aggregate and bitumen must be heated prior to mixing-hence the term “hot mix.” The mixing temperature is equal to the used bitumen viscosity (Mixing temperature (°C) = Bitumen viscosity (170 ± 20 centistokes)), according to the hardness grade of the bitumen. Aggregates and bitumen are combined in a mixing facility in which all of the constituent materials are heated, proportioned and mixed to produce the desired paving mixture. After plant mixing is complete, the hot mix is transported to the paving site and spread with a paving machine in a loosely compacted layer to a uniform, even surface. While the paving mixture is still hot, the material is further compacted by heavy motor-driven rollers to produce a smooth, well-consolidated pavement layer. According to the (U.S. Environmental Protection Agency (EPA), 2011), the production of HMA is a major source of carbon emissions that have a significant environmental impact. EPA estimates the annual emissions of an HMA plant, which generates around 200,000 tons of asphalt mix, is around 13 tons of carbon monoxide (CO), 5 tons of volatile organic compounds, 2.9 tons of nitrogen oxides, 0.65 tons of total hazardous air pollutants and 0.4 tons of sulphur oxides (United States Environmental Protection Agency, 2000).

2.3.2 Warm Mix Asphalt

Warm mix asphalt (WMA) is the general name of technologies that allow the asphalt pavement industry to lower the temperatures at which the material is mixed and placed on the road. Reductions of 20 °C to 40 °C below the temperature required for HMA have been documented (Rubio et al, 2012). Such reductions have the obvious benefits of using fewer fossil fuel resources and reducing the production of greenhouse gases in the manufacturing process (European Asphalt Pavement Association, 2010). In addition, engineering benefits include better flexibility in terms of use, as it cools more slowly than HMA. WMA has the ability to be shipped for longer distance and extends the paving season by being able to pave at lower temperatures.

2.3.3 Cold Mix Asphalt

In response to growing concerns over global warming and rising greenhouse gas emissions, the asphalt industry is paying considerable attention to finding alternatives to HMA (Dinis-Almeida et al, 2016; Vaitkus et al, 2016). An effective solution is the use of CMA technology that allows mixing, laying and compaction of the bituminous mixtures without heating. Cold mix asphalt is a mix of aggregate with a reduced viscosity bitumen binder. It is produced by emulsifying the bitumen in water prior to mixing with the aggregate at ambient temperature (Jenkins, 2000). During the emulsifying stage, the bitumen is less viscous and the mixture is easy to work and compact. The emulsion breaks after enough water evaporates and the cold mix, ideally, takes on the properties of HMA. Cold mix is typically used as a patching material and on lesser-trafficked service roads. Accordingly, these efforts have led to several CMA types around the world as follows:

2.3.3.1 Cold Lay Macadam

Cold lay macadam is a bituminous mixture which consists of aggregate with reduced viscosity bitumen (cutback bitumen) using flux oil or solvent. Flux oil contains a non-volatile fraction of petroleum to dilute the hard bitumen to the required consistency. The efficiency of this mixture mainly relies on the evaporation rate of the flux oil due to the weather conditions and pavements service. Several flux oil types are used in cold lay macadam such as gas oil, white spirit, kerosene and creosotes (Nicholls, 2004). The application of this mixture is normally used for surface dressing, base course, macadam mixtures and filling for temporary reinstatement work. Because of the low stiffness of this mixture due to flux oil, its use has reduced and been replaced with the HMA mixture (Robinson and Thagesen, 2004). Furthermore, the use of cold lay macadam is considered uneconomical and environmentally not friendly due to solvent use (Leech, 1994).

2.3.3.2 Grave Emulsion Mixture

Grave emulsion (emulsion stabilised aggregate) mixture has been particularly used in the warm and dry regions due to the high susceptibility to moisture damage (Needham, 1996). In grave emulsion mixture, dense gradation aggregate is mixed with pre-wetting water then mixed together with a medium setting emulsion which is considered the main binder. It is classified as a dense graded emulsified mixture. This mixture has been used for base courses and as an overlay for strengthening of deteriorated pavements and re-profiling old roads. Also, it can be used as a surface course for low trafficked roads (Thanaya, 2003). Typically, these mixtures need to be laid directly after mixing which is difficult to implement due to the distance between the site and the manufacturing plant. Therefore, a modification to the mixture has been carried out using flux oil, which allows these mixtures to be stockpiled for many days before laying. However, this modification causes a stiffness reduction as a result of softening the bitumen, and increases the period of curing. This mixture can be distinguished from other types of CMA due to the thin films of binder that coated the aggregate particles as a result of the low bitumen content, and this leads to one of the drawbacks of this mixture (Needham, 1996; Thanaya, 2003).

2.3.3.3 Foamed Bitumen Mixture

An alternative cold process uses a foamed bitumen as a binder in manufacturing CMA. Foamed bitumen is produced by mixing hot liquid bitumen with water-derived steam plus a surfactant. The bitumen expands to about fifteen times its volume during the rapid boiling of the water resulting in a foam which is then stabilised by the surfactant. This binder is then mixed with aggregates while it is still in the foamed state, and due to the increased volume of the binder, a high degree of coating is achieved. Normally, bitumen comprises about 97% of the foam mass, where water and foamed agent comprise 2% and 1% respectively (Al-Busaltan, 2012).

2.3.3.4 Cold Bitumen Emulsion Mixture (CBEM)

Cold bitumen emulsion mixture (CBEM) is the most popular type of CMA mixture and used to create a bituminous mixture produced by mixing bitumen emulsion with mineral aggregates. The CBEM industry is interested in using either virgin aggregate and RAP (Reclaimed Asphalt Pavement) or both to gain an optimum gradation (Needham, 1996; Thanaya, 2003). In CBEM, less energy consumption and fewer emissions are considered as the main advantages of using such mixtures compared with HMA. However, this mixture has some problems similar to any CMA mixtures as it has low early strength, a long curing time needed to obtain the maximum performance, high air voids and is hence considered inferior to HMA. Also in contrast to HMA, CBEM might take from a few months to a few years to develop their ultimate strength and associated properties (Nikolaides, 1983). Thus, CBEM has been used in limited applications such as lightly trafficked roads, footways and reinstatements (Leech, 1994; Read and Whiteoak, 2003; Thanaya, 2003; Liebenberg and Visser, 2004; Gómez-Meijide and Pérez, 2014; Ojum, 2015). Doyle et al (2013) reported that due to the long curing time that is required for the CBEM to gain its full strength after paving, it has rarely been used for heavy traffic load pavements. It has also been considered to be a highly sensitive bituminous mixture to rainfall during the early age of construction (Oruc, Celik and Akpinar, 2007). Therefore, using CBEM as a structural layer is limited especially in the UK. CBEM could be used for heavily trafficked roads when overlaid by at least 40 mm of hot bituminous mixture layer (Ibrahim, 1998). Generally, open or semi-dense aggregate gradation are used in producing CBEM to give better aeration within the high air void mixture which helps to evaporate the trapped water and reduce curing time (Nikolaides, 1983). However, recently different gradations have been used in preparing CBEM such as dense gradation and continuous or gap graded gradations (Ibrahim, 1998; Thanaya, 2003; Al-Busaltan et al, 2012b; Al-Hdabi et al, 2014). In addition to the gradation, the characteristics of the CBEM significantly depend on the characteristics and type of the bitumen emulsion, pre-wetting water added, curing process, compaction effort and additives used (Thanaya, 2003).

Different countries are using and developing the CBEM in road works, for example France and the USA (Ojum, 2015). However, this mixture is not preferable and restricted to use for road works in the UK because of the relative wet and cold weather.

2.4 Performance Characteristics of CBEM

To examine the performance of CBEM, several investigations have been conducted. The outcomes of these investigations have identified the main problems of CBEM, and proposed procedures on how to mitigate them. Thanaya (2007) stated that CBEM is comparable with HMA in terms of mechanical properties as shown in Table 2.1. In the same way, Robinson (1997) observed that the indirect tensile stiffness modulus of CBEM improved gradually to meet the requirements of 600 MPa after 10 months of curing time and the stiffness developed to about 800 MPa after 2 years. Thanaya (2007) revealed that CBEM is suitable for low to medium trafficked roads when the creep slopes of such mixtures were considered in this work. Brown and Needham (2000) noted that adding OPC to CBEM has positive effects as this mixture without OPC failed at less than 1000 cycles in the unconfined mode of Repeated Load Axial Tests (RLAT).

Table 2.1: Properties of the CBEMs compared to HMA (Thanaya, 2007)

Mixture type	Compaction effort	Porosity (%)	ITSM (MPa)
CBEM	Heavy	9.7	2275 (Full curing)
CBEM with 1% OPC	Heavy	9.4	3378 (Full curing)
CBEM with 2% OPC	Heavy	9.2	3970 (Full curing)
HMA of 100 pen grade	Medium	4.7	2150
HMA of 100 pen grade	Heavy	3.4	2520

Despite the significant beneficial environmental and economic impacts of using CBEM in pavement engineering, this mixture is still underutilised in the UK compared with other European countries, mainly because of the complexity involved in the design and performance assessment of CBEM (Khalid, 2003). Therefore, road pavement companies would always prefer to place structures that are able to perform their proposed design roles directly after construction. Serfass et al (2004) demonstrated that CBEM is an evolutive material, especially in its early life, where the initial cohesion is low and building up progressively. This behaviour results from the combination of several factors, such as presence of water, aggregate emulsion reactivity, binder film coalescence and cohesion build up. The rapid improvements in emulsion manufacturing technology and site production techniques help to overcome some other problems such as poor aggregate coating, binder stripping and low binder film thickness. Thanaya (2003) observed that the insufficient binder coating is particularly related to the coarser aggregates because of the incompactibility between the emulsion and aggregates, while the emulsion is flocculated on the fines portion. Additionally, as a result of the low binder viscosity of CBEM, Thanaya (2003) revealed that such mixtures can have some problems with binder drainage and binder stripping during storage and compaction. Staple (1997) stated that the CBEM does not meet the UK Standards as it has significantly lower elastic modulus than required even after 18 months of curing due to the high air void content of this mixture.

It is observed from the literature that there are several difficulties to overcome if CBEM is to be used as a fully integrated structure in pavement construction. These difficulties appear during manufacturing stages and service life of this mixture. In addition, it is concluded that the full curing of CBEM on site depends on the weather conditions and curing time, and might extended from 2 months to 24 months (Al Nageim et al, 2012). Accordingly, the cold, humid and rainy weather in the UK is considered not suited to reduce the curing time of CBEM.

2.4.1 Bitumen Emulsion Technology

Bitumen is manufactured in different types and grades ranging from hard and brittle solids to thin liquids. The bitumen used for road works is normally in the middle of these two extremes. Although the paving bitumen is a solid or semi-solid material at ambient temperatures, it can be readily liquefied by heating, adding a petroleum solvent, or by emulsifying it in water. The technology of heating the bitumen, in the production of HMA, is used to liquefy the bitumen to enable it to coat the aggregates and keep workable during transport, laying down and compaction. After that, the bitumen cools and regains its viscosity and other binding properties that make it an effective paving material. In addition to the heating, petroleum solvents such as kerosene and naphtha are added to the base bitumen to make it liquid, the product is called cutback bitumen. The cutback cures and the bitumen's binding properties are restored when the solvent evaporates. When the bitumen is milled into microscopic particles and dispersed in the water with a chemical emulsifier, it becomes a bitumen emulsion (Salomon, 2006; Dulaimi, 2017). When emulsions are used in road works, the water evaporates into the atmosphere, and the chemical emulsifier is retained with the bitumen.

Emulsions were first developed in the early 1900s and used in road works in the 1920s (Salomon, 2006). Their early use was in spray applications and as dust palliatives (Dulaimi, 2017). The growth in the use of bitumen emulsions was relatively slow, restricted by the type of emulsions available and a lack of information as to how emulsion should be used. Nowadays, due to the continuous developments of new emulsion grades and types, coupled with developed construction equipment and practices, different choices are available (Thanaya, 2003; Asphalt Institute, 2008). European Asphalt Pavement Association (2015) listed the bitumen emulsions consumption in different countries as shown in Table 2.2.

Table 2.2: Bitumen emulsion usage (European Asphalt Pavement Association, 2015)

Country	Consumption (Tonnes)	Consumption (kg/person)	Bitumen emulsion used in road works (%)
United States	2,300,000	9	5
France	1,010,000	17	25
Mexico	515,000	6	34
Brazil	400,000	3	5
Spain	350,000	9	18
Japan	316,000	3	5
Thailand	300,000	5	24
United Kingdom	160,000	3	5
Germany	130,000	2	3
Italy	100,000	2	3

2.4.1.1 Composition and Classification of Bitumen Emulsions

Generally, a bitumen emulsion consists of three main constituents: bitumen, water and an emulsifying agent. On some occasions, the bitumen emulsion may include other ingredients, such as stabilisers, coating improvers, antistrips or break control agents. The mixing of bitumen and water using chemical additives and highly specialised equipment is conducted under carefully controlled conditions.

Bitumen is the main ingredient of the bitumen emulsion and in most cases; it composes 50% to 75% of the emulsion. Bitumen grade or hardness significantly affects the produced emulsions which are normally manufactured with bitumen in the 40-250 penetration grade (Salomon, 2006). Occasionally, environmental conditions may require harder or softer base bitumen. In any case, chemical compatibility of the emulsifying agent with the bitumen is an essential factor for manufacturing a stable emulsion. Bitumen principally consists of large hydrocarbon molecules (Dulaimi, 2017). The complex interaction of these molecules makes it practically impossible to predict perfectly the behaviour of the bitumen to be emulsified. Therefore, quality control is necessary on the bitumen emulsion manufacturing.

Water is the second ingredient of the bitumen emulsion. It contains minerals that affect the manufacturing of stable bitumen emulsions. Consequently, drinking water might not be perfect for production of bitumen emulsion. The benefit of the calcium and magnesium ions in the water is to form a stable cationic emulsion because calcium chloride is usually added to the cationic emulsions to improve storage stability. These ions, however, can be harmful in anionic emulsion due to water-insoluble calcium and magnesium salts which are formed in the reaction with water-soluble sodium and potassium salts that are usually used as emulsifiers. On the other hand, carbonate and bicarbonate anions can stabilise the anionic emulsion because of their buffering effect, but these anions destabilise the cationic emulsion by reacting with water-soluble amine hydrochloride emulsifiers. Accordingly, water containing particulate materials or impure water should not be used in emulsion manufacturing as they result in an imbalance of the emulsion components that can adversely affect performance or cause premature breaking.

Emulsifying agents are surface-active agents or surfactants that greatly affect bitumen emulsion properties (Asphalt Institute, 1989; Asphalt Institute, 2008; Dulaimi, 2017). The emulsifiers keep the bitumen droplets in a stable condition and control the breaking time (Thanaya, 2003). Clays and soaps were used as emulsifying agents in the early days of bitumen emulsion manufacturing. Due to the increasing demand for using bitumen emulsion, several effective emulsifiers were obtained. Different emulsifying agents are now commercially available. Most anionic emulsifiers are fatty acids, which are wood-product derivatives such as lignins, tall oils and rosins (Read and Whiteoak, 2003). Anionic emulsifiers are saponified (turned into soap) by reacting with sodium hydroxide or potassium hydroxide. Fatty amines are the most common cationic emulsifiers such as imidazolines, amidoamines and diamines (Thanaya, 2003). The amines are transformed into soap by reacting with acid, generally hydrochloric. Fatty quaternary ammonium salts are another type of emulsifying agent that is utilised to produce the cationic emulsions. These types of emulsifiers are sufficient and stable cationic emulsifiers as they are water soluble salts and do not need the addition of acid.

Bitumen emulsions are classified into three types: anionic, cationic, and non-ionic (Salomon, 2006). Practically, the anionic and cationic types are the most widely used in pavements construction and maintenance. These types refer to the electrical charges surrounding the bitumen particles. The anode pole becomes positively charged and the cathode pole becomes negatively charged when these two poles are submerged in a fluid and an electric current is passed through. If this electric current is passed through a bitumen emulsion containing negatively charged particles of bitumen, these particles will move to the anode, thus the emulsion is classified as anionic. On the contrary, positively charged bitumen particles will migrate to the cathode and the emulsion is identified as cationic. The neutral bitumen particles do not move to either pole and the emulsion is classified in this case as non-ionic.

Emulsions are also classified based on how quickly the bitumen droplets will come together and return to bitumen. This is related to the speed with which an emulsion will become unstable and break after contacting the surface of the aggregates. This classification is simplified and standardised by adopting the terms RS (rapid-setting), MS (medium-setting), SS (slow-setting) and QS (quick-setting). The RS emulsion has no or little ability to mix with the aggregates, the MS emulsion is considered to mix with coarse aggregates, and SS and QS emulsions are preferable to mix with coarse and fine aggregates, with the QS likely to break faster than the SS. In addition, bitumen emulsions are identified using different letters and numbers that indicate the viscosity of the emulsions and the hardness of the base bitumen in accordance with BS EN 13808 (European Committee for Standardization, 2013). The letter “C” at the beginning of the emulsion type indicates that it is cationic. The second letter “B” indicates the binder content. Occasionally, if there is a polymer included the third letter added is “P” and also if the emulsion contents flux (more than 2%), this is the fourth component indicated by the letter “F”. The first number that follows the letter “C” in the bitumen emulsions is related to the percentage of the binder content in the bitumen emulsion. The other number at the end refers to the breaking rate, which ranges from 1 to 7, where the higher the number, the slower the break rate, lower numbers referring to rapid setting. For example, C50BPF3 indicates cationic, binder content of 50%, produced from bitumen which contains polymers and more than 2% flux with a class 3 breaking value.

Anionic bitumen emulsions are identified according to the British Standard Institution (2011) using three elements. The first part indicates emulsion type e.g. ‘A’ for anionic emulsion. The second component indicates the breaking rate or stability ranging from 1 to 4, where 1 indicates rapid setting and 4 indicates slow setting. The third part of the code represents the percentage of bitumen in the emulsion. For instance, A1-60 is an anionic emulsion with rapid breaking and a bitumen emulsion of 60%.

2.4.1.2 Bitumen Emulsion Quality

Different variables affect the production, storage and performance of bitumen emulsions. These variables have a significant effect including:

- The base bitumen chemical properties, hardness, quality and the particle size in the emulsion.
- Emulsifying agent type, concentration and properties.
- The temperature and pressure used during manufacturing.
- Emulsion particles' ionic charge.
- Ingredients' addition order.
- Using additives such as chemical modifiers and polymers.

These features can be varied to suit the available aggregates or pavement construction conditions. It is always recommended to consult the bitumen emulsion suppliers with respect to a particular bitumen-aggregate combination, as there are few rules that apply under all conditions.

2.4.1.3 Production of the Emulsion

The main equipment to produce the bitumen emulsion consists of a high-speed, high-shear mechanical device (usually a colloid mill) to split the bitumen into very small droplets. A schematic plan of a usual bitumen emulsion manufacturing plant is presented in Figure 2.4. Additionally, a heated bitumen container, emulsifier solution container, pumps and flow-metering gauges are required.

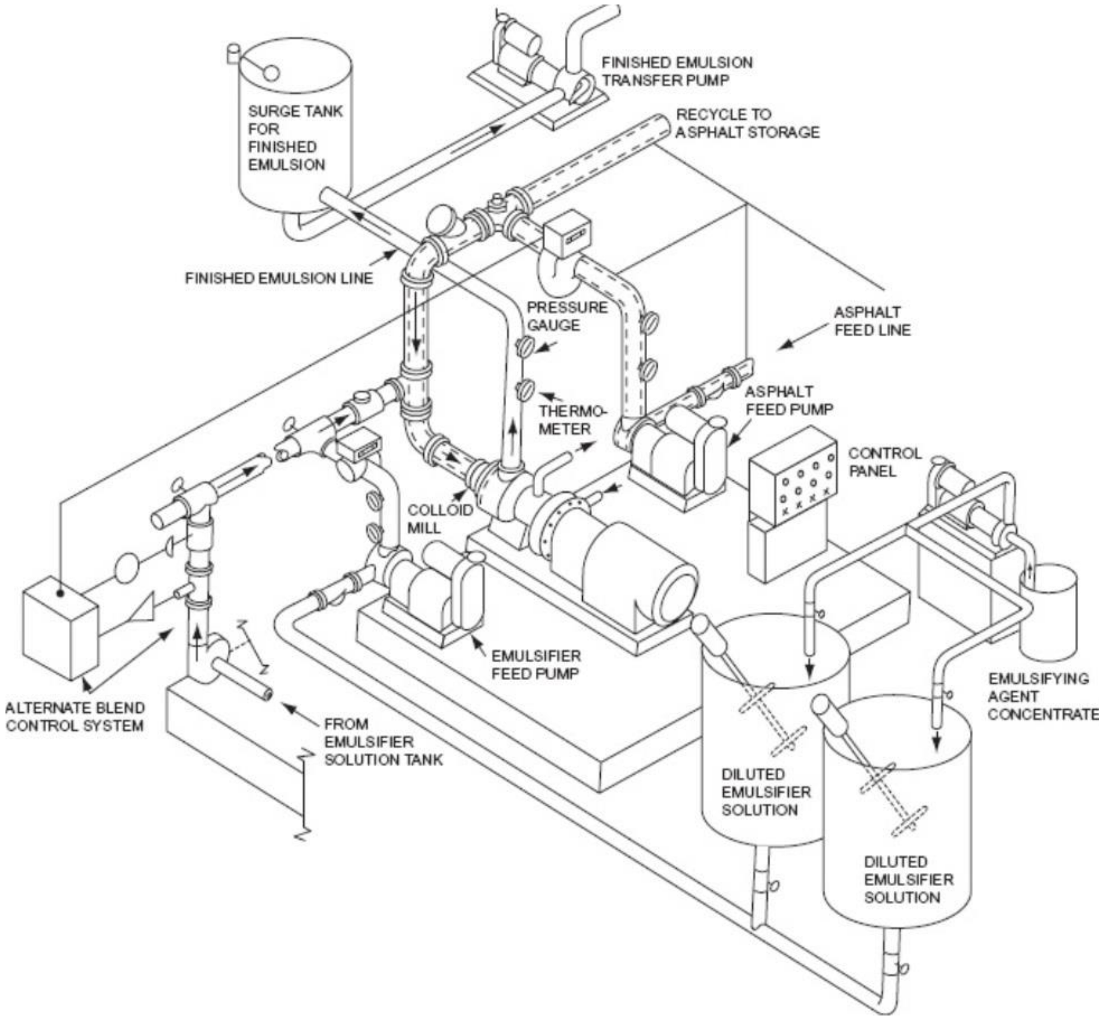


Figure 2.4: Diagram of bitumen emulsion manufacturing plant (Asphalt Institute, 2008)

The colloid mill has a high-speed rotor that rotates at 1,000 cycles to 6,000 cycles per minute. Generally, bitumen emulsion has very small droplet sizes about 0.001 millimetres to 0.010 millimetres and these droplet sizes are effected by the mechanical energy intensity that is provided by the mill. Separate pumps are used to supply the bitumen and emulsifier solution into the colloid mill.

The bitumen and water are heated individually to the desired temperature prior to the emulsification process. The bitumen and water containing the emulsifier are pumped into the colloid mill where it is separated into very small droplets. If the emulsion temperature, where it leaves the mill, is higher than the boiling point of water, a heat exchanger must be used to cool the emulsion. Then, the produced emulsion is usually fed into bulk storage containers. The solution of the bitumen and emulsifier must be proportioned accurately and this is usually carried out with flow meters. Proportioning can be controlled by monitoring the temperatures of the bitumen and emulsifier solution entering the mill, and the discharge temperature. Bitumen particle size is an essential parameter in producing a stable emulsion. A microscopic image of a typical emulsion as shown in the Figure 2.5 exposes these average particle sizes:

- 20% are less than 0.001 millimetres.
- 57% are 0.001–0.005 millimetres.
- 23% are 0.005–0.010 millimetres.

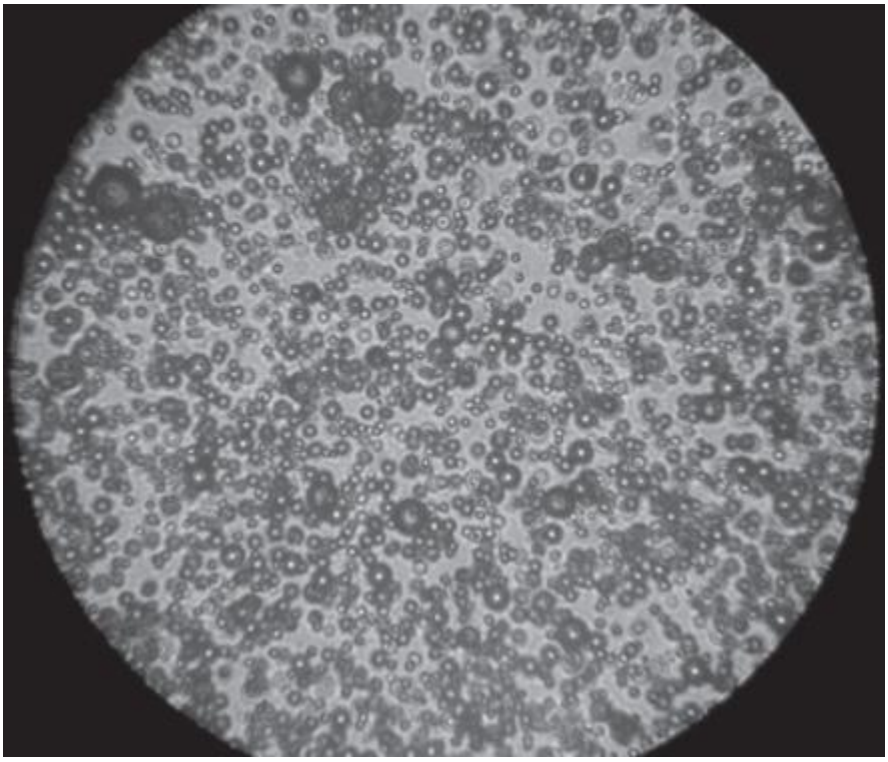


Figure 2.5: Bitumen particles size and distribution in the emulsion (Asphalt Institute, 2008)

2.4.1.4 Emulsion Breaking and Curing

If the bitumen emulsion is used as a binder to the aggregates in road works and to ensure the emulsion performs its ultimate function, the water must separate from the bitumen emulsion and evaporate. This separation is called “breaking”. According to the bitumen emulsion uses, they are formulated to break by one of the two breaking mechanisms: chemical and evaporative. The evaporation mechanism is mainly performed for the slow-setting emulsion grades, whilst the chemical mechanism is used for breaking the medium-setting and rapid-setting grades. The breaking time of the rapid-setting emulsion is considerably shorter than the time needed for medium and slow-setting emulsions. The emulsifiers’ type and concentration play a vital role in breaking the emulsion, and other factors (explained below) can also control the rate of breaking. In order to meet the specific requirements of using bitumen emulsions in pavement engineering and to obtain optimum results, it is essential to control all of these factors.

Curing includes the development of the mechanical properties of the bitumen. To do this, the water must completely evaporate or be absorbed and the bitumen emulsion particles should join and bond to the intended surface. Petroleum solvents can be used in some bitumen emulsions to help in the mixing and coating process, and however, the time of the curing process will be affected by the type and quantity of the solvents used.

Breaking and curing time of bitumen emulsions are affected by several factors that include:

- Water absorption: A rough-textured and porous mix reduces the setting time by absorbing water from the emulsion.

- Aggregate moisture content: In spite of the fact that the wet aggregate may help in the coating process, it tends to increase the curing time needed for evaporation.
- Environmental conditions: Water evaporation rate is affected by temperature, humidity, and wind velocity.
- Mechanical pressure: slow moving pressure from the compactors during the compaction stage forces the water to leave the mix and helps in cohesion, curing and stability.
- Surface area: Increasing of the aggregate surface area (when more fine aggregate used) can shorten the breaking time of the bitumen emulsion.

2.4.1.5 Selecting the Proper Emulsion Type and Grade

Perfect bitumen emulsion performance requires selecting the proper type and grade for the intended use. There are several applications of bitumen emulsion such as a plant mix (central or mixed-in-place), recycled mix, prime coat, fog seal, slurry seal, micro surfacing or chip seal. After selection, other project variables must then be taken. Environmental conditions expected during construction and geographical location are significant considerations. Additionally, aggregate type, gradation and availability are other factors that affect the emulsion selection.

Each grade of bitumen emulsion is designed for specific uses. Table 2.3 shows the typical uses of bitumen emulsion types and grades with various breaking rates.

2.4.2 Design Procedure

Asphalt mixes are composite materials that mainly consist of, asphalt as a binder, aggregate and voids. They have generally been used as a material for constructing flexible road pavements because of the good adhesion that exists between binder and aggregates (Wu, Ye and Li, 2008). However, due to increasing traffic volume in terms of traffic load repetitions, high and low temperatures and water sensitivity, various types of distresses can appear on the surface of flexible pavements, such as rutting (permanent deformation), segregation and cracking. The perfect flexible pavement design should be durable, strong and resistant to permanent deformation and cracking, thus resisting these types of failures, or at least delaying future pavement deterioration. Although bituminous mixtures with additives such as polymers, crumb rubber and natural rubber have previously been used as an attempt to overcome deterioration, permanent deformation and fatigue cracking problems still exist. These problems occur because the tensile and shear strength of bituminous layers are weak (Mahrez and Rehan, 2010).

Table 2.3: Bitumen emulsion uses with different braking rates (Dulaimi, 2017)

Application	Breaking or setting rate		
	Rapid	Medium	Slow
Plant mixes			
Open graded		√	
Dense graded			√
RAP mixes		√	√
Stockpile mix		√	
Pre-coated chips		√	√
Mix paving			
Open graded		√	
Slurry seal			√
Slurry for Cape seal			√
Microsurfacing			√
In-place mixes			
RAP mixes		√	√
Dense graded			√
Soil stabilisation			√
Spray applications			
Chip seal	√		
Fog seal	√	√	
Tack coat		√	√
Prime coat			√
Dust palliative			√
Penetration macadam	√		

A mix design procedure is required for CBEM. It is necessary that trial mixtures be manufactured in the lab to find the grade and percentage of emulsion and mixture properties of workability, water sensitivity, stability, and strength. Different design procedures are suggested for CBEM by road pavement authorities and research organizations because there is no universally accepted design method. Most of these procedures are modifications of the American design procedures (Asphalt Institute or AASHTO). The following sections summarise four main design methods for CBEM, namely: Asphalt Institute design procedures, the design procedure of the Ministry of Public Work, Republic of Indonesia, Nikolaides' design procedure and the Nynas test procedures. These procedures may be used as guides for developing mix design method templates reflecting local materials and conditions.

2.4.2.1 Asphalt Institute Design Procedures

Asphalt Institute Manual Series No.14, MS-14 (Asphalt Institute, 1989) standardises two design methods for emulsified bitumen aggregate cold mixtures. One procedure is for the design of mixes using a modified Haveem Method and the other one is using the Marshall Method. These procedures may be used as guides for developing mix design method templates reflecting local materials and conditions. The Marshall Method for emulsified bitumen aggregate cold mixture design was established through research conducted at Illinois University. This design method is defined in the manual series MS-14 and adopted by the current study. The design procedure includes:

- Aggregate selection: Aggregates meeting the requirements of British Standard are among those suitable for bitumen emulsion mixtures. For the gradations containing coarse and fine aggregates, aeration or drying prior to mixing and compaction may be required.

- Bitumen emulsion: Different types of bitumen emulsions are used for producing bitumen emulsion mixtures. Obtaining a design starting point for the trial emulsion and residual bitumen contents is based on empirical formulas. The formulas are based on the percentage of aggregate passing sieve No. 4 (4.75 millimetres) and in most cases give a satisfactory starting point.
- Coating and adhesion testing: The initial assessment of each bitumen emulsion selected for mixture design is carried out through coating and adhesion tests. The pre-wetting water is combined with the trial emulsion determined above. Carrying out the coating test is to evaluate the ability of the bitumen emulsion to coat the aggregate particles and decide the optimum pre-wetting water content. The coating is visually estimated as satisfactory or unsatisfactory for the intended use of the pre-wetting water in the mix.
- Optimum total liquid amount at compaction: Optimum total liquid amount at compaction can be determined from the compacted specimens based on the maximum dry density of CBEMs.
- Optimum residual bitumen content: Determine optimum residual bitumen content for the selected grading.

The Asphalt Institute in association with the Asphalt Emulsion Manufacturers Association (AEMA) in 1997 published a new version (manual) on asphalt emulsion. This manual is the Basic Asphalt Emulsion Manual (MS-19), 3rd edition (Asphalt Institute, 2008). It is considerably based on the MS-14 with some modifications. Firstly, the bitumen emulsion can only be used if the degree of coating of aggregate particles after a specific adhesion test remains within an acceptable range. Secondly, there are no requirements for the optimum total liquid content at compaction in comparison to MS-14, but mixtures should be air dried until neither too wet nor too dry for compaction. In addition, the compacted specimens are conditioned by keeping them in their compaction moulds in the oven at 60 °C for 48 hours, and then additional compaction with 178 KN static load for one minute is applied at the same temperature using a double plunger at each side of the specimen.

2.4.2.2 Ministry of Public Works of Indonesia Design Procedure

Thanaya (2003) described the design procedure that is adopted by the Ministry of Public Works in Indonesia 1990. It covers two main types of mixtures; open and dense graded emulsion mixtures. This design procedure is mainly based on AASHTO and similar to the Marshall design procedure explained in the Asphalt Institute (MS-14) with some modifications that take regional and national conditions in Indonesia into account. A modified Marshall Stability test procedure is used in which the specimens are tested at ambient temperature. Therefore, pre-conditioning the specimens in water at 60 °C for 30 minutes is not recommended for this test.

2.4.2.3 Nikolaides Design Procedure

In 1990, Nikolaides developed a hybrid design procedure by combining both the American Standard and the Ministry of Public Works Republic of Indonesia procedures. In this procedure, permanent deformation performance is characterised by controlling the maximum allowable bitumen content. Based on the permanent deformation performance, maximum permissible value of residual bitumen content is considered. Consequently, a relationship between the residual bitumen content and the creep stiffness coefficient is required to indicate this value (maximum residual bitumen content). Nikolaides (1994) specified that the creep stiffness coefficient is determined from the static creep test which is performed by one hour static applied load (0.1 MPa) at 40 °C. The mixture stiffness for a specific test of any bitumen content can be determined at any time of loading.

2.4.2.4 Nynas Test Procedures

The Nynas Company designed three tests that are only used on loose mixtures during storage or before laying and these tests are known as run-off, wash-off and workability tests. In the run-off test, 500 g of loose bitumen emulsion mixture is placed into a funnel with a mesh size (< 2 mm) at the bottom. The run-off value refers to the quantity of bitumen that runs off in 30 minutes. This is followed by the wash-off test which is conducted instantly after the runoff test while the mixture is still in the funnel. Water (200 ml) is poured over the mixture and both the wash water and any wash-off bitumen is collected and measured. Lastly, the workability test is performed using a Nynas workability tester. In this test, scraping a small part of the top of a loose CBEM during storage or just before placing is applied to measure the maximum force required to shear off this part.

2.4.3 Processing Stages

There are three different process stages to prepare CBEMs where the bitumen emulsion is expected to perform different functions (Taylor, 1997), namely:

- First stage: During mixing the emulsion with the aggregates, the emulsion must keep stable and coat the coarse and fine aggregate particles uniformly.
- Second stage: During storage and laying of the CBEMs, the emulsion must keep workable and be partially set or broken to resist moisture and rain. The CBEMs must also be undrained (the emulsion should not drain off due to its low viscosity) after mixing with the aggregates.

- Third stage: During the compaction process, the emulsion must break quickly and return to its original base bitumen. Most emulsions require relatively long time of curing to allow evaporation of the volatiles that lead to a full breaking thus achieving maximum strength.

2.4.4 Curing of CBEM

Curing is one of the most important requirements for CBEM (Thom, 2008). It has been stated that the performance of CBEM is directly related to the properties of the materials that are used in the mixture and to the curing condition (Needham, 1996; Jenkins, 2000; Thanaya, 2003; Oruc, Celik and Akpinar, 2007; Niazi and Jalili, 2009; Bocci et al, 2011). Curing of CBEM is defined as the process whereby the compacted mixtures discharge water through evaporation, particle charge repulsion or pore-pressure induced flow paths (Jenkins, 2000). The reduction in the mixture's water content helps in developing the strength of the CBEMs. Roberts, Engelbrecht and Kennedy (1984) reported that the tensile strength of cold mix increased significantly when curing temperature was increased from 23 °C to 60 °C. Bocci, Virgili and Colgrande (2002) found a substantial development in the performance of cold mixtures as curing time and curing temperature increase, curing for 14 days at 20 °C is practically equivalent to 7 days at 40 °C. Full curing could occur between two months and two years in the field (Santucci, 1977; Leech, 1994; Thanaya, 2007). Bocci et al (2011) displayed that the CBEM requires a certain time of curing to develop the required mechanical properties such as strength and stiffness as can be seen in Figure 2.6.

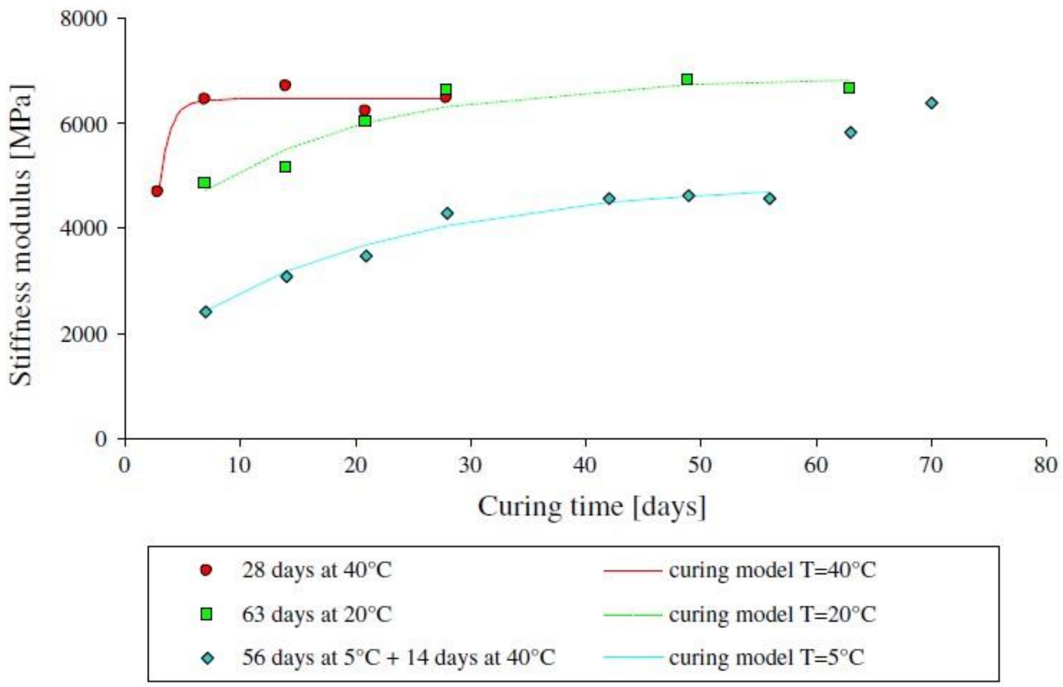


Figure 2.6: Effects of curing time and temperature on the ITSM of bitumen emulsion mixtures (Bocci et al, 2011)

Jenkins (2000) accordingly revealed that the curing temperature is a major factor to mixture preparation as temperature and moisture are dependent variables with temperature affecting the rate of moisture loss. Moisture can impede emulsion distribution, workability and compaction of the mixture and also moisture increases the time of curing and decreases the strength and density of the compacted mixtures. Serfass et al (2004) showed that assessing cured cold mixtures in the lab is evidently necessary, however replicating exact field curing conditions is complicated and, above all, time consuming, and thus an accelerated curing process is necessary. Therefore, the curing procedure should be as short as possible and the bitumen ageing should be avoided.

Serfass et al (2004) found that the moisture content of small samples evaporates quickly at any temperature, whilst for large samples it takes longer. In addition to the curing time, at high temperatures (for example 60 °C), the drying of samples is too quick, which can cause cracking of large samples. In the field, the cold mixtures have been considered rarely to be completely dry, the moisture content of such mixtures in the field has often been found to be between 0.5% to 1.5% in the roads in temperate climates. Accordingly, in order to obtain cold mixtures without deterioration to the samples, it has been proposed that such samples should be cured for 14 days at 35 °C to 40 °C. This procedure does not damage the samples (Lanre, 2010). 35 °C to 40 °C was selected because it is realistic and less than the bitumen softening point.

Kim, Im and Lee (2011) presented that there is a direct relation between the moisture loss and strength gain and this is clear at higher temperatures over the curing time. This is true for CBEMs that have inert filler such as limestone filler, as increasing the curing temperature leads to easing the water evaporation. In the case of active filler such as cementitious material, further to that, a special benefit is gained because cement hydration reactions require the existence of water; the use of cementitious material accelerates the emulsion curing process by reducing the amount of free water (Needham, 1996; García et al, 2013; Al-Hdabi, 2014; Dulaimi, 2017).

2.4.5 Enhancement

Hot mix asphalt (HMA) is the main source of flexible pavements used in 95% of the world's paved roads (Arabani and Kamboozia, 2013). However, this mixture is considered environmentally unfriendly because it needs substantial amounts of energy to heat the aggregate and asphalt producing CO_2 emissions during both production and laying (Al-Hdabi, Al Nageim and Seton, 2014b; Yuliestyan et al, 2017). Nowadays, several flexible pavement design technologies have been invented to eliminate, or reduce, emissions and save energy regarding asphalt paving production (Jamshidi et al, 2016). CBEM is one of these technologies. CBEM is defined as a bituminous mixture of aggregates and asphalt emulsion, mixed at ambient temperature which does not require the same amount of energy to produce the same CO_2 emissions as HMA (Dulaimi et al, 2016). In addition, CBEM can offer the following advantages:

- CBEM is not dependent upon warm weather.
- It can be mixed on site or off site.
- Eco-friendly option during all production processes made from water-based materials at ambient temperatures, which reduces emissions, energy consumption and toxic fumes.
- Cost-effective solution for paving or repairing rural roads that are nowhere near a hot mix plant, as minimal material and transportation costs required where CBEM used in remote areas.

However, CBEM has been considered an inferior mix compared to HMA, mainly in terms of its mechanical properties, the extended curing period required to achieve an optimal performance and its weak early life strength (Dulaimi et al, 2017a). Poor asphalt mix quality and inadequate design may result in an inefficiently designed layer. Different studies have been conducted to understand the behaviour of CBEMs and to enhance their performance. Several aspects to improve the performance of such mixture have been performed such as incorporating various types of materials and applying different preparation techniques. Ibrahim and Thom (1997) focused on the influence of curing procedures and compaction types, and concluded that the increasing of curing time develops the indirect tensile stiffness modulus. CBEM is generally identified to have low early strength, long curing times and high air voids (Thanaya, Forth and Zoorob, 2009). Therefore, such mixture tends to be comparatively low quality to the hot mixture. Accordingly, the use of CBEM is restricted to reinstatement road works and to pavement layers on low volume traffic. Previous researchers, to enhance the poor performance of CBEM, have performed different methods and techniques.

2.4.5.1 Compaction Enhancement

The mechanical properties of CBEMs are mainly affected by compaction, as suitable compaction is required for optimum performance. Increasing of compaction efforts leads to improving the degree of emulsion combination when using granite aggregate with 20 mm aggregate maximum size (Brown and Needham, 2000). Thanaya (2003) reported that the air voids of CBEMs could be within the specification limits by adopting heavy compaction (120 revolution, 240 kPa, 2° angle of gyration) rather than medium compaction (80 revolution, 240 kPa, 2° angle of gyration). The aimed air voids content of the compacted CBEMs (between 5% to 10%) could be obtained by applying 240 gyrations, which are categorised as extra heavy compaction (Thanaya, 2003). Additionally, a heavy compaction application is crucial to achieve breaking of the emulsion and ensure that mixtures strengthen properly (Thanaya, 2007). The excessive amount of liquids in CBEMs reduces the compaction effect and prevents mixtures from obtaining their acceptable air voids leading to decreased stiffness and strength properties. Serfass et al (2004) described a relationship between compaction efforts and stiffness modulus of CBEMs as shown in Figure 2.7.

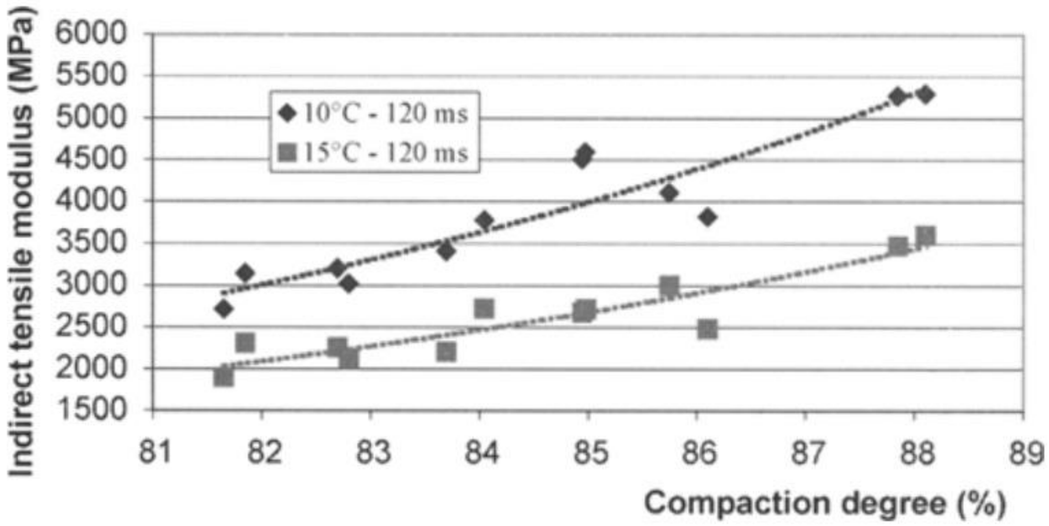


Figure 2.7: Effect of compaction on the indirect tensile stiffness (Serfass et al, 2004)

2.4.5.2 Polymers Enhancement

Khalid and Eta (1997) carried out a laboratory investigation to study the impact of polymers modified emulsions on the mechanical properties of emulsified bitumen macadam. Close graded surface course and dense graded binder course were used as aggregate grading with a cationic emulsion containing 65% base bitumen of 100-penetration grade. It was concluded that Ethylene Vinyl Acetate (EVA) and Styrene-Butadiene-Styrene (SBS) polymers have positive effects on modification of the bitumen emulsion in terms of enhancing the stiffness and permanent deformation of CBEMs. In addition, fatigue resistance of 4% SBS and 6% EVA modified CBEMs were developed about 45 and 35 times, respectively, in comparison with the fatigue resistance of unmodified CBEMs. In further research, polyvinyl acetate was added to a rapid-setting emulsified bitumen to improve the compressive strength of CBEM (Chávez-Valencia et al, 2007). Two different mixing methods were applied to prepare the CBEMs: the aggregates were coated in the first method by a film of bitumen-polyvinyl acetate binder, and in the second method, the aggregate was mixed with a diluted polyvinyl acetate-emulsion to cover it with the polymer. As a result of the improvement in void content, it was determined that the second method achieved 31% improvement in compressive strength. Recently, Xu et al (2015) used a specially developed polymer modified emulsifier in AC-13 asphalt mixture. It was concluded that in terms of moisture susceptibility, high temperature and resistance to low-temperature crack, the mixture met performance specification requirements in addition to an improvement in rutting resistance performance.

2.4.5.3 Cement Enhancement

Additives can play a main role in governing the engineering properties of bituminous mixtures in terms of stiffness, permanent deformation resistance, fracture resistance and moisture sensitivity. Some of these additives are used as a filler replacement in the mix such as cement and lime. Cement can be technically defined as a material that if mixed with other non-cohesive particles gives a hard mass. It is a fine powder such as Portland, slag, pozzolanic and high alumina which generates very strong and durable binding materials because of the hydration processes (O’Flaherty, 2007). The use of cement in bituminous mixtures is not a new idea. Terrel and Wang (1971) carried out one of the first studies that used cement in emulsion-treated mixtures. It was concluded from this study that using cement as an activator in the bitumen emulsion mixtures can accelerate the rate of development of the resilient modulus due to the accelerated rate of curing of such mixtures. This means that Ca^{2+} ions from cement neutralise the anionic emulsifier allowing emulsion droplets to coalesce and adhere to the aggregates. This helps in breaking the emulsion quickly and absorbing water from the mixture thus decreasing curing times (Schmidt, Santucci and Coyne, 1973). Head (1974) found that adding 1% OPC (Ordinary Portland Cement) as a modifier to the cold asphalt mixtures increases the Marshall Stability by 300% compared with untreated mixtures. Dardak (1993) stated that the OPC modified emulsion mixtures decreases the layer thickness about 50% as a result of stability improvements (200% to 300%). Li et al (1998) reported that the cement-asphalt emulsion composite has a longer fatigue life, less temperature susceptibility and higher toughness. Brown and Needham (2000) evaluated the effects of incorporating OPC into the bitumen emulsion mixtures. Accordingly, stiffness modulus (Figure 2.8), resistance to permanent deformation and fatigue strength were enhanced due to the increased pH which helps the emulsion to break.

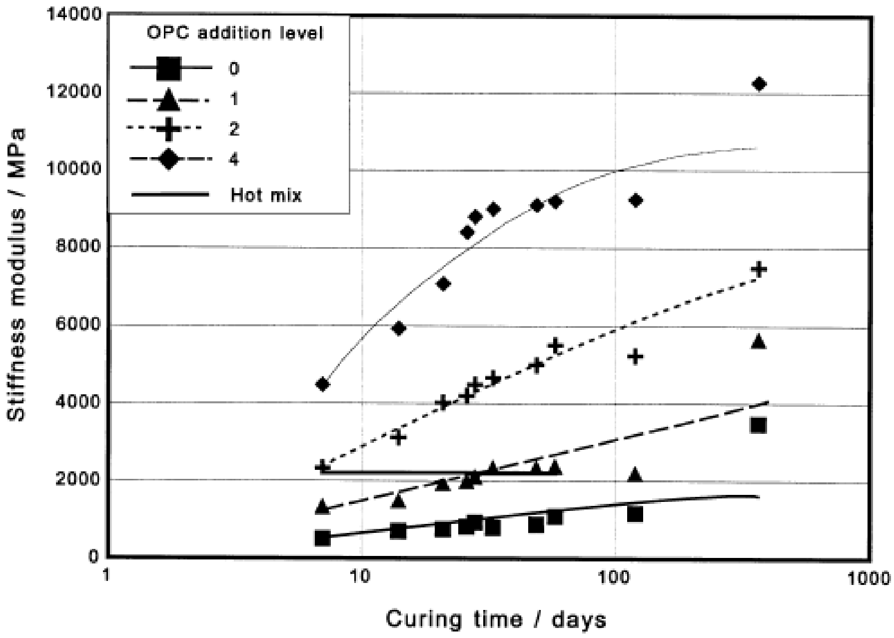


Figure 2.8: Effect of the OPC on stiffness modulus of bitumen emulsion mixtures (Brown and Needham, 2000)

Cement type affects the rate of increase in strength of CBEMs (Thanaya, 2003). Thanaya testified that Rapid Setting Cement (RSC) gives a better rate of increase in strength in comparison to the OPC. The stiffness of the modified CBEMs with RSC was about 2000 MPa to 2500 MPa after a few weeks of curing, whilst the unmodified mixtures needed 16 weeks to achieve same stiffness values. This is because the RSC behaves as an active filler in CBEMs causing an increase in the pH.

Oruc, Celik and Aksoy (2006) and Oruc, Celik and Akpinar (2007) carried out laboratory studies to evaluate the addition of 0% to 6% OPC as a filler replacement to the emulsified asphalt. The results showed significant developments in the mechanical properties of these modified mixtures with higher percentage of OPC as presented in Figure 2.9.

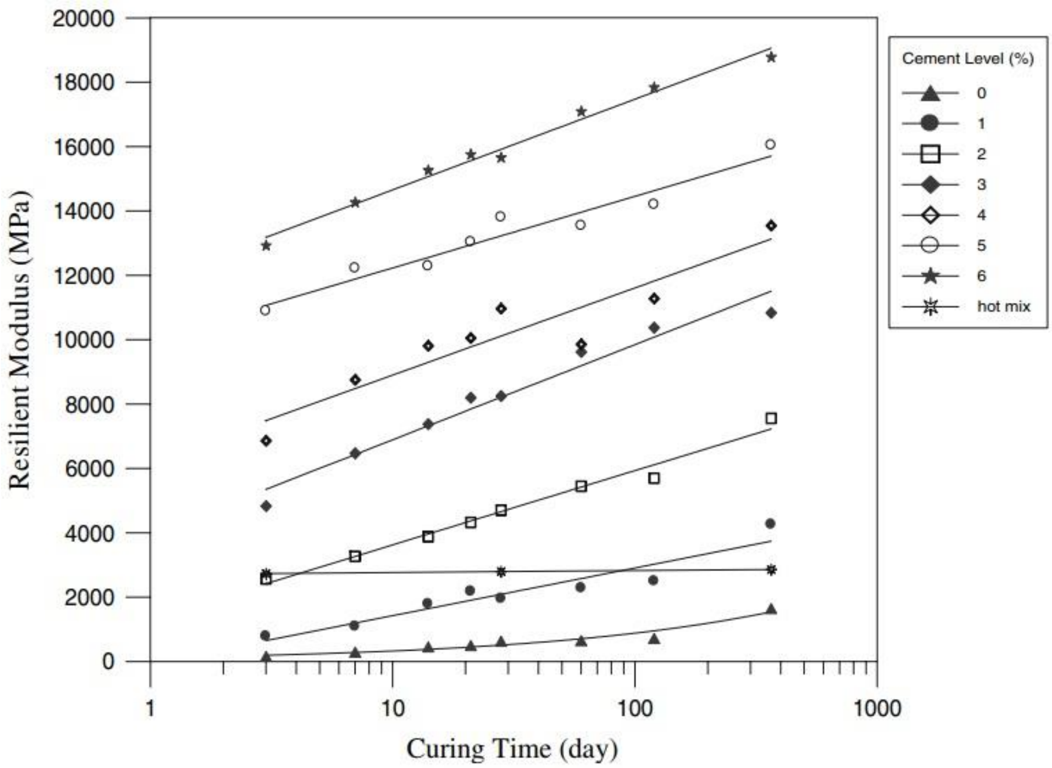


Figure 2.9: Effect of cement on resilient modulus of the emulsified asphalt mixtures (Oruc, Celik and Akpinar, 2007)

Wang and Sha (2010) found that the cement in the cement asphalt emulsion mixtures can improve the micro hardness of the interface. García et al (2013) investigated various cement percentages on the mechanical properties of CBEMs that were cured at different environmental humidity levels (35%, 70% and 90%) RH. However, samples cured at 90% relative humidity hardened slower than samples cured at low relative humidity. Also, it was proved that incorporation of cement into bituminous mixtures results in changes in the pH of the emulsion leading to breaking it quickly, as shown in Figure 2.10.

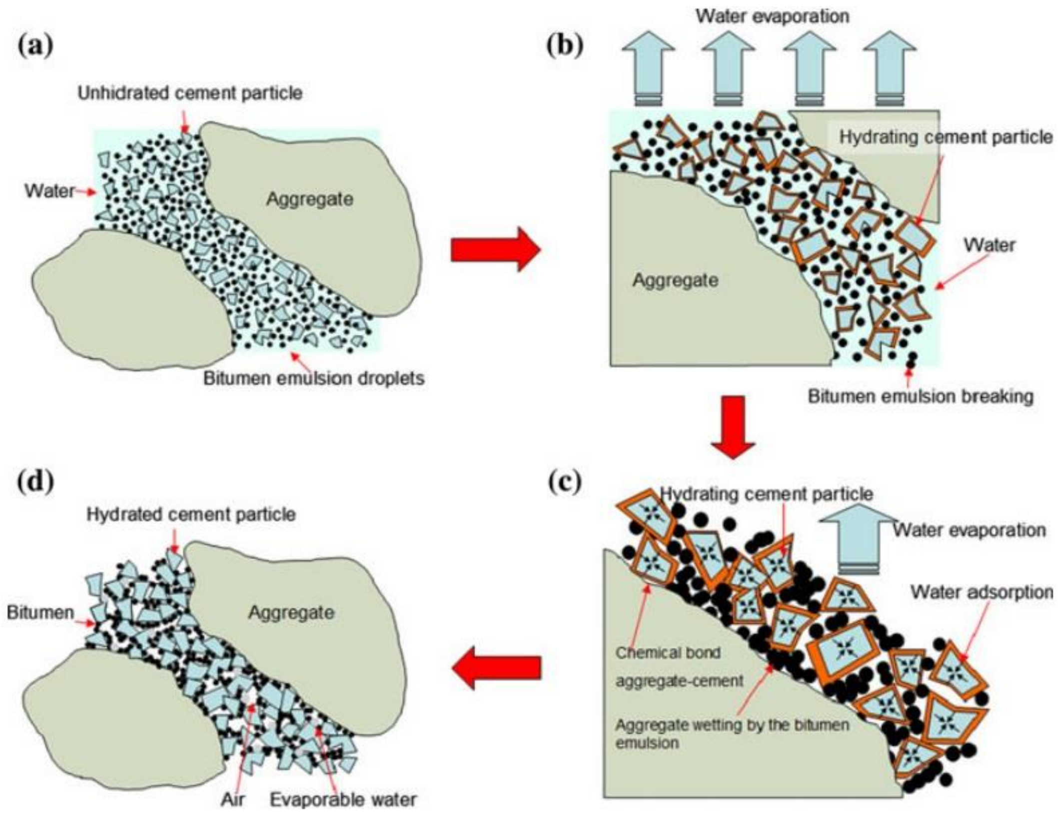


Figure 2.10: Graphical representation of the hardening process of an asphalt-emulsion composite (García et al, 2013)

Al-Hdabi, Al Nageim and Seton (2014a) studied the effect of replacing all the conventional mineral filler with OPC in order to develop a new cement treated CBEM made with gap grading. The results indicated that gap-graded, cold rolled asphalt mixtures gained significant enhancements in mechanical properties, resistance to water damage and temperature susceptibility. Fang et al (2016) investigated the use of rapid hardening cement to accelerate the mechanical properties development of cement bitumen emulsion and obtain better understanding of the role of cement in such mixtures. After one day curing of mixtures with calcium sulphoaluminate and calcium aluminate cements, the mechanical properties were comparable to those mixed by using Portland cement after one week of curing.

It can be summarised that cement has been widely used in developing of CBEMs. However, cement production is a very energy intensive process leading to environmental harm (Schneider et al, 2011). Manufacturing of 1 tonne of OPC includes the consumption of 1.5 tonnes of quarry material, 5.6 GJ of energy and 0.9 tonnes of CO_2 emission. According to O'Rourke, McNally and Richardson (2009), 5% of total global carbon dioxide CO_2 emission is generated by the cement industry. Ravikumar, Peethamparan and Neithalath (2010) stated that the recent awareness about the ecological effects of using cement in construction encourages researchers and industrial companies to use waste and by-product materials as a replacement or partial replacement for cement.

2.4.5.4 Waste and By-products Materials Enhancement

Using of waste and by-product materials in the pavement industry, specifically in the production of CBEMs, is one way to enhance the mechanical properties and durability, gaining economic and ecological benefits. The economic benefits are represented by the low or zero cost of production, and the ecological benefits are represented by eliminating the need for expensive disposal as these materials contain toxic ingredients that can be hazardous to the human health when disposed in lakes, streams or landfills. These materials have cementitious and pozzolanic properties depending on their reactions. The materials that generate cementitious compounds when they react with water are called cementitious materials. The materials that do not have any cementitious properties but when used with cement or any other cementitious materials react to form cementitious compounds are called pozzolanic.

Previous studies have established that the use of cementitious materials in CBEMs has positive effects in terms of the engineering properties. Unfortunately, these materials have two main drawbacks; their environmental impact and cost. Therefore, the use of waste and industrial by-products materials in CBEM construction is reasonable for technical, economic and ecological reasons as explained earlier. Thanaya (2003) conducted a study of using various waste materials in CBEMs to improve the mechanical properties of such mixtures. Results indicated that red porphyrin sand, synthetic aggregates made from sintering quarry fines and crushed glass, can be used in CBEMs and still allow acceptable stiffness values, whilst using steel slag was risky as it leads to an expansion in volume in wet conditions and crumb rubber results in cracks at early stages of compaction. Thanaya, Zoorob and Forth (2006) revealed that the stiffness of the modified CBEMs by pulverised fly ash as a filler is comparable to hot mixtures at full curing condition thus confirming it is suitable to use. Ground Granulated Blastfurnace Slag (GGBS) was used with bitumen emulsion in CBEMs that consisted of recycled aggregates. The stiffness and strength were developed when GGBS is added in high humidity conditions.

Recently, Al Nageim et al (2012) carried out a laboratory study on using waste materials and industrial by-products in CBEM that had developed mechanical properties compared to traditional HMA. Waste domestic fly ash, namely LJMU-FA1, replaced the conventional mineral filler and caused another binder into the mixture generated from the process of hydration between LJMU-FA1 and the trapped water. Al-Hdabi et al (2014) used a Waste Fly Ash (WFA) as a filler replacement in cold-rolled asphalt (CRA) to enhance the mechanical properties and water sensitivity of such a mixture. A silica fume, as a by-product material, was also used as an additive to enhance the engineering properties and durability of CRA. The results confirmed that in addition to the moisture damage resistance enhancement there was a significant improvement in stiffness modulus and uniaxial creep tests. Nassar et al (2016) utilised binary and ternary blended fillers (BBF and TBF) to observe the mechanical properties enhancement of CBEMs. For the BBF, fly ash and GGBS were used whilst the silica fume (SF) was added to the BBF to obtain TBF. Based on the enhanced mechanical and durability properties of CBEMs, the TBF was more suitable than BBF for CBEMs production. Furthermore, it is suggested that the addition of SF to BBF mixtures can increase the formation of hydration products caused by the bitumen emulsion. Dulaimi et al (2016) developed a new cold asphalt concrete mixture for a binder course by incorporating a new binary blended filler material produced from high calcium fly ash and a fluid catalytic cracking catalyst (FC3R) instead of the traditional limestone filler. It was proved that using such materials shows a significant development in permanent deformation and fatigue resistance of CBEMs.

More recently, Dulaimi et al (2017a) used a waste alkaline NaOH solution as an activator to the binary blended filler to produce an alkali activated binary blended cementitious filler (ABBCF) to develop a new fast curing and environmentally friendly CBEM for the binder course. It was observed that a considerable enhancement was achieved in terms of mechanical properties and water susceptibility.

2.4.5.5 Fibres Enhancement

Some strengthening techniques have been trialled in flexible pavements. In bituminous mixtures manufacturing, strength and bonding can be enhanced by the addition of fibres (Wu et al, 2006; Ye, Wu and Li, 2009). The reinforcement of asphalt pavements is one method to improve the performance when pavements do not meet traffic, climate and pavement structural requirements. Fibre reinforcement improves the life of a pavement by increasing resistance to permanent deformation and cracking (Abiola et al, 2014). The addition of fibres to hot and cold mixtures as a reinforcing material, enhances the strength, bonding and durability of such mixes (Ferrotti, Pasquini and Canestrari, 2014). These fibres have desirable properties and are used to reinforce other materials which also require such properties (Xiong et al, 2015; Yang, Kim and Yoo, 2016; Fakhri and Hosseini, 2017; Fu et al, 2017; Jaskuła, Stienss and Szydłowski, 2017). There is a better chance of improving the tensile strength and cohesion of bituminous mixtures by using fibres which have high tensile strength, as compared to bituminous mixtures alone (Xue and Qian, 2016). The essential roles of these fibres as reinforcing materials are to increase the tensile strength of the resulting mixtures and provide more strain resistance to fatigue cracking and permanent deformation (Abtahi, Sheikhzadeh and Hejazi, 2010). Draining-down of asphalt concrete mixtures is prevented by using fibres, rather than polymers, during the paving and transportation of materials, therefore, fibres are specifically recommended (Chen et al, 2009; Park et al, 2015). In addition, fibres improve the viscosity of bituminous mixtures (Fakhri and Hosseini, 2017), resistance to rutting (Fazaeli et al, 2016; Mirabdolazimi and Shafabakhsh, 2017; Tanzadeh and Shahrezagamasaei, 2017), stiffness modulus (Tabaković et al, 2017), moisture susceptibility (Fakhri and Hosseini, 2017) and retard reflection cracking for pavements (Doh, Baek and Kim, 2009; Fallah and Khodaii, 2015). The modification of bituminous mixtures with additives has also been found to decrease permanent deformation and increase durability (Vaitkus et al, 2009; Moghaddam, Karim and Abdelaziz, 2011; Zhang and Leng, 2017; Zaumanis, Poulikakos and Partl, 2018).

Currently, natural and synthetic fibres are used as reinforcing materials in bituminous mixtures because of their high stiffness and strength properties, and are considered the most appropriate reinforcing materials (Abiola et al, 2014). A variety of experimental research has been conducted to evaluate the effect of natural and synthetic fibres on the mechanical behaviour of bituminous mixtures in terms of hot mix asphalt. The results of these studies indicate that these fibres have a positive impact on the performance of bituminous mixtures (Chen et al, 2009; Saeid, Saeed and Mahdi, 2014; Yang, Kim and Yoo, 2016; Guoming, Weimin and Lianjun, 2017). The performance of reinforced mixtures is mainly affected by fibre length, content, type, diameter and surface texture (Chen et al, 2009; Abtahi, Sheikhzadeh and Hejazi, 2010; Saeid, Saeed and Mahdi, 2014; Guoming, Weimin and Lianjun, 2017). Bueno et al (2003) investigated the use of fibre to enhance the mechanical properties of cold emulsion, densely graded, emulsified bituminous mixtures. Three different polypropylene fibre lengths (10 mm, 20 mm and 40 mm) were mixed with three different percentages (0.10%, 0.25% and 0.50%) by aggregate weight to reinforce the bituminous mixtures. Ferrotti, Pasquini and Canestrari (2014) conducted a laboratory investigation on reinforcing CBEM by three types of fibres (cellulose, glass-cellulose and nylon-polyester-cellulose) with two different contents (0.15% and 0.30%). The reinforced mixtures were tested at different curing times (1 day, 7 days, 14 days and 28 days) and conditions (dry and wet). The results indicated that the mixture with 0.15% cellulose fibre showed a comparable or even better performance than the conventional mixture.

2.5 Behaviour of the Bituminous Mixtures

The current pavement design procedures are mainly based on the measured mechanical properties, which results in a very important issue in that they provide little understanding of the inherent mechanical nature of the material, which can thus hardly reflect the in-situ performance deterioration of the flexible pavement structures when subjected to continuous traffic and environmental loading. Asphalt or bitumen are widely used in flexible pavements as aggregate binders because of their high adhesion properties. Bituminous mixtures' behaviour is strongly dependent on the bitumen even though the mixture contains less than 10% by volume of bitumen (Ossa, Deshpande and Cebon, 2005). Understanding the mechanical behaviour of bituminous mixtures depends on an understanding of the behaviour of the bitumen. Flexible pavements are generally subject to cyclic and sometimes excessive loads during their service life (Bai, Yang and Zeng, 2016; Xiao et al, 2018). Their surface is also temperature sensitive in terms of high temperature permanent deformation and low temperature cracking (Al-Hadidy and Yi-qiu, 2009; Ye, Wu and Li, 2009). In countries where high temperatures are the norm, permanent deformation is the major distress encountered in flexible pavements and considered to be one of the more complex issues in pavement structure (Arabani, Jamshidi and Sadeghnejad, 2014). Permanent deformation (rutting) development occurs frequently in flexible pavements due to the non-linear, viscous and plastic behaviours of asphalt mixes (Safaei and Castorena, 2017). Permanent deformation can be defined as the irrecoverable vertical deformation of pavements under a vehicle wheel path caused by high temperatures and load repetition. Such accumulated permanent deformation has been attributed to different variables including temperature, traffic volume, wheel load and repetition, tyre pressure, material properties and bituminous layer thickness (Fang et al, 2004). Rutting can be limited to the asphalt surface layers comprising the viscoelastic and viscoplastic properties of asphalt and the plastic characteristics of aggregates (Imaninasab, Bakhshi and Shirini, 2016).

Cheung (1995) indicated that the steady-state behaviour of bitumen at a particular temperature can be represented by a power law equation after performing different uniaxial tension and shear tests for pure bitumen over a wide range of stress, strain rate, and temperature conditions. Cheung also reported that, at temperatures above the glass transition (at which bitumen changes from a glassy to a fluid condition; it usually ranges from -40 °C to 0 °C), the deformation behaviour of pure bitumen was linear viscous at low stress levels and showed power law creep at high stress levels. Khanzada (2000) found that the deformation behaviour of bituminous mixtures has the same form as pure bitumen with linear behaviour at low stress levels and nonlinear behaviour at high stress levels when uniaxial tests on HRA mortar, 30/10 HRA and 10 mm dense bitumen macadam over a range of temperatures and loading stress were performed. Taherkhani (2006) carried out more uniaxial tests on bituminous mixtures over a wide range of stress conditions and also found that the deformation behaviour of bituminous mixtures were nonlinear power law creep.

2.6 Constitutive Models of Bituminous Mixture

Flexible pavement design methods are based on linear elastic calculations, however, new pavement design techniques are required to account for undesirable environmental conditions and heavy loading, these being common sources of rutting (Chazallon et al, 2009). Flexible pavement responses to traffic loadings are mainly affected by the properties of the materials (Chen, Zhang and Wang, 2015). Elastic and viscoelastic responses are seen at low traffic volume and low temperatures, while plastic and viscoplastic responses occur at high traffic volume and high temperatures. Constitutive modelling of bituminous mixtures requires an understanding of the functional relationship between stresses and strains at different loading conditions. It is much more complex than soil and rock because of the complex behaviour of bitumen. The following parameters should be considered in the constitutive model of bituminous mixtures (Taherkhani, 2006):

- Time, temperature, loading rate, non-homogenous, inelastic, non-linear and anisotropic dependent behaviour of the mixtures.
- Dilatancy.
- Mixture characteristics under tension and compression.
- Presence of permanent deformation at the end of each loading cycle.
- The moisture, ageing and air voids content effects on the permanent deformation of bituminous mixtures.

Different techniques are available to predict rutting in bituminous mixtures such as finite difference methods (Doh, Baek and Kim, 2009), analytical methods (Fallah and Khodaii, 2015), multilayer elastic theory (Abiola et al, 2014), hybrid methods (Nik, Nejad and Zakeri, 2016) and finite element methods (Kim and Buttlar, 2009; Ambassa et al, 2013). A variety of three-dimensional (3-D), finite element simulations have been developed to analyse the responses of flexible pavements (Chazallon et al, 2009; Kim and Buttlar, 2009; Ameri et al, 2011; Hu and Walubita, 2011; Li and Li, 2012; Ghauch and Abou-Jaoude, 2013). The strain experienced by bituminous mixtures under wheel loads has recoverable components (elastic and viscoelastic) and irrecoverable components (plastic and viscoplastic) (Littel, Bhasin and Allen, 2017). Selecting an appropriate constitutive law that takes into account bituminous mixtures' creep behaviour and calibration of its parameters using creep and creep recovery testing is important to simulate permanent deformation of flexible pavements by finite element modelling (Imaninasab, Bakhshi and Shirini, 2016). Picoux, El Ayadi and Petit (2009) simulated the distribution of vertical deformation to a flexible pavement, subjected to different wheel loadings based on viscoelastic deformation theory. Allou et al (2015) developed a 3-D linear viscoelastic model to characterise the dynamic modulus and Poisson's ratio of bituminous mixtures. Dave et al (2006) developed viscoelastic models to analyse the response of asphalt overlay using thermomechanical impact under different combinations of loading time and temperature. Kai and Fang (2011) conducted a 3-D, finite element model of asphalt pavements based on the elastic half-space theory, again examining the effect of load and temperature. Xue et al (2013) developed a dynamic model to describe the settlement of the surface of asphalt pavements under different temperatures. Pérez, Medina and del Val (2016) simulated a nonlinear, elasto-plastic Mohr-Coulomb numerical model for recycled flexible pavements, to determine the response of these pavements under two different loads and four types of soil subgrade. Gu et al (2016) evaluated the effect of geogrid-reinforced flexible pavements by developing two pairs of geogrid-reinforced and unreinforced pavement models. Finite element modelling revealed that rutting resistance is better in the geogrid-reinforced pavement in comparison to the unreinforced pavement.

However, given that flexible pavements are subjected to different loading and environmental conditions which impact on their performance, it is somewhat surprising that the impact of these aspects has not been fully simulated to date (Chazallon et al, 2009). With specific reference to repeated loading, there is no technique currently available to investigate rutting on CBEM pavements and no model available to predict permanent deformation for such pavements.

It is difficult to satisfy all the requirements above. Therefore, simplified constitutive models have been developed in recent years. Some of them are listed in the following sections.

2.6.1 Elastic Model

The elastic layer theory for a two-layer pavement was developed in 1943, which was then applied for more layers (Burmister et al, 1943). In this theory, bituminous materials are generally assumed to be homogenous isotropic and linear elastic and considered constant time-independent of proportionality between stress and strain (Huang, 1967). The loading curve of the elastic material is identical to the unloading curve, and all strains are recovered upon the removal of the applied load. Based on Hooke's law, the relationship between stress and strain for elastic material is given in Equation 2.2:

$$\sigma = K\varepsilon \qquad 2.1$$

where σ and ε are the stress and the strain tensor, respectively; K is the stiffness matrix of elasticity which is expressed as a function of Young's modulus *E* and Poisson's ratio *v*.

Preston (1991) indicated that the ability of the bituminous layer to distribute load, and reduce the stress transferred to the underlying layer depends on the stiffness modulus of the bituminous layer. The elastic model is accurate enough to enable prediction of bituminous mixture behaviour at lower temperatures and short loading times (Eisenmann, Lempe and Leykauf, 1977; Ullidtz et al, 1987).

2.6.2 Viscoelastic Model

Viscoelasticity is the property of a material that performs both viscous and elastic behaviours when subjected to deformation (Huang, 2004). Viscous materials can resist shear stresses and show linear strain patterns over time when loading is applied. Elastic materials strain instantaneously on loading, returning back to their original state without permanent deformation when the load is released. Asphalt mixtures have elements of both these characteristics and present time-rate dependent behaviour. They are considered viscoelastic materials when the deformation is small (Arabani and Kamboozia, 2013). Bitumen is typically a viscous material when mixed with elastic aggregate to produce asphalt mixtures, hence viscoelasticity is expected. Viscosity can be represented by a dashpot, following the Equation 2.2:

$$\sigma(t) = \eta \frac{d\varepsilon(t)}{dt} \quad 2.2$$

where $\sigma(t)$ and $\varepsilon(t)$ are stress and strain, respectively, and η is the viscosity. Elasticity can be represented by a spring, which follows the Equations 2.3 and 2.4:

$$\sigma(t) = E\varepsilon(t) \quad 2.3$$

$$\varepsilon(t) = D\sigma(t) \quad 2.4$$

where E and D are the modulus and compliance of elasticity, respectively.

Different combinations of dashpots and springs represent a variety of viscoelastic models. For instance, the Maxwell model consists of one dashpot and one spring in series (Figure 2.11-a), while the Kelvin-Voigt model consists of one dashpot and one spring in parallel (Figure 2.11-b). After application of a single load, instantaneous and retarded elastic strains predominate and the viscous strain is negligible. However, under multiple load applications, the accumulation of viscous strain is the cause of permanent deformation (Huang, 2004). Huang suggested that a single Kelvin model is not adequate enough to cover the long period of time over which retarded strain takes place, and that a number of Kelvin models may be needed. In consequence, to describe the isotropic viscoelastic behaviour of bituminous mixtures, a generalised model has been used in this study. This model consists of one Maxwell model and two Kelvin models connected in a series as shown in Figure 2.11-c. The total strain at time t of the generalised model is given as follows in Equation 2.5 (Shan et al, 2016):

$$D(t)=\frac{\sigma}{E_\circ}\left(1+\frac{t}{T_\circ}\right)+\sum_{i=1}^{N}\frac{\sigma}{E_i}\left(1-e^{-\frac{t}{T_i}}\right) \quad 2.5$$

where *D(t)* is the creep compliance; E_o the initial elastic modulus at time zero; T_o the relaxation time; *t* the loading time; T_i the retardation time ($T_i = \eta / E$); E_i the elastic modulus at any time and *N* the number of Kelvin models in the Prony series model. This equation is also known as a Prony series expansion.

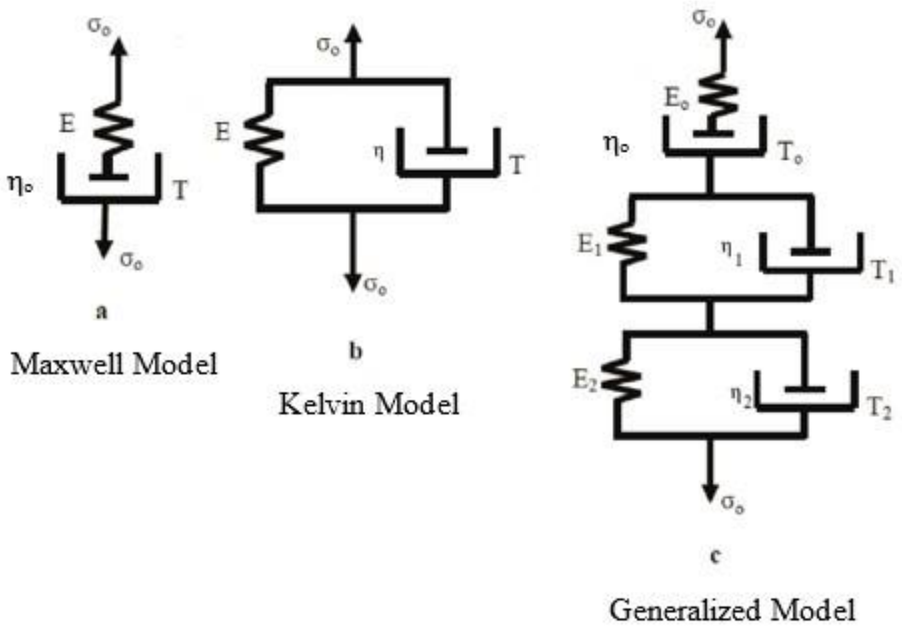


Figure 2.11: Mechanical models for viscoelastic materials

The phenomenon of permanent deformation (rutting) can be evaluated by carrying out creep and relaxation tests (Zhang et al, 2017). Both creep compliance *D(t)* and relaxation modulus *E(t)* are required to develop a viscoelastic model; creep compliance is required to predict deformation and the relaxation modulus to determine pseudo strain. In this study, Prony series coefficients have been fitted to experimental data to represent the viscoelastic (time-dependent) properties of the bituminous mixtures. The experimental data were obtained from creep and relaxation tests for reinforced and unreinforced cold mix asphalt mixtures.

The creep and relaxation test for asphalt mixtures, a typical strain-time curve, can be divided into three distinct strain stages: decelerated creep, the first stage where the strain rate decreases; standard creep, the second stage with a constant strain rate and accelerated creep, the third stage which sees an increase in strain rate. These three stages of asphalt mixture behaviour are shown in Figure 2.12. The total strain in asphalt mixtures usually consists of four constituents: (1) recoverable elastic strain which is time-independent; (2) recoverable viscoelastic strain which is time-dependent; (3) irrecoverable plastic strain which is time-independent, and (4) irrecoverable viscoplastic strain which is time-dependent. During recovery time, elastic strain is instantaneously recovered deformation while delayed recovered deformation is viscoelastic strain. Viscoelastic strain needs adequate time to fully recover. Permanent strain is the combination of both plastic and viscoplastic strains.

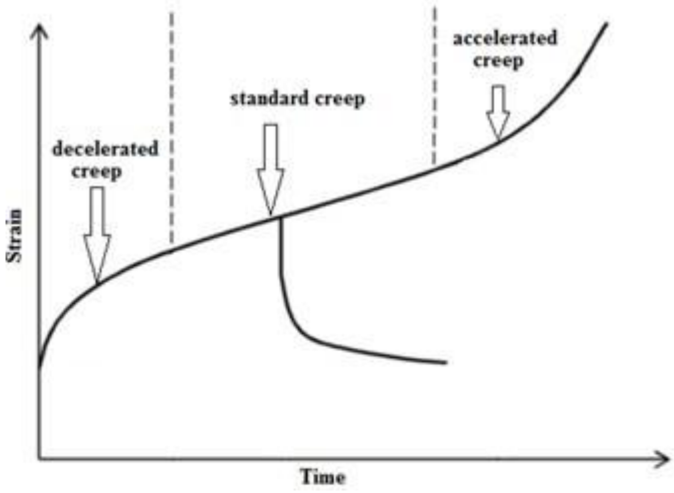


Figure 2.12: Creep and relaxation behaviour at constant stress

2.6.3 Elasto-visco-plastic Model

Perl, Uzan and Sides (1983) established a constitutive model for bituminous mixtures subjected to repeated loading including elastic, plastic, viscoelastic and viscoplastic strain components. The elastic strain is found to rely only and linearly on the stress. The plastic strain is linearly relative to the applied stress and shows a power-law dependence on the number of loading cycles. The viscoelastic strain component is nonlinear with respect to stress and is governed by a power law of time. The viscoplastic strain is nonlinear with respect to stress and thus can be represented by the product of a second-order polynomial of stress and two power laws of time and number of cycles. A series of creep and creep recovery tests were carried out under constant stresses of different magnitudes at different temperatures and found that the total strain contains recoverable and irrecoverable elements, some of which are time dependent and some are time independent. Figure 2.13 displays the graphic illustration of strain components under repeated loading. It can be seen that there are instantaneous elastic (ε_e) and plastic (ε_p) strains at $t = t_0$ when the load is applied. Viscoelastic (ε_{ve}) and viscoplastic (ε_{vp}) strains are developing as loading continued from t_0 to t_1. Once the load is released, at $t = t_1$, the elastic strain (ε_e) recovered, the viscoelastic strain (ε_{ve}) is recovered gradually with time between t_1 and t_2. At the end of each cycle, the residual strain consists of irrecoverable plastic and viscoplastic strain components.

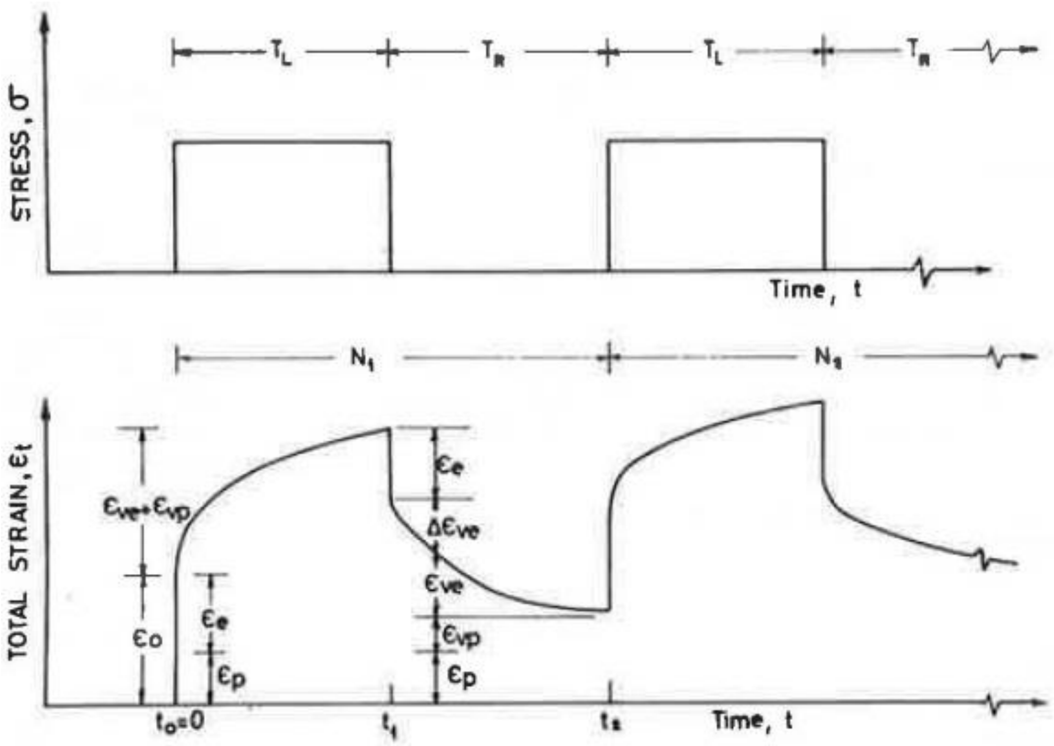


Figure 2.13: Representation of the strain components under repeated loading (Perl, Uzan and Sides, 1983)

This study focuses on the evaluation of the response of natural and synthetic fibre-reinforced CBEM to permanent deformation, using 3-D finite element modelling and experimental tests. The main objectives are to identify the most accurate and effective approach to describe fibre-reinforced CBEMs using finite element modelling. A 3-D, finite element model is developed and included attention to viscoelastic and viscoplastic material behaviours to precisely predict the behaviour of natural and synthetic fibres reinforcement on the development of permanent deformation resistance. Finally, the predicted results from the model are compared with those measured in the laboratory to identify and verify the applicability of the developed model.

2.7 Summary

This chapter reviews the three main types of asphalt mixture: Asphalt Concrete, Hot Rolled Asphalt and Stone Mastic Asphalt. These mixtures classify into three categories depending on the temperature of manufacturing.

As an alternative road material, the properties of CBEMs, either under field condition or at laboratory scale, are gradually becoming understood. Understanding of the key factors affecting CBEM properties is also progressively improving. The effects of bitumen emulsion technology, design procedure, processing stages, moisture content, curing method, binder content, temperature etc. have been clearly defined. Some guidance and specifications related to material components and end product performance have been introduced. All these contribute to the improvement of CBEM application.

This chapter also focuses on the previous studies to enhance the performance of CBEMs. Different techniques have been used to enhance the mechanical properties of such mixtures to make them environmentally friendly, economical and sustainable alternatives to traditional hot mix asphalt mixtures because they can be mixed with aggregates without the need to heat huge amounts of aggregates and bitumen in comparison to the conventional hot mix asphalt mixtures. However, weak early strength, long curing times to obtain full strength and high porosity of compacted CBEMs have been cited as the main barriers to wide utilisation. The inclusion of OPC in CBEMs has some advantages in that satisfactory strength can be reached in a short period of time. However, OPC is not a green material and has a negative impact on the environment. The re-use of waste materials in CBEMs is commonly promoted for two reasons; environmental sustainability and economic advantages. Reinforcing bituminous mixtures using natural and synthetic fibres has been considered one of the most important ways to enhance the engineering properties of these mixtures to resist different types of failures.

A number of constitutive models are available to describe the behaviour of bituminous mixtures. These models have been practically successful although a large number of calibration factors are needed in a quantitative analysis of pavement structures.

Chapter 3

Research Methodology

3.1 Introduction

The methodology used in this study contains the following stages: **Stage I**: this stage included conducting a comprehensive literature review in order to develop a suitable investigation procedure. It considered, in particular, materials preparation, characterization and initial laboratory investigation. **Stage II**: comprises optimizing the mix design of CBEMs, fibres' length and content, using the indirect tensile stiffness modulus test and identifying the most suitable test for performance characterization. **Stage III**: extensive evaluations of the mechanical, durability and microstructure of CBEMs after reinforcement with candidate fibres were carried out. **Stage IV**: included conducting a 3-D finite element model to investigate the effect of the fibres' reinforcement on the permanent deformation performance of CBEMs and applying the developed and validated model to predict rutting performance. **Stage V**: uses the validated model to predict rutting in reinforced and unreinforced CBEMs under the effects of other parameters that cannot be performed in the laboratory.

In this chapter, an overview is given of the experimental procedures adopted to study the engineering behaviour of the cold mix asphalt (CMA) under different loading and environmental conditions. The materials and the specimen preparation are also described. The details of the laboratory tests, including indirect tensile stiffness modulus test and wheel tracking test, are provided. The number of repeated tests for each value are identified later in this chapter. Besides, the purpose of this chapter is to outline the analytical approach used in this research, present the research framework, identify the data sources used for the analysis and describe the method of parameter calibration and results validation used. In addition, the importance of recognizing the mechanism controlling the behaviour of the asphalt mix is also described.

3.1.1 The Motivation of the Proposed Experimental Work

Due to the limited data available to understand the mechanical behaviour of CBEM, experimental tests were conducted to provide an understanding of the behaviour of such mixtures under different loading and environmental conditions. This will provide useful data on the CBEM responses. Also due to the limitations of the laboratory data, there is no global mix design procedure for CBEM. The Asphalt Institute has proposed some procedures for designing CBEM and most of these are based on the procedures that were developed by the American Asphalt Institute, with some improvements. The Asphalt Cold Manual MS-14 (Asphalt Institute, 1989) introduces two approaches for designing CBEM: Modified Hveem and Marshall Methods for emulsified asphalt-aggregate cold mixture design. The Marshall method is used in this research with some modifications (indirect tensile stiffness modulus is used instead of Marshall Stability). The stiffness modulus of a mixture indicates the ability of this mixture to distribute the loads and thus reduce stress concentration into the bituminous layer and on the underlying layers (Dulaimi et al, 2017a). The indirect tensile stiffness modulus test is the common means of measuring this property of bituminous mixtures in the UK (Wu, 2009). Several tests are performed in the current study to investigate the mechanical behaviour of CBEM under a range of loading and environmental conditions. These tests are very commonly used for hot mix asphalt (HMA).

During the service life of the road pavement structures, the surface of such pavements might be distressed due to load repetitions, high and low temperatures and water sensitivity. Consequently, various types of distresses can appear on the surface of flexible pavements, such as rutting (permanent deformation), segregation and cracking. Thus, it is necessary to study the effect of the mixture properties on the performance of flexible pavements in terms of resisting these kinds of damages. In addition, the most common laboratory tests used in this matter are indirect tensile stiffness modulus, wheel tracking, fatigue, crack propagating and water sensitivity tests (Al-Hdabi et al, 2014; Dulaimi et al, 2017a; Shanbara, Ruddock and Atherton, 2018a).

The recommended practices (Abtahi, Sheikhzadeh and Hejazi, 2010; Abiola et al, 2014) mentioned that using natural and synthetic fibres as a reinforcing material in the asphalt mixtures enhances the performance of such mixtures to resist deformation. To date, there is a lack of literature review is available on the effect of using natural fibres as a reinforcing material in CBEM. Hence, this study includes examining the effect of these fibres on the mechanical properties of CBEM. The fibres are very useful reinforcing material due to many advantages such as their high strength and durability. As it is an additional material in the mix, it is recommended to optimise the fibres' length and content to ensure that they are most effective. For the comparison purposes, conventional HMA was utilised.

Based on laboratory testing of CBEM and HMA, a validated numerical model is used in this study to investigate the critical factors in the rutting of bituminous mixtures. It was considered essential that the laboratory data would be used to develop parameters as input data to the model to predict rutting. Additionally, the laboratory data was also used to validate the model by comparing the predicted rutting from the model with those measured using the wheel tracking test.

The framework for this study is shown in Figure 3.1. The study has three main parts: evaluation of the performance of reinforced and unreinforced CBEMs using laboratory testing; finite element modelling using ABAQUS software; and model validation using the wheel tracking test.

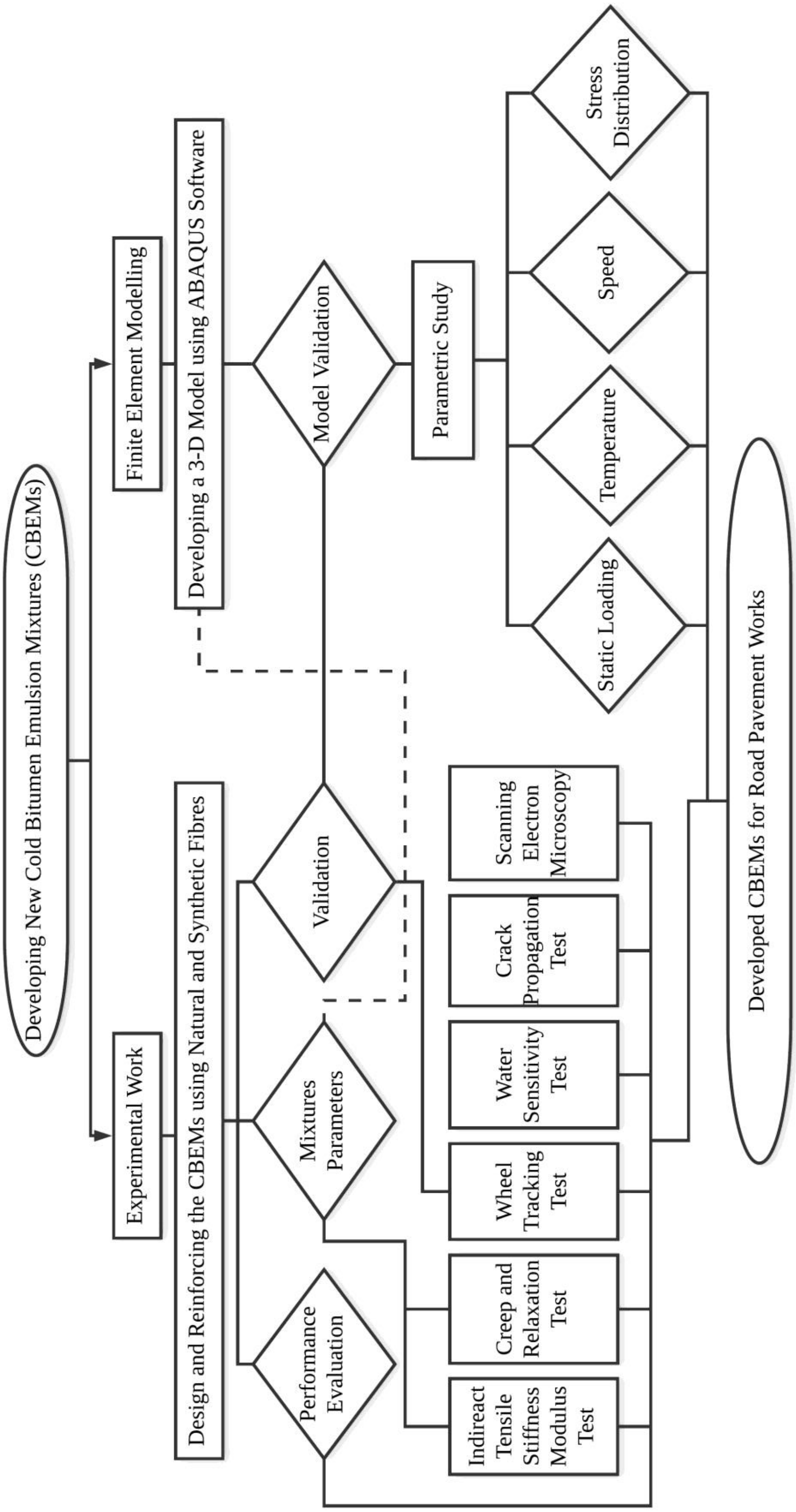


Figure 3.1: Study framework

3.2 Material Characterisation

Material characterisation used in this study is discussed in the following subsections. Alongside the bitumen, bitumen emulsion, aggregate, filler and water, particular attention was given to the use of natural and synthetic fibres as a reinforcing material. This is essential as the influence of different fibres for reinforcement is considered the core of the present study. Thus, this study deals with six types of bituminous mixtures, namely, conventional cold mix (CON), glass fibre-reinforced cold mix (GLS), hemp fibre-reinforced cold mix (HEM), jute fibre-reinforced cold mix (JUT), coir fibre-reinforced cold mix (COI) and conventional hot mix (HMA). Glass fibre is used as a synthetic fibre whilst hemp, jute and coir fibres are used as natural fibres.

3.2.1 Virgin Aggregate

The aggregate used in this study for producing asphalt concrete (AC) was crushed granite, which was obtained from Bardon Quarry, Leicestershire, UK. The aggregate material consisted of aggregates of gradation 14 mm, AC close graded surface course, in according with the European Committee for Standardization (European Committee for Standardization - Part 1, 2012). Based on this Standard, the selected aggregate is one of the most common aggregates used in the production of asphalt and it is considered hard, durable, clean, having suitable shape, providing a suitable level of roughness, skid resistance and resistance to permanent deformation. This selection was in order to ensure an appropriate interlock between the particles in the mixtures. In addition, the influence of aggregate moisture absorption on asphalt mixture moisture is found to be aggregate-type-dependent (Ibrahim and Thom, 1997). The sieve analysis was carried out and aggregate mixture designs calculated to meet with the target grading. The grading is as shown in Figure 3.2 along with the specification for a 14 mm close graded surface course. Table 3.1 shows the gradation and the physical properties of aggregate materials used.

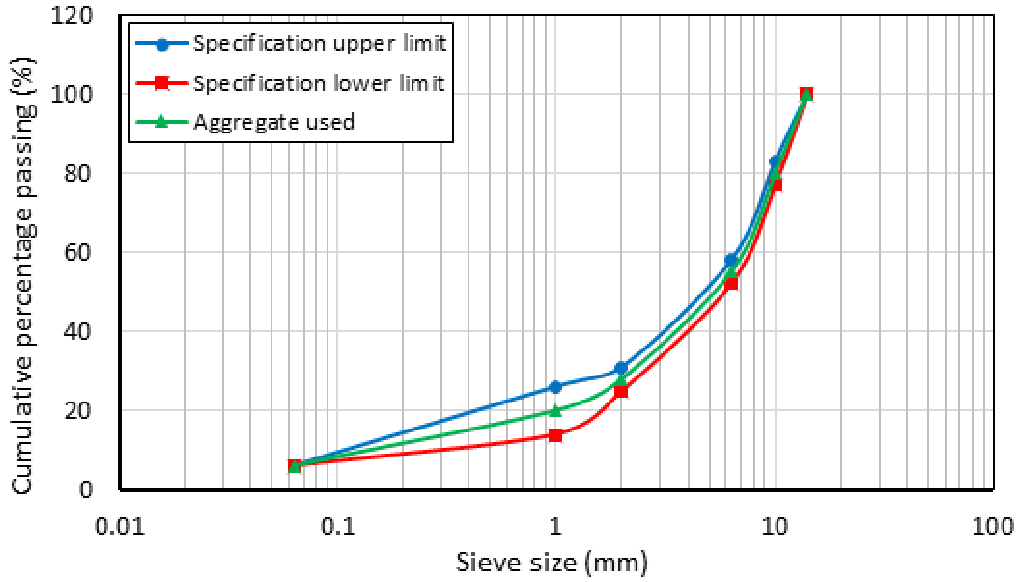


Figure 3.2: 14 mm close graded surface course

Table 3.1: Physical properties of the aggregate

Material	Property	Value
Coarse aggregate	Bulk particle density, Mg/m^3	2.62
	Apparent particle density, Mg/m^3	2.67
	Water absorption, %	0.8
Fine aggregate	Bulk particle density, Mg/ m^3	2.54
	Apparent particle density, Mg/ m^3	2.65
	Water absorption, %	1.7
Traditional mineral filler	Particle density, Mg/ m^3	2.57

3.2.2 Bitumen Emulsion

A commercial cationic slow setting bituminous emulsion (C50B3) with 50% bitumen content was used as a binding agent for manufacturing the CBEMs to ensure high adhesion between aggregate particles. This type of emulsion is called Cold Asphalt Binder (CAB 50) based on 40/60 penetration grade base bitumen and is supplied by Jobling Purser, Newcastle, UK. The high stability and high adhesion of this cationic emulsion were the reasons for selection as recommended by the supplier. The relevant properties of the selected bitumen emulsion are shown in Table 3.2. The bitumen emulsion was kept in air-tight sealed containers stored at room temperature and stirred every day at least two times to keep it stable. The bitumen emulsions were stirred well into a homogenous state (visual inspection) before being used in the production of the CBEMs.

Table 3.2: Properties of the selected bitumen emulsion

Property	Value	Standard
Type	Cationic	
Appearance	Black to dark brown liquid	
Breaking behaviour	110-195	EN 13075-1
Base bitumen Penetration (0.1 mm)	50	EN 1426
Softening Point (°C)	50	EN 1427
Bitumen content (%)	50	EN 1428
Viscosity (2mm at 40 °C)	15-70	EN 12846
pH	5	
Boiling point (°C)	100	
Adhesiveness	≥ 90%	EN13614
Relative density at 15 °C (g/ml)	1.05	
Particle surface electric charge	positive	EN 1430
Density (g/cm^3)	1.016	

3.2.3 Bitumen

In the present study a traditional binder consisting of 100/150 penetration grade bitumen supplied by Jobling Purser, Newcastle, UK was used for HMA production. The reason for selection of this grade is that this grade of bitumen is commonly used in the UK for manufacturing HMA mixtures and according to the European Committee for Standardization (European Committee for Standardization - PD 6691, 2010) , this grade is the most preferred grade for producing HMA with the AC 14 mm close graded surface course aggregate gradation. The properties of the bitumen used in this study are presented in Table 3.3.

Table 3.3: Properties of 100/150 bitumen used in the study

Property	Value
Appearance	Black
Penetration at 25 °C (0.1 mm)	141
Softening Point (°C)	43.5
Kinematic viscosity at 135 °C (mPa.s)	179
Density (g/cm³)	1.02

3.2.4 Water

Tap water was used in this study for all types of CBEMs. The water was obtained from the domestic water supply pipe in the Henry Cotton Building at Liverpool John Moores University, UK and supplied by United Utilities.

3.2.5 Filler

Conventional limestone dust was used in this study as a natural filler obtained from Francis Flower Ltd, UK. Limestone filler plays a physical role through filling the pores between aggregate particles and improving the backing properties.

3.2.6 Fibres

Four different types of fibres were used in this study as reinforcing materials, including synthetic fibre, which is glass fibre (supplied by the Fibre Technologies International Limited-UK), and natural fibres, which are: hemp and jute (supplied by the Wild Fibres-UK) and coir (supplied by The Upholstery Warehouse-UK). These fibres are always as single (mono) fibres. The physical properties of these fibres are presented in Table 3.4.

Table 3.4: Natural and synthetic fibre properties

Items	Fibre type			
	Glass	Hemp	Jute	Coir
Density (kg/m^3)	1380	1500	1450	1250
Tensile strength (MPa)	1600	900	450	175
Diameter (µm)	15-19	17-23	16-21	18-23
Moisture content (%)	0.5	10	11	14

3.3 Testing Programme and Procedures

The CBEM design considered in this study relies on the results obtained from the fundamental tests that were used to assess the proposed mixtures. The literature shows that CBEM design methods are similar to those of HMA, but without a universally accepted method or procedure (Lanre, 2010). Laboratory mechanical tests are commonly used in order to evaluate the mechanical properties of HMA. The testing programme was conducted in two phases. In the first phase, fibres were investigated to establish the optimum fibre length and content. In the second phase, the conventional CBEM (CON) and HMA mixtures, and the optimised fibre-reinforced CBEMs with four different fibres (glass (GLS), hemp (HEM), jute (JUT) and coir (COI)), were investigated using different laboratory tests as detailed below.

3.3.1 Indirect Tensile Stiffness Modulus Test

The indirect tensile stiffness modulus (ITSM) test is a non-destructive test where cylindrical samples are positioned vertically and a diametrical load then applied, as shown in Figure 3.3. This test is used in the current study to determine the stiffness modulus of the bituminous mixtures. Results of the stiffness modulus of the bituminous mixtures provide the pavement designer with definitive information related to fundamental properties of the pavement materials. Stiffness modulus can be measured in the laboratory by subjecting a cylindrical sample to repeated load pulses, with a rest period, across the vertical diameter of the sample, using two loading strips 12.5 mm in width and monitoring the resultant horizontal displacement at right angles. This is equivalent to Young's modulus for elastic materials. Loading is applied in a half sine wave form and the loading time is controlled during the test. The rise-time, measured from when the load pulse commences and the time taken for the applied load to increase from initial contact load to the maximum value, is 124 ± 4 ms. The peak load value is adjusted to achieve a target peak, a transient horizontal deformation of 0.005% of the sample diameter. The applied load is measured using a load cell with an accuracy of 2%, the pulse repetition period being 3.0 ± 0.1 s. The ITSM uses five conditioning pulses to self-adjust and bed in the specimen. A further five measuring pulses are then applied, and the average stiffness modulus is then calculated.

The stiffness modulus of the bituminous mixtures is dependent on the applied load, the resultant deformation, dimensions of the sample and Poisson's ratio, which is material and temperature dependent. Indirect tensile stiffness modulus is calculated in units of MPa using Equation 3.1 shown below (European Committee for Standardization - Part 26, 2012). Stiffness of the bituminous materials is also dependent on speed of loading due to the viscoelastic and viscoplastic nature of the binder (Needham, 1996).

$$ITSM = \frac{L}{y*h}(\nu + 0.27) \qquad 3.1$$

where:

ITSM = indirect tensile stiffness modulus (MPa)

L = the peak level of the applied vertical load (N)

y = the peak horizontal diametric deformation resulting from the applied load (mm)

h = the mean thickness of the test specimen (mm)

ν = Poisson’s ratio for the material at the temperature of test.

The ITSM test was used throughout this study to evaluate the mechanical properties of the cold mix asphalt mixtures and in particular to monitor the changing properties of specimens during the curing period. This is essential to the work as the influence of different factors on curing rate, or the absolute stiffness values at a given time after laying, were to be quantified. The ITSM test is perfectly suited for this requirement, as it is practically non-destructive when used on the types of materials it was developed for.

In order to determine the stiffness modulus (Al-Hdabi et al, 2014; Al-Hdabi, Al Nageim and Seton, 2014b; Al-Hdabi, Al Nageim and Seton, 2014a; Dulaimi et al, 2016; Dulaimi et al, 2017a; Dulaimi et al, 2017b; Dulaimi et al, 2017c), all CBEM specimens were kept in their mould for one day at room temperature (20 °C). This represents the first stage of curing, followed by different curing times (2, 7, 14, 28, 90, 180 and 360) days. Adopting a normal curing temperature (room temperature) in this study was performed to simulate the production, compaction and placing of such mixtures in field conditions and avoiding any premature ageing of the binder (Khalid and Monney, 2009; Ojum et al, 2014). Prior to testing, the samples were conditioned at the test temperature for at least 4 hours. The tests were conducted at 20 °C following the European Committee for Standardization (European Committee for Standardization - Part 26, 2012) using Cooper Research Technology HYD 25 testing apparatus. The stiffness modulus was set at the average value of five tested samples.

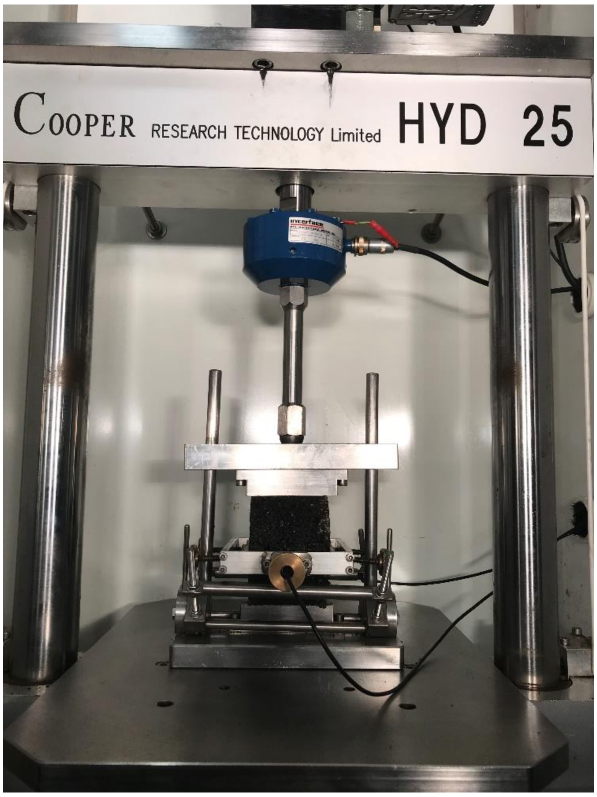


Figure 3.3: HYD 25 indirect tensile apparatus

3.3.2 Wheel Tracking Test

Wheel tracking tests were used to measure the rut depth (permanent deformation) of the bituminous mixtures at two different temperatures, 45 °C and 60 °C. The selection of these two temperatures was based on the European Committee for Standardization (European Committee for Standardization - PD 6691, 2010). The temperature 45 °C represents moderate to heavily stressed sites requiring high rut resistance, while 60 °C represents very heavily stressed sites requiring very high rut resistance. Prior to carrying out the tests, the loose bituminous mixtures were prepared and then compacted in steel moulds using a steel roller compactor, resulting in solid slabs measuring 400 mm (length) × 305 mm (width) × 50 mm (thickness). The specimens were treated in the same way and were kept in the mould for 24 hours at room temperature. Following this, the CBEM slabs were cured for 14 days inside a ventilated oven at 40 °C to achieve full curing (obtain the final strength) (Al-Busaltan et al, 2012a; Al-Busaltan et al, 2012b; Al Nageim et al, 2012; Dulaimi et al, 2016; Dulaimi et al, 2017b). This curing temperature is significant as it needs to be less than the bitumen softening point (50 °C) and thus prevents the bitumen from ageing (Dulaimi et al, 2017a; Dulaimi et al, 2017c). However, curing of such mixtures on site may take from 2 months to 2 years to obtain the final strength of these mixtures depending on the weather conditions (Al-Busaltan, 2012). For the test, a single wheel with a standard vehicle tyre pressure of 0.7 MPa was applied to the surface of the bituminous slab as shown in Figure 3.4. The wheel was rolled on the surface of the bituminous slab covering a distance of 230 mm at a rate of 42 (±1) times/min (speed 16.1 cm/s) along the centre line of the slab, for 460 minutes (about 20,000 wheel load repetitions) under dry conditions. The output from this test consists of accumulative vertical deformation of a specimen against the repeated moving wheel with respect to time. This test was carried out in accordance with the European Committee for Standardization (European Committee for Standardization - Part 22, 2003). The rutting value was set at the average value of three tested samples.

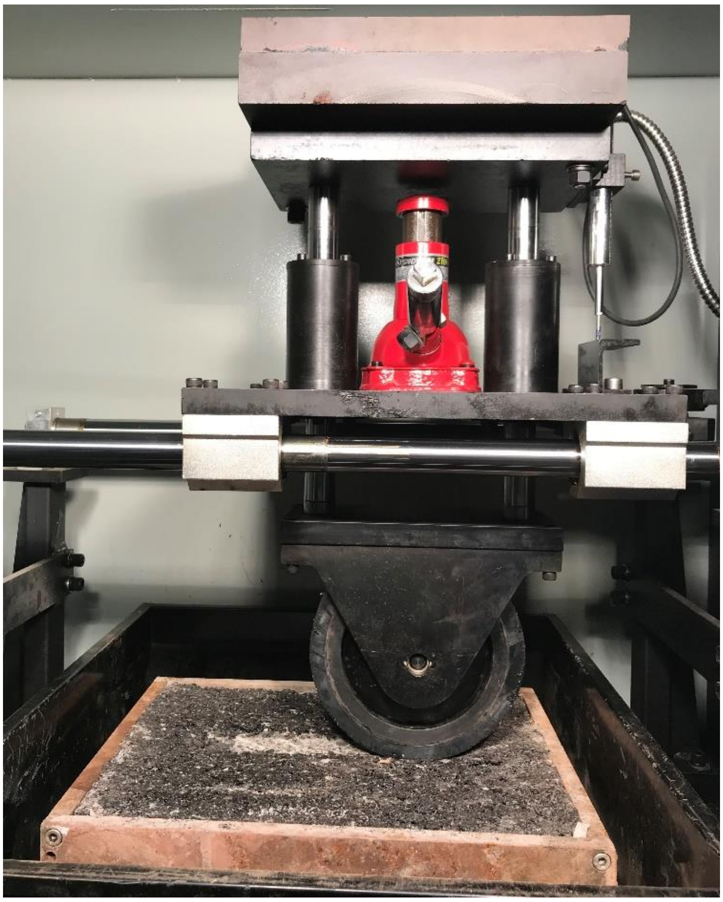


Figure 3.4: Wheel-tracking test equipment

3.3.3 Scanning Electron Microscopy

In order to characterise the microstructure and fracture surfaces of the raw fibres, scanning electron microscopy (SEM) analysis was conducted using an EDX Oxford Inca x-act detector, Inspect FEI SEM model. SEM is a high resolution, electronic imaging technique used to observe the morphology of objects. Prior to conducting SEM observations, the fibre samples were dried, glued directly onto a carbon film sample holder and then coated with a thin layer of gold, using a vacuum sputter coater, to improve visibility. The tests were conducted with a SEM resolution of 3 nm to 4 nm, a high vacuum and a test voltage of 10 kV.

3.3.4 Water Sensitivity Test

The ability of a bituminous mixture to resist moisture distress is critical to its long-term performance (Dulaimi et al, 2016). These mixtures are identified as being sensitive to moisture if the laboratory specimens fail in a water sensitivity test. In this study, the water sensitivity testing was conducted in accordance with the European Committee for Standardization (European Committee for Standardization - Part 12, 2008). This test exposes any loss of adhesive bond between the aggregate and bitumen of cylindrical specimens, due to the existence of water. During the test, the compacted specimens were divided into two groups; the first group for dry testing, the second for saturated testing (the test specimens (both groups) were of the same age). The specimens in the dry group were tested without moisture conditioning as they were kept in the mould (after compaction) for one day at room temperature (20 °C), extruded and left on a flat surface at room temperature for another seven days before the ITSM test. The specimens in the second group were saturated as part of the moisture pre-conditioning protocol. Each specimen (after one day in the mould at room temperature), was extruded and immersed in a water bath at 20 °C for four days and then transferred to the vacuum container. A combination of vacuum pressure and duration (6.7 kPa for 10 min) was applied to achieve the required degree of saturation. After completing the vacuum process, the specimens were kept in the vacuum container for another 30 minutes, removed from the container and placed on a flat surface in a water bath at 40 °C for three days, before being tested. All specimens (dry and wet) were then tested at 20 °C in accordance with the European Committee for Standardization (European Committee for

Standardization - Part 12, 2008). Five sets of each sample were tested for each mixture type. Water sensitivity of asphalt mixtures can be measured by either the indirect tensile strength ratio (*ITSR*) or indirect tensile stiffness modulus ratio (*SMR*) (Al-Busaltan et al, 2012b; Al Nageim et al, 2012; Al-Hdabi et al, 2014). Water sensitivity was calculated using the stiffness modulus ratio (*SMR*) as shown in Equation 3.2 (Al-Busaltan et al, 2012b; Al Nageim et al, 2012; Al-Hdabi et al, 2014; Dulaimi et al, 2017a):

$$SMR = (\text{wet stiffness } \div \text{dry stiffness}) \times 100 \qquad 3.2$$

3.3.5 Semi-circular Bending Test

The European Standard specifies the use of the semi-circular bending (SCB) test to determine tensile strength, or fracture toughness, of bituminous mixtures to assess for potential crack propagation. This test involves determining the resistance of bituminous mixtures to crack propagation during a constant loading speed of 5 mm/min. Slab samples of length 400 mm, width 305 mm and depth 50 mm, were prepared and compacted using a steel roller compactor which simulated pavement compaction in the field. After full curing (the slabs were cured for 14 days inside a ventilated oven at 40 °C to achieve full curing) (Al-Busaltan et al, 2012a; Al Nageim et al, 2012; Dulaimi et al, 2016), three cylindrical specimens measuring 150 mm in diameter and 50 mm in height, were cored from each slab using an electrical extruder (European Committee for Standardization - Part 44, 2010). Each specimen (core) was then cut into two equal halves (semi-circular specimens), each half cut in the centre with a notch of 10 mm depth and 0.35 mm width to act as a pre-crack initiator. These specimens were loaded under three-point bending in such a way that the middle of the base of the specimens were subject to tensile stress (Figure 3.5). During the test, deformation increases at a constant rate of 5 mm/min. The corresponding load increases to a maximum value (F_{max}), directly related to the fracture toughness of the specimens. Six replicated specimens were considered for each value.

As per the European Committee for Standardization (European Committee for Standardization - Part 44, 2010), the maximum stress at failure (σ_{max}), and the fracture toughness (K_{IC}), have been calculated in accordance with Equations 3.3 and 3.4, respectively.

$$\sigma_{max} = \frac{4.263 \times F_{max}}{R \times h} \ N/mm^2 \qquad 3.3$$

where:

R = the diameter of specimen (mm)

h = the thickness of specimen (mm)

F_{max} = the maximum force of specimen in Newton

$$K_{IC} = \sigma_{max} \times f\left(\frac{z}{W}\right) \ N/mm^{3/2} \qquad 3.4$$

where:

W = height of specimen (mm).

z = notch depth of specimen (mm).

σ_{max} = stress at failure of specimen (N/mm^2).

$f(\frac{z}{W})$ = geometric factor of specimen, for $9 < z < 11$ mm and $70 < W < 75$ mm, then, $f(\frac{z}{W}) = 5.956$.

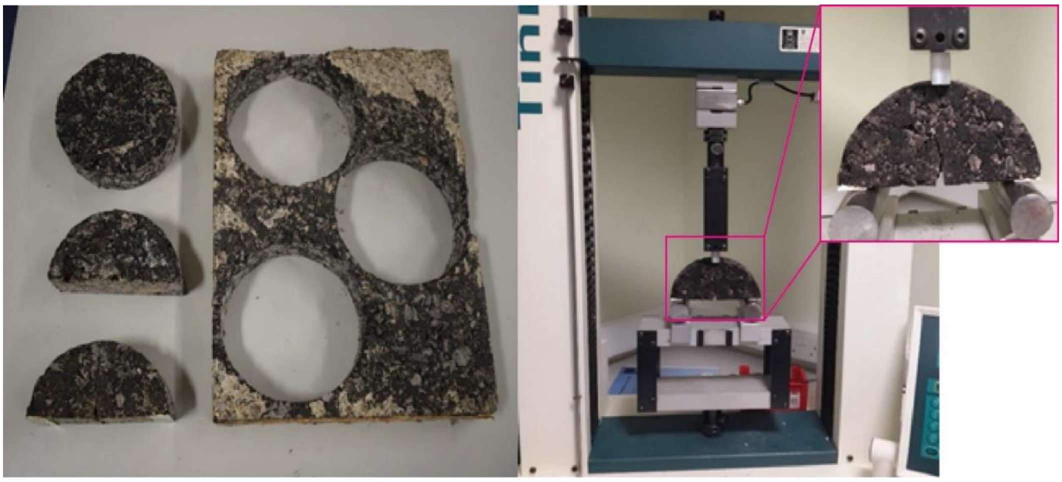


Figure 3.5: SCB specimen preparation and fracture test

3.3.6 Creep and Relaxation Test

This test describes a method for determining the creep parameters of bituminous mixtures by means of uniaxial static creep and relaxation testing with some confinement present. In this test, a cylindrical specimen is subjected to a static stress. To achieve a certain confinement, the diameter of the loading plate is designed to be smaller than that of the sample. Creep curve displays the cumulative strain, expressed in %, of the specimen height as a function of the time of load applications. Generally, the following stages can be distinguished in the creep curve (Figure 2.12 in Chapter two):

- Stage 1: the decelerated creep part of the strain curve, where the strain rate decreases with increasing loading time.
- Stage 2: the constant strain rate part of the strain curve, where the strain rate is quasi constant and with a turning point in the strain curve.
- Stage 3: the accelerated creep part of the strain curve, where the strain rate increases with increased loading time.

Depending on the testing conditions and on the mixture properties, one or more stages might be missing.

This test method determines the viscoelastic and viscoplastic properties of a cylindrical specimen of bituminous mixture by loading and unloading condition. The specimens may be either prepared in the laboratory or be cored from a pavement. A cylindrical test specimen with a diameter of 150 mm is placed between two plane parallel loading plates. The upper plate has a diameter of 100 mm. A schematic representation of the test device is given in Figure 3.6. The specimen is subjected to a static pressure. There is no additional lateral confinement pressure applied. During the test, the change in height of the specimen is measured at specified loading time. From this, the cumulative strain (permanent deformation) of the test specimen is determined as a function of the loading time. The results are represented in a creep curve as given in Figure 2.12 in Chapter two. From this, the creep characteristics of the specimen are computed. Prior to the test, the specimens were kept at the test temperature within ±1.0 °C from 4 to 7 hours. The creep tests at 5 °C, 20 °C, 45 °C and 60 °C, were used to study the influence of reinforced and unreinforced mixtures on creep performance to assess their viscoelastic and viscoplastic properties. The test was conducted under 0.1 MPa stress in accordance with the European Committee for Standardization (European Committee for Standardization - Part 25, 2005). The creep and relaxation curves were set at the average value of three tested samples.

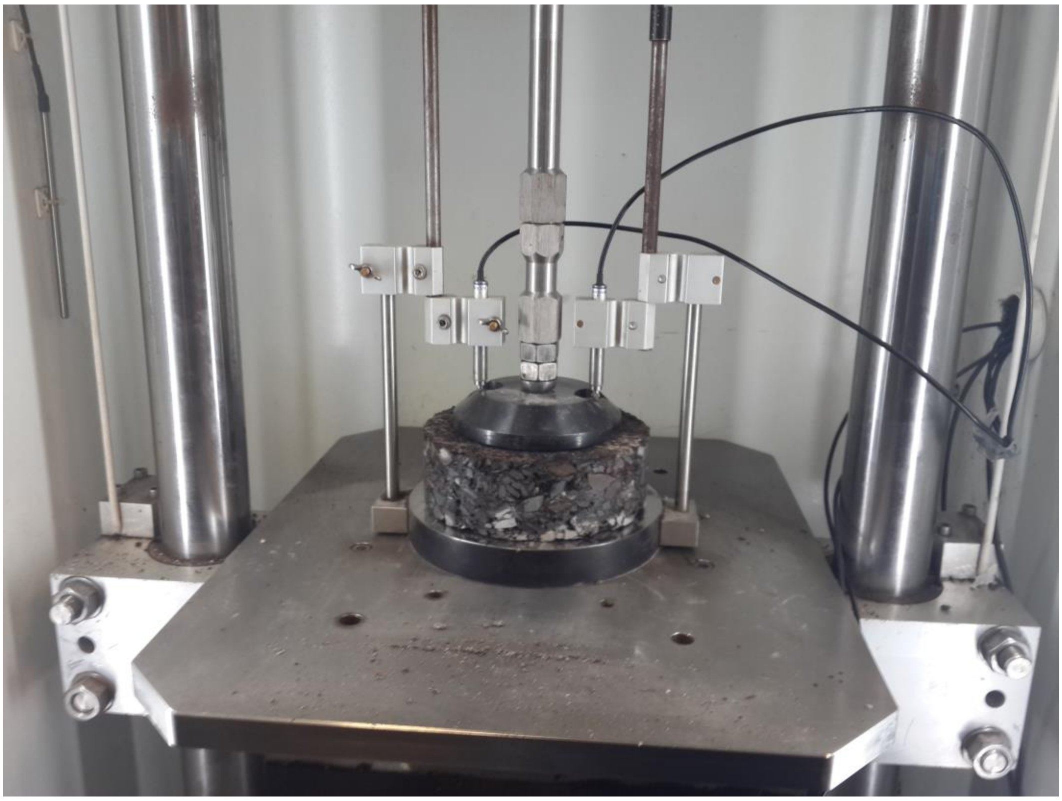


Figure 3.6: Representation of creep test

3.4 Specimens Preparation

CBEM specimens were prepared according to the Marshall method for emulsified asphalt aggregate cold mixture designs (MS-14), as adopted by the Asphalt Institute (1989). According to this procedure, the optimum pre-wetting water content, optimum total liquid content at compaction, optimum residual bitumen contents and optimum emulsion content were 3%, 12.4%, 6.2% and 12.4%, respectively. These results are comparable to those published by (Al-Busaltan et al, 2012a; Al-Hdabi et al, 2014; Dulaimi et al, 2017a). The fibres were added and blended into the mixtures to improve the mechanical properties and prevent binder drain-down. To ensure a consistent distribution of the fibres, water and emulsion in the mixtures, the aggregate together with the fibres and the pre-wetting water were added to an electric blender (Figure 3.7) then mixed for 1 minute (Chen et al, 2009).

Subsequently, the bitumen emulsion was added progressively throughout the next 30 seconds of mixing, and the mixing continued for the next 2 minutes. This process allows for the best fibre distribution in the mixtures (Abtahi, Sheikhzadeh and Hejazi, 2010). In addition, the mixed specimens were placed in the moulds, and then directly compacted with 100 blows (for which Marshall specimens were prepared), 50 on each side of the specimens using standard Marshall Hammer (impact compactor) as shown in Figure 3.8, or compacted using a steel roller compactor (for which bituminous slabs were prepared) as shown in Figure 3.9.

Figure 3.7: Electric blender

Figure 3.8: Marshall hammer

Figure 3.9: Steel roller compactor

Fibre reinforcement of bituminous mixtures is deemed a random, direct inclusion of fibres into the mixture. If the fibres are too long, they might not be mixed well with other materials because some of the fibres may lump together creating a clumping or balling problem. On the other hand, too short fibres might not perform well as a reinforcing material, serving only as an expensive filler in the mixture. Therefore, it is necessary to optimise the fibres' length and content to avoid such problems and to ensure the uniformity of fibre distribution in the mixtures. In this study, in order to find the optimum fibre length and content, fibres of varying lengths (10, 14 and 20) mm were used according to literature available (Liu, Cheng and Chen, 2017). These lengths were selected based on the aggregate maximum size, where, 10 mm is shorter, 20 mm is longer and 14 mm is the same as the aggregate maximum size. Based on the fibre reinforcing of HMA and concrete pavements (Chen et al, 2009; Xu, Chen and Prozzi, 2010; Abiola et al, 2014; Hesami, Ahmadi and Nematzadeh, 2014; Jeon et al, 2016; Yang, Kim and Yoo, 2016; Liu, Cheng and Chen, 2017), fibre contents of 0.15%, 0.25%, 0.35%, 0.45% and 0.55% of total aggregate weight for all fibre lengths were included in the CBEM mixtures. Based on the results of the ITSM test, an optimised fibre length and content were selected and used for the other experimental tests (Fu et al, 2017).

HMA specimens were prepared for comparison purposes according to the European Committee for Standardization (European Committee for Standardization - PD 6691, 2010). The aggregate gradation of 14 mm close graded surface course was manufactured with (100/150) bitumen grade and according to the European Committee for Standardization (European Committee for Standardization - PD 6691, 2010), this grade is the preferred grade for producing HMA with the 14 mm close graded surface course aggregate gradation that been used for producing the CBEMs.

Optimum binder content of 5.1% by weight of aggregate was added according to the same Standard for the Asphalt Concrete (AC) 14 mm close graded surface course. The HMA mixtures were mixed and compacted at a temperature of 160 °C to 170 °C (in accordance with the European Committee for Standardization - Part 13 (2000), shall not exceed 180 °C).

3.5 Summary

The details of the laboratory tests were presented in this chapter, including the materials used, specimen preparation and test procedures. The main tests to obtain mechanical properties of CBEM and HMA were undertaken. Bitumen emulsion and bitumen were used for manufacturing CBEM and HMA samples with the same aggregate type. The mix design procedure for CBEM was explained using different parameters. HMA testing was performed for comparison purposes. Four different fibre types were used as a reinforcing material in CBEM. The CBEMs were reinforced with glass fibre as a synthetic fibre and hemp, jute, and coir as natural fibres to examine the effect of fibres' reinforcement on the structural response of such mixtures. The instrumentation used for all tests was presented.

Chapter 4

Experimental Results and Discussion

4.1 Introduction

In order to be able to use a material in an engineering structure, its mechanical properties must be known to enable the engineer to design the structure so that the material can resist the stresses and strains placed upon it. As flexible pavements technology depends on performance based design, this is as true for roads as it is for any other structure. The laboratory investigation of the bituminous mixtures provides essential results to evaluate the performance of such mixtures under different loading conditions. These experimental results can also be used to validate predictions derived from laboratory tests and pavement modelling. Results obtained from such tests enable the engineer to design mixtures and pavement structures based on recipes learnt through experience. Over the years, several test protocols have been proposed for the design of cold mix employing a range of mixture and sample preparing methods and tests for evaluating mechanical properties (Gadallab, Wood and Yoder, 1977; Waller, 1980; Arya and Jain, 1993; Marchal, Boussad and Julien, 1993; Nikolaides, 1993). This chapter presents experimental results of reinforced and unreinforced CBEMs, and conventional HMA subjected to different loading and environmental conditions. The effects of using natural and synthetic fibres as reinforcing materials in CBEM on the mechanical properties of such mixtures are discussed in this chapter. Following this, the outcomes of the specimens tested with different parameters, i.e. fibre reinforcement, curing time, temperature, water action and loading conditions are evaluated and analysed. Subsequently, this chapter covers the results of different tests of CBEM and HMA specimens.

The methods used to measure the mechanical properties of the bituminous mixtures in this study were all based at the Liverpool John Moores University, pavement laboratory. The laboratory equipment employs engineering principles and, therefore, the results obtained are related to the fundamental properties of the mixtures.

4.2 Mix Design

Basically, the objective of any mix design is to produce mixtures that meet their structural and functional requirements. Regarding current experience, some authorities and researchers have proposed cold mix design guidelines based on empirical equations, experimental work or previous experience such as that documented by the Asphalt Institute, (1989); Lee et al, (2001); Thanaya, (2003) and Wirtgen (2004). Thus, it is necessary that optimisation of CBEM parameters should be carried out in order to develop the technology in the use of such mixtures, as claimed by Lee et al (2001). It is, therefore, important to design and optimise CBEM components in order to achieve appropriate properties (Lee et al, 2001; Kim, Lee and Heitzman, 2007). Some of the studies reported in the literature on CBEM have focused on using the method adopted by the Asphalt Institute (1989) (Marshall Method for Emulsified Asphalt Aggregate Cold Mixture Design), with some modifications (Thanaya, 2003; Forth, Zoorob and Thanaya, 2006). The following steps describe the main methodology of the Asphalt Institute procedure (Thanaya, 2003):

1. Determine the appropriate aggregate gradation.

2. Determine the approximate initial amount of the bitumen emulsion based on empirical equation.
3. Determine the optimum water content at compaction.
4. Determine the optimum total liquid content (bitumen emulsion and pre-wetting water content) taking into account the mechanical and volumetric properties of trial mixtures until obtaining a trend to the best criteria.
5. Establishment of the job mix formula.

As there is no general existing equipment made specifically for the testing of cold mixtures, those used for testing hot mixtures are most frequently employed with slight modifications. These modifications are required because cold mixtures being intermediate materials behave as unbound granular materials in their early life stages (because of the presence of moisture). This behaviour is responsible for the various modifications that have been introduced to cold mix design over the years. However, there is no direct set of rules that can be followed. All produced specimens in this study were prepared according to the method adopted by the Asphalt Institute (Marshall Method for Emulsified Asphalt Aggregate Cold Mixture Design (MS-14)). In this method, the indirect tensile stiffness modulus test was used instead of Marshall Stability. Details of mix design are summarised in the next sections.

4.2.1 Determination of Initial Emulsion Content

According to the selected aggregate and bitumen emulsion, the initial emulsion content (IEC) was determined based on the Equations 4.1 and 4.2 below and according to the MS-14:

$$P = (0.05F + 0.1B + 0.5C) \times (0.7) \qquad 4.1$$

where,

P: % of initial residual bitumen content by weight of total dry aggregate.

F: % of aggregate retained on sieve 2.36 mm.

B: % of aggregate passing sieve 2.36 mm and retained on sieve 0.063 mm.

C: % of aggregate passing sieve 0.063 mm.

The *IEC* could be found by dividing *P* by the percentage of bitumen content in the emulsion. According to the aggregate gradation selection and by application of Equation 4.1, the initial residual emulsion content (*P*) is 6.16% of the aggregate weight. Due to the variation between American and British sieve openings, a little estimation was applied during this calculation. The base bitumen content in the emulsion is 50%, thus according to the MS-14:

$$IEC\ (\%) = \frac{P}{X} \qquad 4.2$$

where,

X: the bitumen content of the emulsion, which is 50%.

IEC = 6.16 / 0.5 = 12.32% of the aggregate weight.

4.2.2 Determination of Optimum Pre-wetting Water Content (Coating Test)

There are two different liquid types inside the CBEMs, bitumen and water. The water includes two different sources; a proportion of the bitumen emulsion content and the additional water in the mix, named the pre-wetting water content. The pre-wetting water content is defined as the amount of water added to the cold mixture before adding the bitumen emulsion. This addition is to improve the ability of the bitumen emulsion to coat the aggregate and to improve the workability of the mixture (Nassar, 2016).

Considering *IEC*, the coating test must be conducted after mixing all of the dry aggregate batches and filler with different amounts of pre-wet water to ensure an appropriate binder coating (Dulaimi, 2017). The ability of bitumen emulsion to coat the aggregates during the mixing is sensitive to the pre-wet water content of aggregate (Nassar, 2016). Insufficient pre-wet water results in balling of the bitumen with the fines leading to unsatisfactory coating (Thanaya, 2003). In addition, Thanaya reported that this pre-wetting water content helps the emulsion to distribute uniformly onto the aggregates surface allowing for better binder coating. Ojum (2015) stated how pre-wetting water lubricates and activates the aggregate particles surface before adding the bitumen emulsion. The optimum pre-wetting water content depends on aggregate grading and the physical properties of aggregates. The Asphalt Institute (1989) recommended applying different contents of pre-wetting water with the determined *IEC* to obtain the lowest pre-wetting water content needed to achieve maximum percentage of coated aggregates with the binder. Five percentages of pre-wetting water content (2.5%, 3%, 3.5%, 4% and 4.5%) of the total aggregate were investigated to obtain the lowest water percentage that ensures the optimal coating. One minute of mixing time is sufficient to mix aggregates with water. Emulsion was added afterwards and blended for about 2 to 3 minutes until an even coating was obtained. The optimum pre-wetting water content (*OPWwc*) is a percentage in which the mixture gives the optimal bitumen coating on the aggregate’s surface, i.e. the mixture is not too sloppy or too stiff. The coating degree should not be less than 50% of coated aggregate by visual observation. *OPWwc* of 3% was selected using visibility judgment as shown in Figure 4.1.

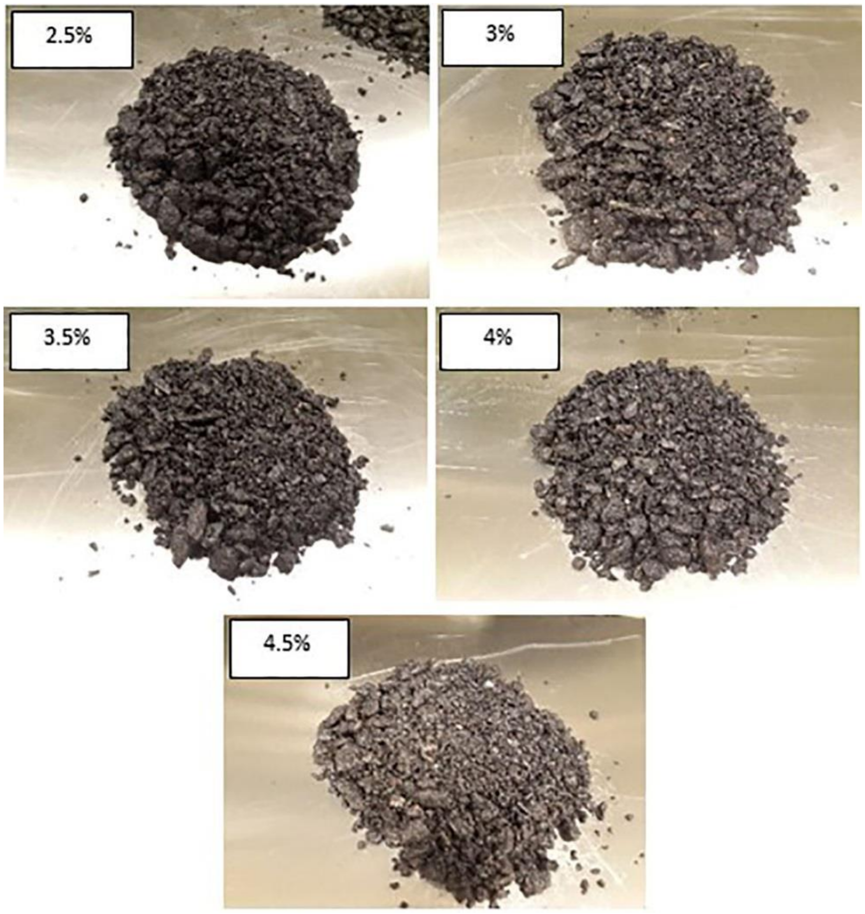


Figure 4.1: The mixture with different percentages of pre-wetting water content

4.2.3 Determination of Optimum Total Liquid Content at Compaction

Water amount percentage during specimens' compaction is very critical. With a high percentage of water, dissipated compaction effort, low density and undesirable mechanical properties are expected. On the other hand, low workability, low density and high air voids result from low water content. Therefore, optimisation of water content during compaction enhances the desired mixture properties. According to MS-14, different water content during compaction (the loose mixtures were prepared at *OPWwc* and compacted at different water contents in 1% steps by air drying) were investigated as Marshall specimens. This stage gives the optimum water content at compaction at which the dry density of the sample is a maximum.

Initial emulsion content (*IEC*) = 12.32%

Optimum pre-wetting water content (*OPWwc*) = 3%

Total liquid content at compaction is 15.32%.

To find the optimum total liquid content (*OTLC*) at compaction, five percentages of total liquid content were investigated (15.32%, 14.32%, 13.32%, 12.32% and 11.32%). The water content of each mixture was calculated after leaving the loose mixtures for different periods to reduce the total liquid content. Then, the Marshall Hammer was employed to compact the mixtures; 50 blows applied on each face. Figure 4.2 shows that the total liquid content of 12.32% gives maximum dry density. Consequently, the *OTLC* was 12.32% by the aggregate mass. The result for each point represents the average of results of three specimens.

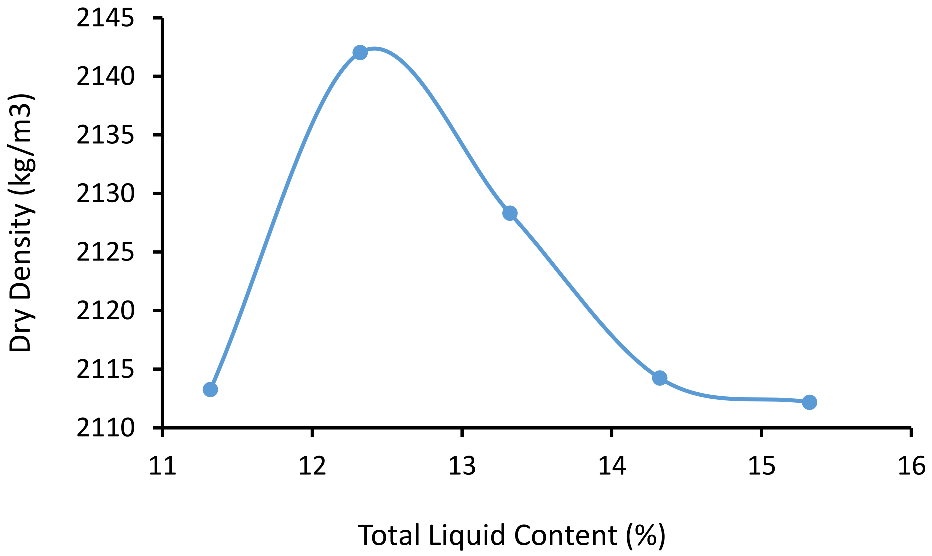


Figure 4.2: Optimum liquid content (%)

4.2.4 Determination of Optimum Residual Emulsion Content

Different emulsion contents above and below the calculated initial emulsion content were selected to prepare the Marshall samples, where the total liquid content remained the same (15.32%). Indirect Tensile Stiffness Modulus test (ITSM) was used to determine the optimum residual emulsion content (*OREC*), which was observed to be 6.2% of aggregate weight (12.4% emulsion content) for soaked samples. Whilst, ITSM decreased with an increase in the residual bitumen content for dry samples, as shown in Figure 4.3. However, emulsion content of 6.2% was adopted to be the *OREC*, because the wet condition is the governing situation.

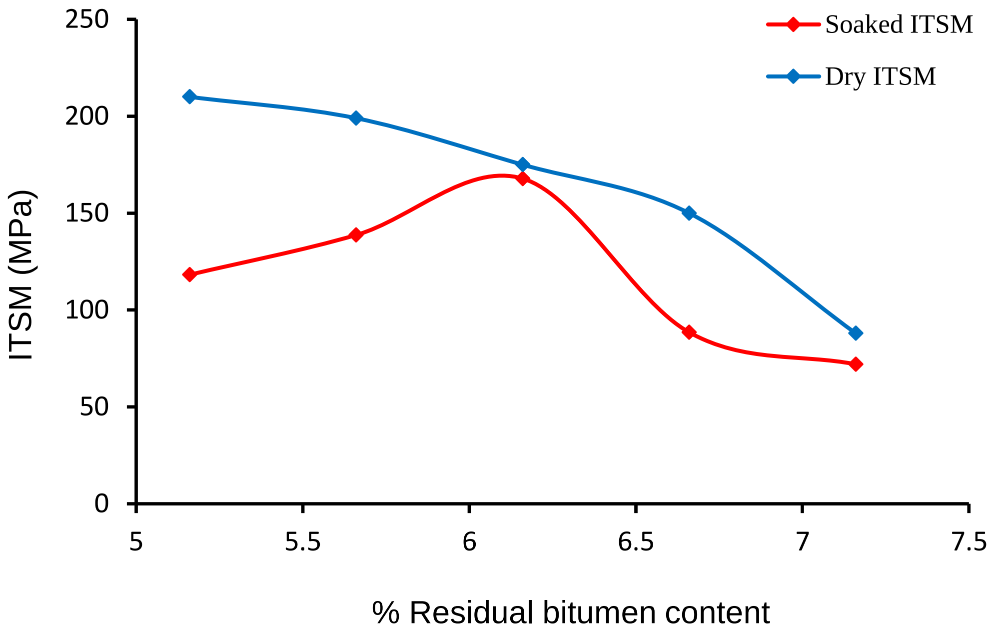


Figure 4.3: Optimum residual emulsion content

4.3 Indirect Tensile Stiffness Modulus Test

The stiffness modulus of a mixture indicates the ability of this mixture to distribute the loads and thus reduce stress concentration into the bituminous layer and on the underlying layers (Dulaimi, 2017). The indirect tensile stiffness modulus test is the common means of measuring this property of bituminous mixtures in the UK (Wu, 2009). Apart from being inexpensive, the test is simple and can be quickly conducted in comparison with the other traditional means of testing stiffness modulus of bituminous mixtures. Brown (1995) reported that up to 100 samples can be tested for ITSM in a working day. Another benefit of this test is that it allows cylindrical samples, usually either 100 or 150 mm in diameter, to be tested. The test sample does not need to be long, typically 30 to 80 mm, which is convenient when coring pavements. The effect of using fibre reinforcement on stiffness modulus in CBEM is investigated in this section. The reason for presenting such results and analysis is to find the importance of using natural and synthetic fibres as reinforcing materials in understanding and evaluating the stiffness of the bituminous mixtures.

4.3.1 Fibre Optimisation

An optimisation process was carried out to determine the optimum fibre length and content to be used as a reinforcing material in CBEM. The indirect tensile stiffness modulus (ITSM) is regarded as key when evaluating the effect of different fibre lengths and contents on CBEM performance, taking into account the effect of curing time and condition. Based on the literature (Al-Hdabi et al, 2014; Al-Hdabi, Al Nageim and Seton, 2014b; Dulaimi et al, 2016; Dulaimi et al, 2017a), this test is used to optimise CBEM additives. Figure 4.4 - 4.7 show that ITSM initially increases then decreases, with increased fibre content, for all fibre lengths and types. The CBEM reinforced with 0.35% fibre content by weight of dry aggregate, had a higher ITSM than the other mixtures for all fibre lengths. This is in agreement with other researchers such as Chen et al (2009) and Xu, Chen and Prozzi (2010) who recommended that the optimum fibre content should be between 0.3% and 0.4%, based on the results from similar tests. 14 mm long fibres, cured for 2 days, developed the ITSM of the reinforced CBEMs to the maximum value. Accordingly, the desirable mechanical responses in terms of ITSM were defined as being a maximum to achieve the highest performance. This indicates that the reinforced mixture with 14 mm fibre length and 0.35% content adheres well to the bitumen (Abiola et al, 2014). According to Liu, Cheng and Chen (2017) and Shanbara, Ruddock and Atherton (2018b), short fibres (10 mm) cannot properly reinforce mixtures that have a larger size of aggregate (maximum 14 mm) while long fibres (longer than the maximum size of the aggregate) can lead to a reduction in mixture strength, because these fibres tend to lump together during the mixing process. The results found here were similar to those found in the literature (Jeon et al, 2016). Because of the use of an appropriate length of fibre (14 mm in this research), the placement and distribution of this fibre in the bituminous mixture produced an enhanced interlocking between the fibre and the paste. Hence, the lateral strain will be delayed corresponding to improving the strength of mixture (Saeid, Saeed and Mahdi, 2014).

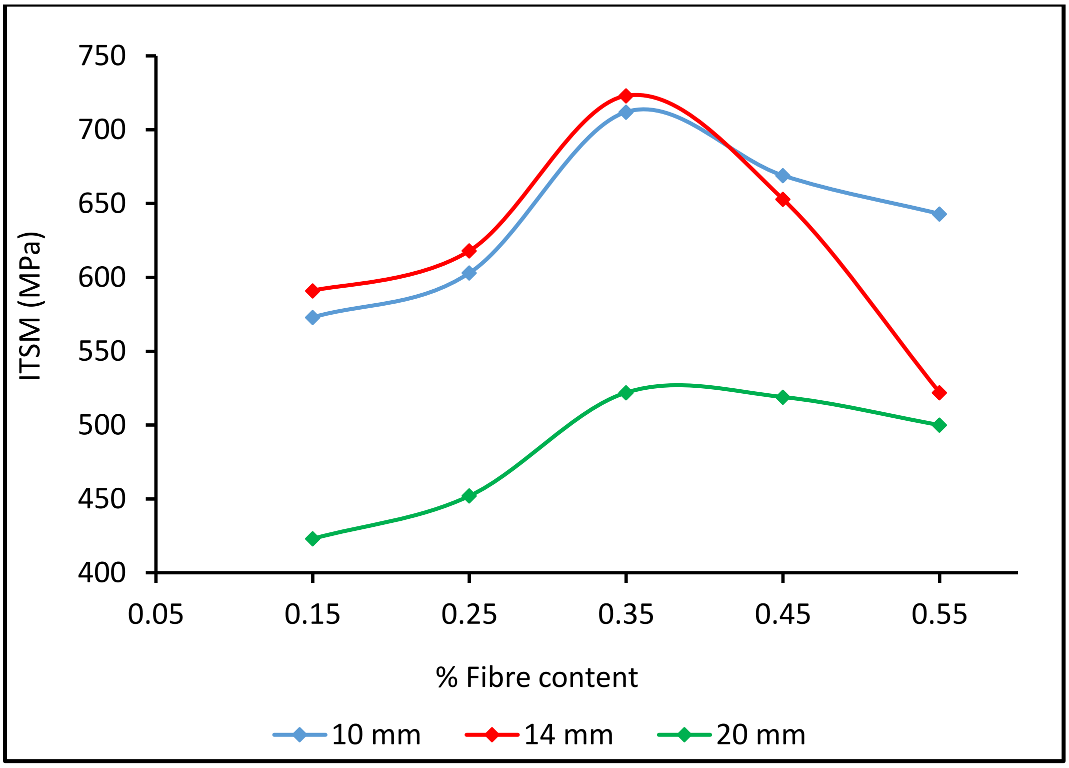


Figure 4.4: Glass fibre optimisation at 20 °C after 2 days

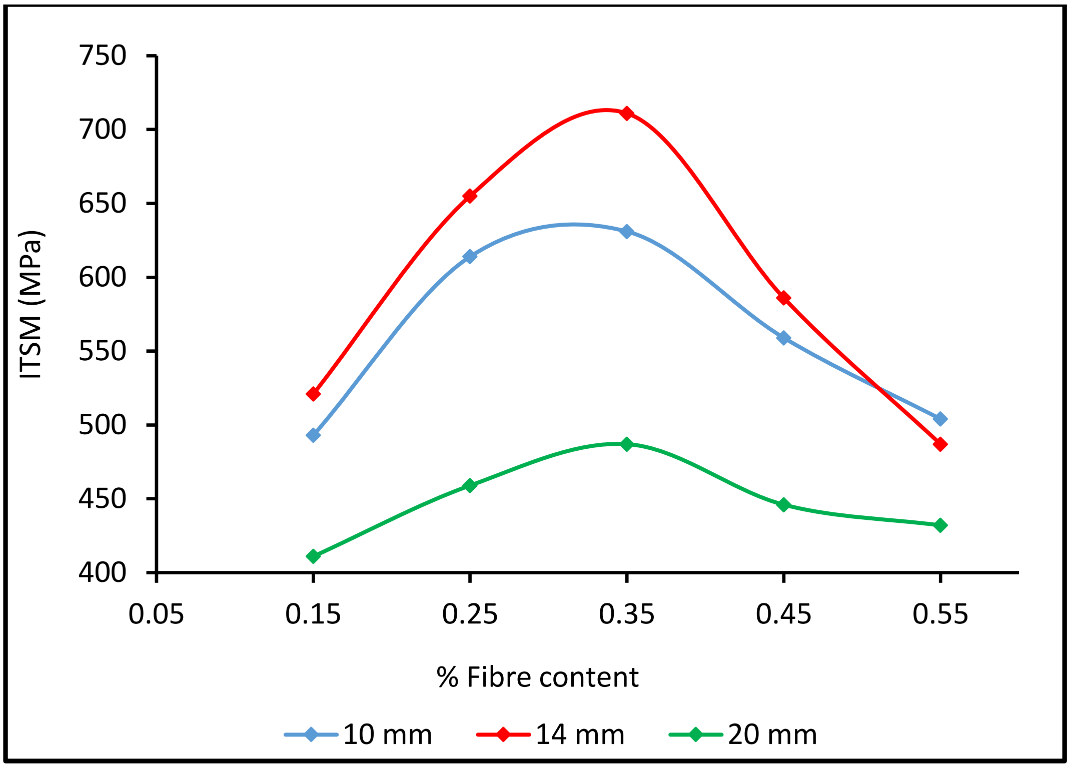


Figure 4.5: Hemp fibre optimisation at 20 °C after 2 days

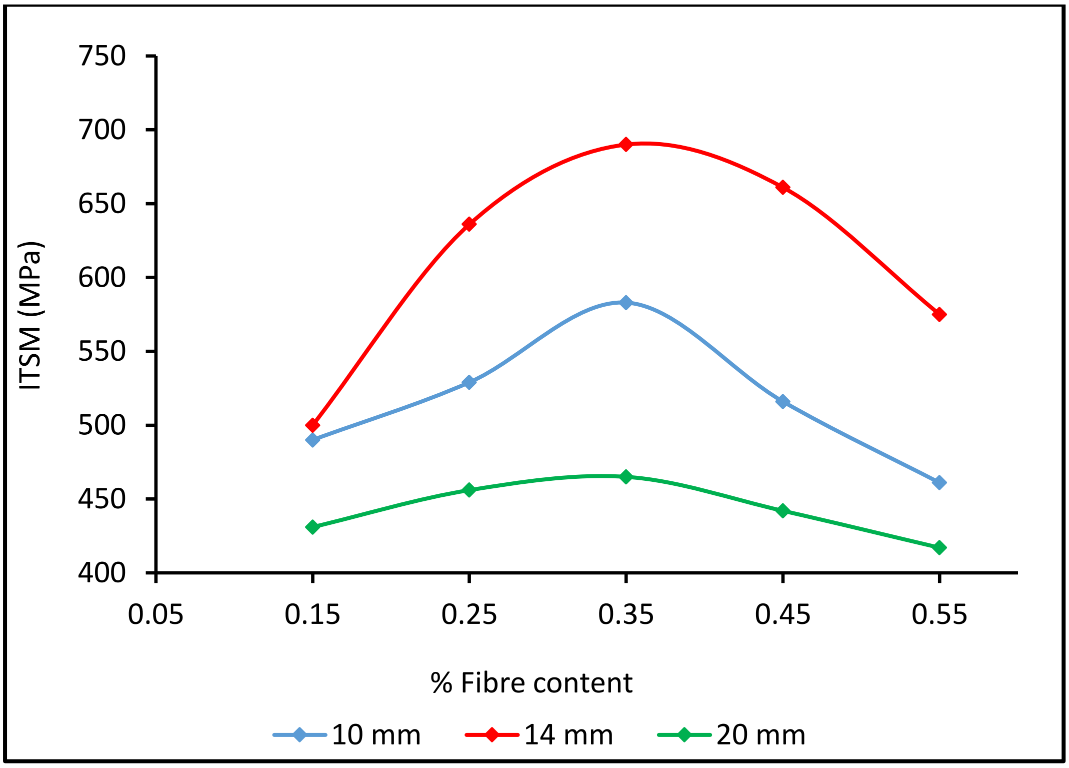


Figure 4.6: Jute fibre optimisation at 20 °C after 2 days

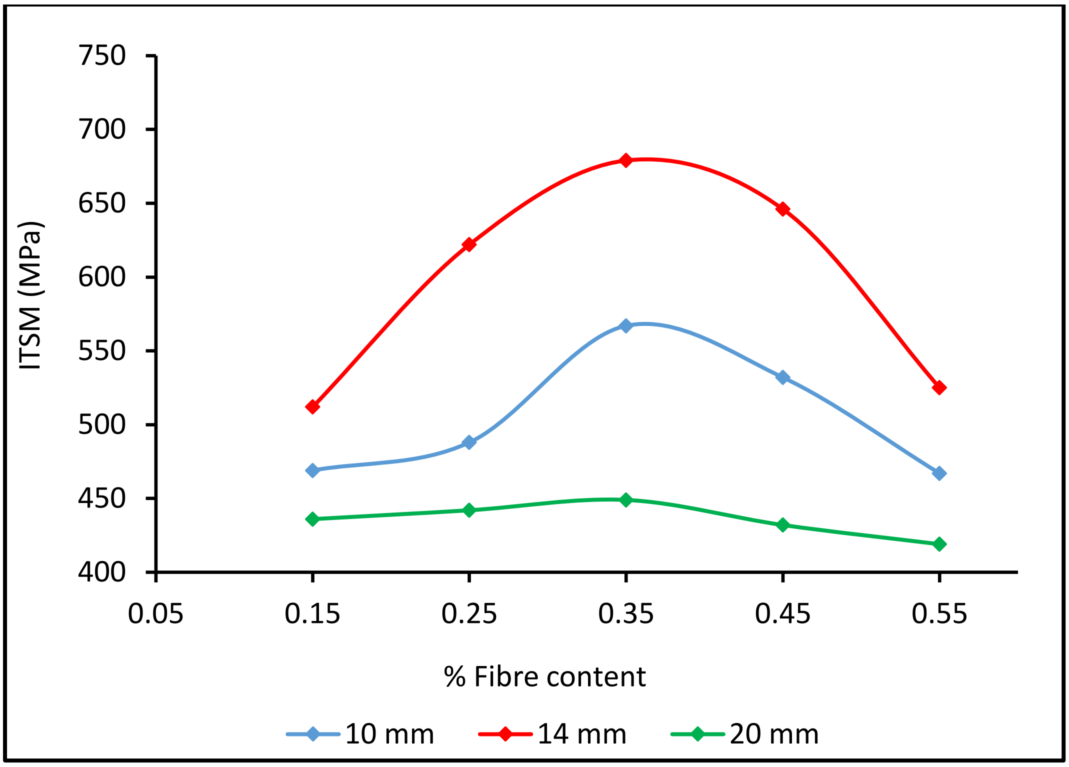


Figure 4.7: Coir fibre optimisation at 20 °C after 2 days

4.3.2 Fibre-reinforced Cold Mix Asphalt

According to the European Committee for Standardization (European Committee for Standardization - Part 26, 2012), ITSM test is used to rank bituminous mixtures on the basis of stiffness, as a guide to relative performance in the pavement, to obtain data for estimating the structural behaviour in the road and to judge test data according to specifications for bituminous mixtures. The results of the ITSM tests are shown in Figure 4.8 for both reinforced and unreinforced CBEMs. The results for HMA are also presented for comparison purposes. Each set of specimens was tested at various curing times (2, 7, 14, 28, 90, 180 and 360) days. The results indicate that average stiffness modulus values increase significantly, with curing time, at early to medium ages (2 to 28 days), followed by a reduction in the rate of increase due to reaching a definitive level, this was achieved after about 28 days of curing. This behaviour is attributed to the bitumen emulsion emitting volatile components, allowing the CBEMs to be cured and reach their final strength (Ferrotti, Pasquini and Canestrari, 2014). The HMA presents no significant change in stiffness modulus over time (Al-Hdabi, Al Nageim and Seton, 2014b; Dulaimi et al, 2017c). It can also be seen from Figure 4.8 that the significant development in ITSM specifically depends on the fibres as these provide a three-dimensional reinforcement for the CBEMs (Chen and Xu, 2010; Xu, Chen and Prozzi, 2010; Abiola et al, 2014; Ferrotti, Pasquini and Canestrari, 2014; Vale, Casagrande and Soares, 2014). Therefore, the stiffness modulus of CBEMs, reinforced with natural and synthetic fibres, reached or exceeded the stiffness of HMA at between 40 and 80 days, depending on the fibre type. Conventional (unreinforced) CBEM still has low stiffness in comparison to HMA, after one year of curing. For all types of fibre, the reinforced CBEMs provide almost the same, or slightly higher, stiffness modulus compared to the HMA mixture, over medium curing times (28 to 90 days). This means that roadwork activities should be able to guarantee adequate performance in a short to medium time after construction, if natural and synthetic fibre-reinforced CBEMs are used. When it is possible to have a longer curing time, the natural and synthetic fibre-reinforced CBEMs are able to ensure higher performance, significantly exceeding the performance of the HMA mixture.

During development of the stiffness modulus over time, it can be observed that the CBEMs with natural and synthetic fibres had higher stiffness modulus than the conventional CBEM over the entire period of time, which exceeded 1000 MPa after 28 days of curing and exceeded 2000 MPa after 360 days. Contrary, the conventional CBEM had the lowest stiffness modulus, which was slightly above 750 MPa after 360 days of curing.

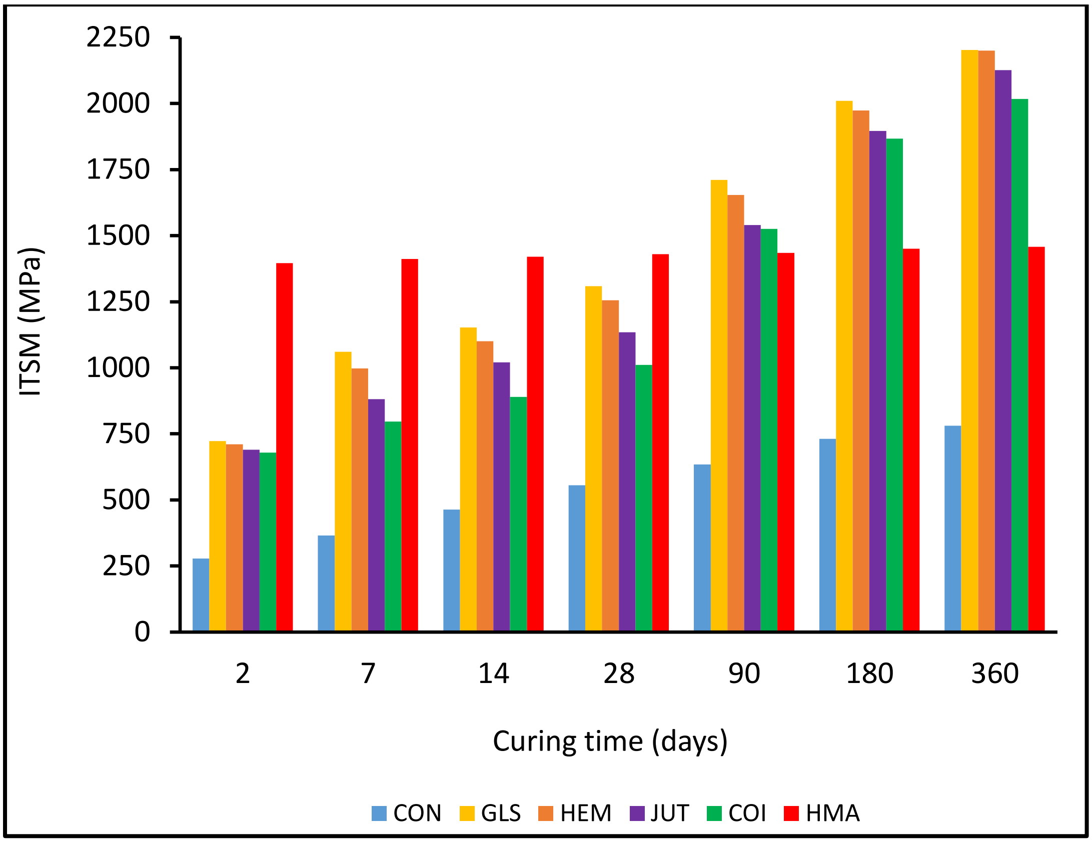


Figure 4.8: Effect of curing time on stiffness modulus

Regarding the range of curing times investigated, the increase in ITSM value as a function of curing time (t), can be represented with a logarithmic regression, according to the following Equation 4.3:

$$ITSM = a\ln(t) + b \qquad 4.3$$

Where a and b are regression parameters. Parameter a represents the time development coefficient of the ITSM and parameter b is a constant representing the initial ITSM of the mixtures. For each set of specimens, the regression parameter values are reported in Table 4.1, together with the corresponding R^2 (correlation coefficient squared). From this table, the time development coefficient (a) of the HEM has the highest value indicating the ITSM of such a mixture has the best time development. On the other hand, the lowest time development coefficient was observed in HMA. That means there was no effect of curing time on the ITSM of such mixture (Figure 4.9). According to the values of the constant parameter (*b*), the HMA has the highest value indicating the high initial ITSM of this mixture, whilst CON has the lowest *b* value indicating the low initial ITSM.

Table 4.1: Logarithmic regression parameter values

Mixture type	a	b	R^2	Regression equation
CON	100.07	198.49	0.99	$100.7\ln(t) + 198.49$
GLS	287.91	457.66	0.98	$287.91\ln(t) + 457.66$
HEM	290.16	410.59	0.97	$290.16\ln(t) + 410.59$
JUT	284.33	344.32	0.96	$284.33\ln(t) + 344.32$
COI	281.88	281.23	0.93	$281.88\ln(t) + 281.23$
HMA	11.51	1388.9	0.98	$11.51\ln(t) + 1388.9$

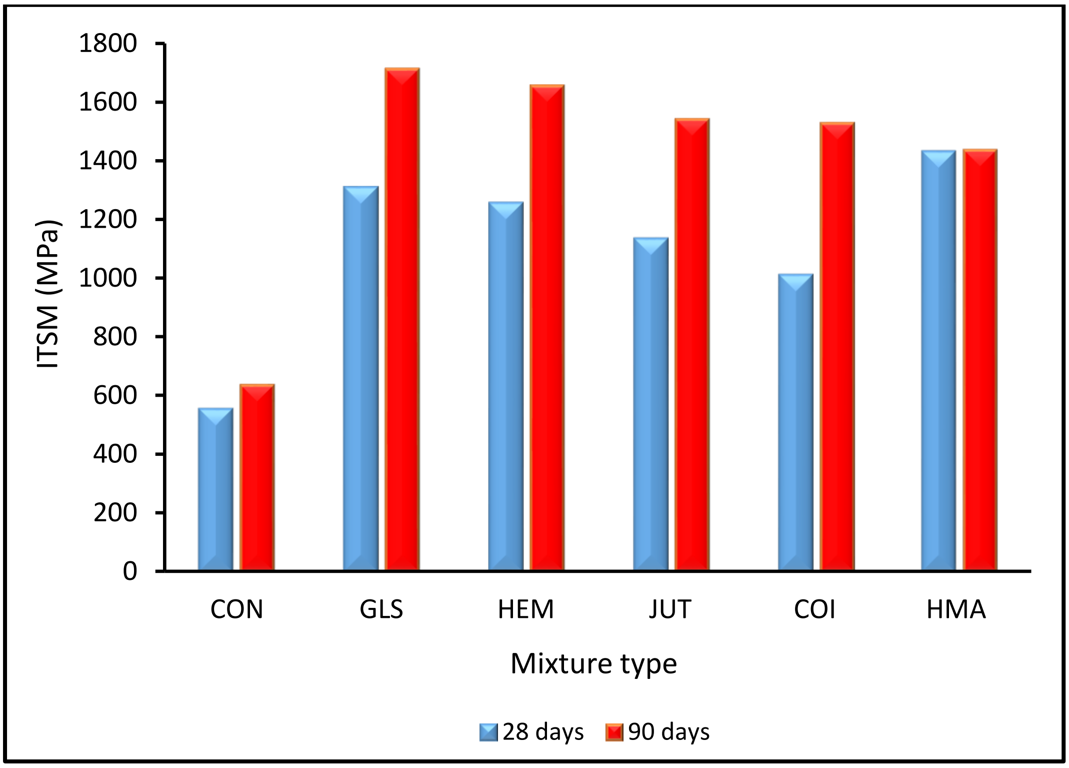


Figure 4.9: Stiffness modulus after 28 and 90 curing days

4.3.3 Temperature Sensitivity

Discovering the temperature susceptibility of bituminous materials is required in order to have a good knowledge of such materials in service under extreme conditions. Naturally, bitumen is a temperature susceptible material, i.e. it becomes brittle at low temperatures and gets increasingly less viscous and ready to flow at high temperatures. According to this behaviour, such materials are susceptible to cracking at low temperatures, while they are susceptible to rutting at high temperatures. A properly designed bituminous mixture should be able to resist these extreme environmental conditions without necessarily reducing the overall structural integrity of the road pavement. An attempt was thus carried out to find the thermal susceptibilities of the six bituminous mixtures. Indirect tensile stiffness modulus of the conventional CBEM and HMA, as well as the reinforced CBEMs with natural and synthetic fibres CBEMs after 28 days of curing at 20 °C was performed at different testing temperatures, namely 5 °C, 20 °C, 45 °C and 60 °C to evaluate the thermal sensitivity of such mixtures. Sunarjono (2008), Nassar (2016) and Dulaimi (2017) reported that measurements of ITSM could also be used as an indicator of the quality of bituminous mixtures in terms of temperature sensitivity. The stiffness modulus of all mixtures decreased with the increase of testing temperature as seen in Figure 4.10. The decreasing rate in the ITSM can indicate that the temperature sensitivity, where the higher rate of change, represents higher sensitivity to the temperature. However, in the reinforced CBEMs, the decreasing rate in the stiffness modulus decreased as compared to the conventional CBEM and HMA mixtures. Depending on the fibre type, the variation of ITSM of the reinforced mixtures with different temperatures exhibited a robust stiffness trend. Both the conventional CBEM and HMA lost around 98% and 84%, respectively of their stiffness if heated from 5 °C to 60 °C. In contrast, the range of loss in stiffness of the reinforced CBEMs was between 70% to 75% depending on fibre types. The decrease in the stiffness modulus of the reinforced mixtures, i.e. GLS, HEM, JUT and COI indicates that these mixtures are more thermally stable and they have less susceptibility to the temperature change, specifically hot temperatures. This is considered as a positive point in terms of bituminous mixtures' performance in hot weather, decreasing their tendency to high temperature rutting. Additionally, these mixtures are less likely to suffer from low temperature cracking. Using fibres as reinforcing materials in CBEM ensures better stiffness properties at high and moderate temperatures.

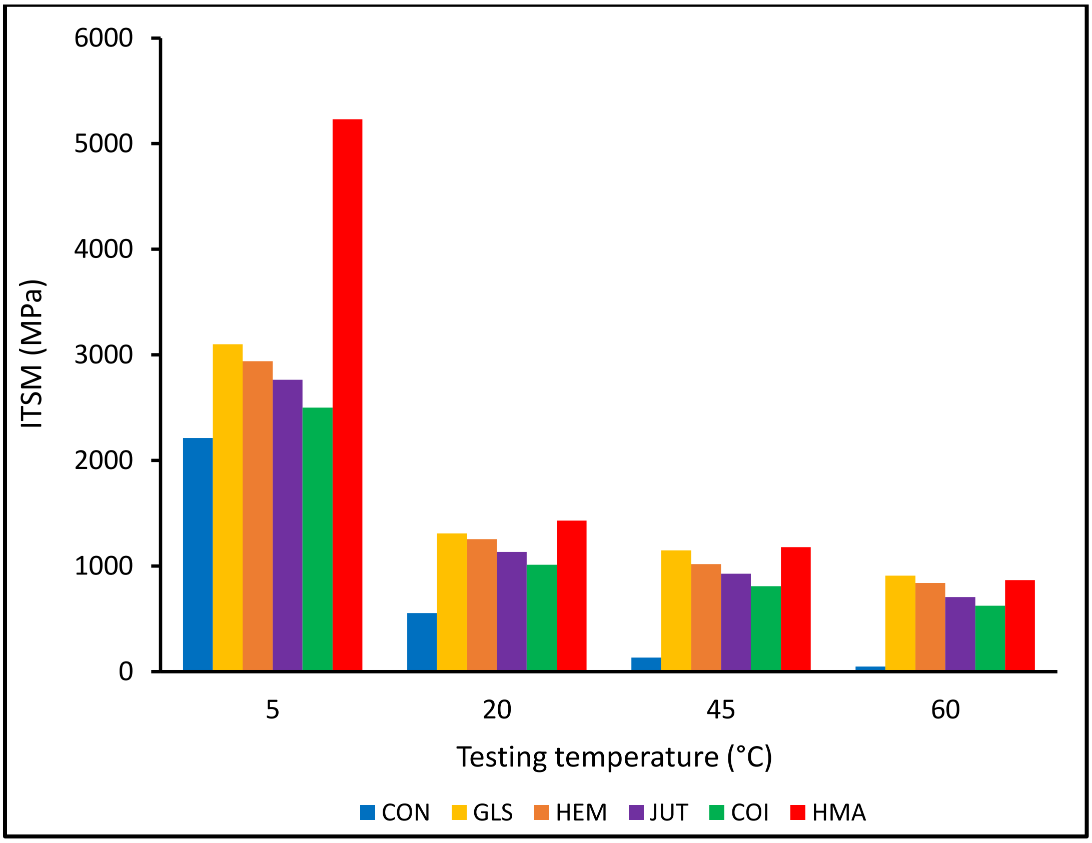


Figure 4.10: Stiffness modulus under different temperatures

4.4 Rutting

In addition to the stiffness modulus, the other factor to evaluate the bituminous mixtures is the permanent deformation or rutting. Surface layers of flexible pavements are subjected to continuous flexing under traffic loading that generates repeated stresses, and accordingly strains. Because bitumen is a viscoelastic or viscoplastic material, application of load results in a small amount of viscous associated with plastic flow of the binder that is displayed as permanent strain. By the accumulation of many small strains on the pavement surface layers (under the action of traffic), a significant amount of permanent deformation happens. This is commonly known as rutting and is seen as depressions underneath the vehicle wheel path relative to the surrounding pavement. There are two main mechanisms, in which permanent deformation occurs, as defined in the literature due to the repeated loading. The first mechanism is the secondary compaction that results in densification of the bituminous road mixture after the initial compaction. The potential of rutting to occur can be limited if the pavement, during the construction, is properly compacted. The second mechanism is the plastic shear deformation due to the repeated action of shear and tensile stresses. In this case, mixture resistance to rutting depends on binder properties and internal friction of aggregate. Rutting is affected by the bituminous mixture properties, i.e. volumetric composition and material properties (Sunarjono, 2008; Nassar, 2016). Rutting is seen as unevenness in the road profile and if the deformations become substantial, a decrease in ride quality and even danger to the road users is ensured. As the region of maximum stress in a road is along the wheels' path, where higher deformation occurs. Whilst, rutting cannot be considered a structural failure, unless accompanied by cracking, in the UK a 10 mm rut is classed as a critical situation that requires a remedial action, while a 20 mm rut corresponds to "failure" (Needham, 1996).

In CBEMs, the effect of using natural and synthetic fibres as reinforcing materials on rutting behaviour was evaluated in the current study. Hence, two different testing temperatures (45 °C and 60 °C) were considered to simulate the moderate to heavy and very heavy stresses. This will assist to further understand the behaviour of CBEM and to raise confidence in adopting these materials in pavement design.

The test results shown in Figure 4.11 and 4.12 show the variation in accumulated rutting depth under cumulative loading cycle times at 45 °C and 60 °C, respectively. It is clear that the reinforced CBEM mixtures significantly reduced accumulated rutting (permanent deformation). The accumulated rutting in CBEM with synthetic fibre (glass) is slightly lower than that with natural fibres at both test temperatures. If compared with conventional mixture, glass, hemp, jute and coir fibres have a reduced rut depth by 766%, 636%, 610%, and 462%, at 45 °C after 20000 wheel passes (28600 seconds), respectively. These figures also show that at the initial stage of the test, there is a rapid increase in rutting induced by the consolidation of the mixtures under the vertical pressure of wheel loading (Xu, Chen and Prozzi, 2010). It was observed that after a certain number of load repetitions a negligible change in rate of rutting depth was produced. This is mainly attributed to the high shear strength of the reinforced CBEMs under shear stress (Chen and Xu, 2010; Xu, Chen and Prozzi, 2010). At this stage, the increase in the rate of rutting depth with time tends to be almost negligible, indicative of the high stiffness modulus of the bituminous mixture. In contrast, the development of rutting for the conventional CBEM is initially faster, followed by a gentle decrease. The faster the rutting development rate, the earlier the road pavement enters into its failure stage (Zhang et al, 2017). In this case, it is highly probable that the serviceable life of bituminous pavements might be shortened.

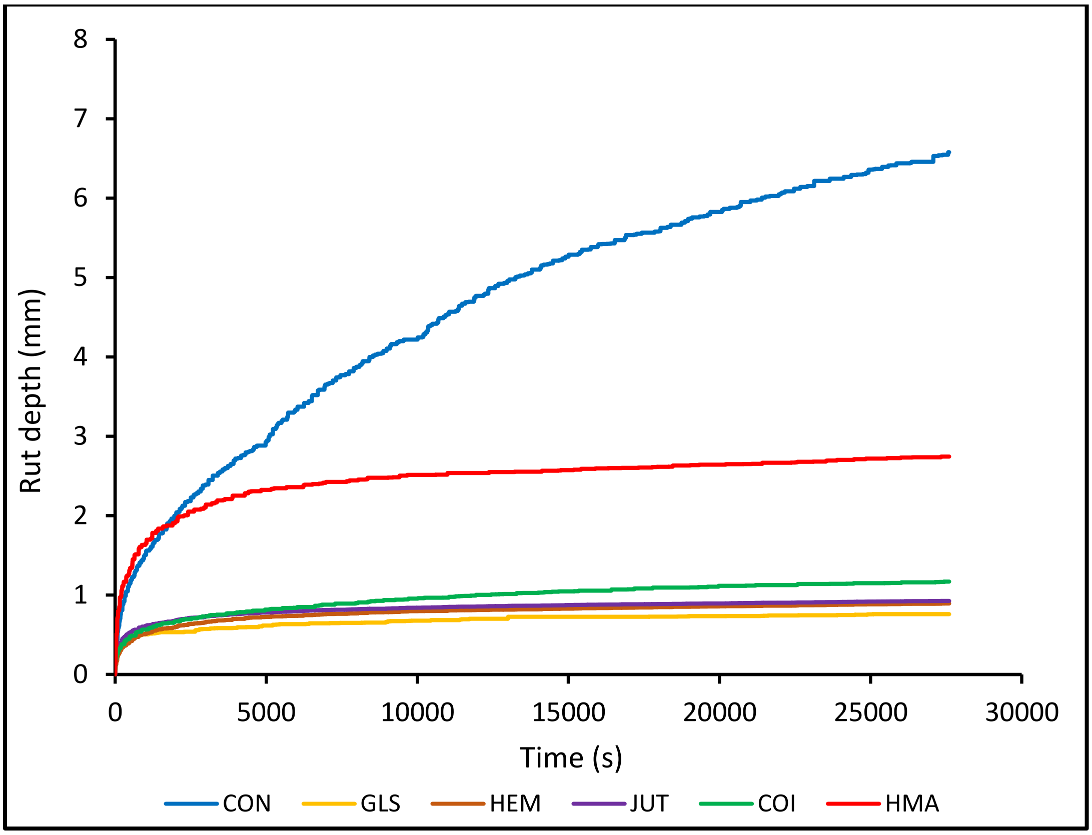


Figure 4.11: Rut depth at 45 °C

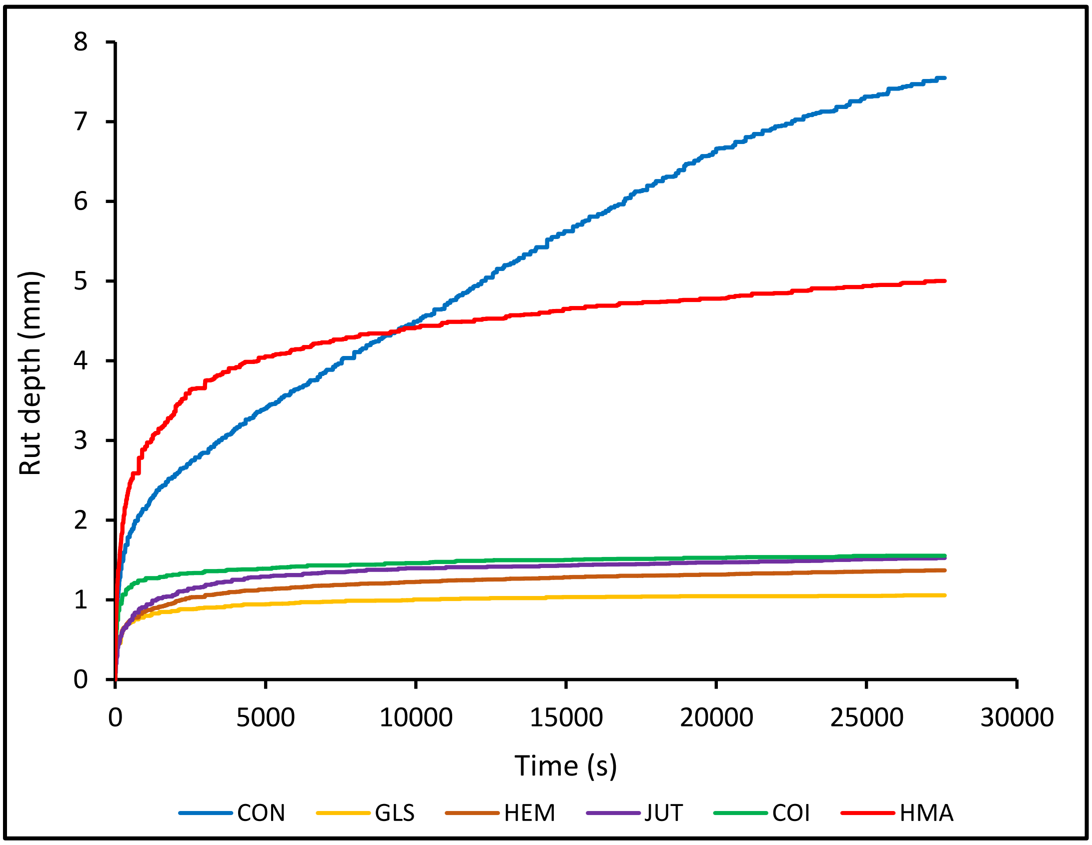


Figure 4.12: Rut depth at 60 °C

The significant reduction in rutting depth of the reinforced CBEMs could be partially due to the ability of the fibres to stabilise and hold the bitumen on their surface, thus resisting the flow of bitumen at high temperatures (Chen and Xu, 2010). The fibres form a three-dimensional network in the bituminous mixture, thus reinforcing the skeletal structure, resisting shear and tensile stresses and reducing fluidity (Chen and Xu, 2010; Xu, Chen and Prozzi, 2010). In summary, the analysis of rutting depth indicates that the mixtures containing natural and synthetic fibres significantly reduce rutting depth in comparison to conventional cold and hot mixtures.

4.5 Fibres Microstructure Characteristics

The scanning electron microscopy (SEM) of fibres, shown in Figure 4.13 – 4.16, reveals both the shape of the fibres and their surface roughness characteristics. Figure 4.13 shows SEM images of the glass fibre where it is seen that the surface area has some protrusions resulting in a rough surface texture that can enhance the interlock between the mixture and fibres (Monich et al, 2017). Figure 4.14 shows the surface morphology of the jute fibre. This fibre has an uneven surface with irregularities (more surface area), rough cavities on its outer surface and some voids. The presence of these cavities could improve the quality of the fibre/mixture interface (Maache et al, 2017). The surface of the hemp fibre (Figure 4.15) is observed as a rough surface with strip protrusions, which provide good structural stability. The SEM images of coir fibres, presented in Figure 4.16, show a uniform fibre formation. There are however, small irregularities on the fibre surface that create an irregular morphology. This fibre has globular particles that show as protrusions fixed in specific pits of the fibre surface area. The rough surface area of these fibres can improve the interlock between the mixture and fibres (Silva et al, 2011; Sheng et al, 2017).

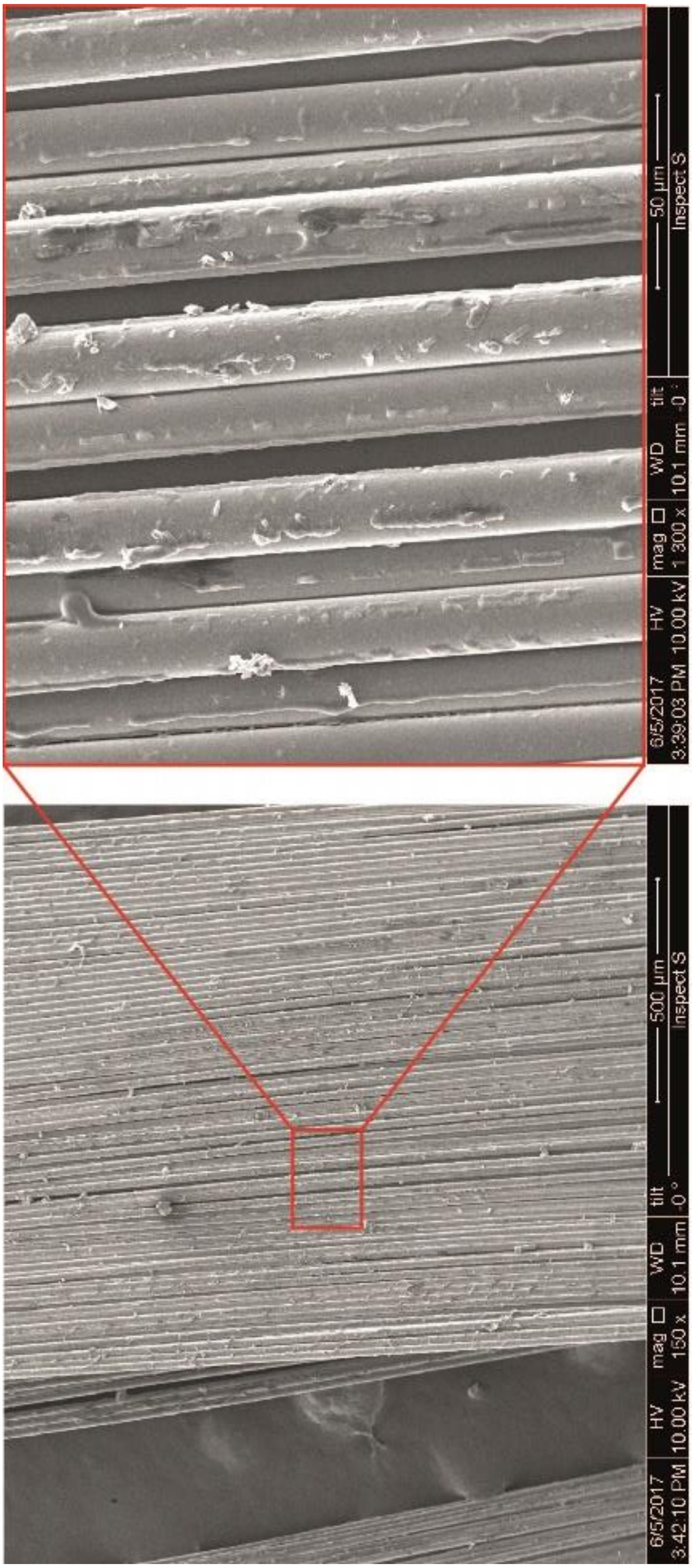


Figure 4.13: Glass fibre and its microstructure

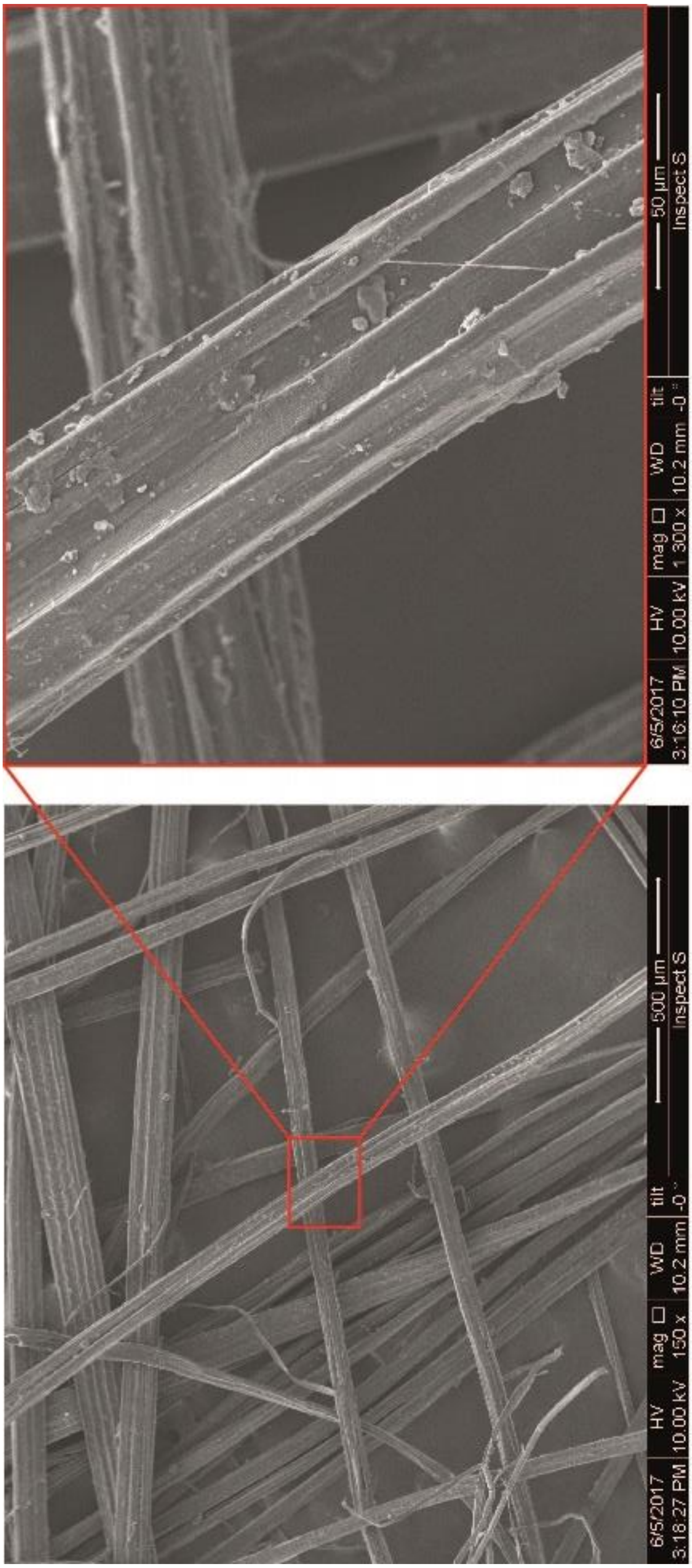


Figure 4.14: Hemp fibre and its microstructure

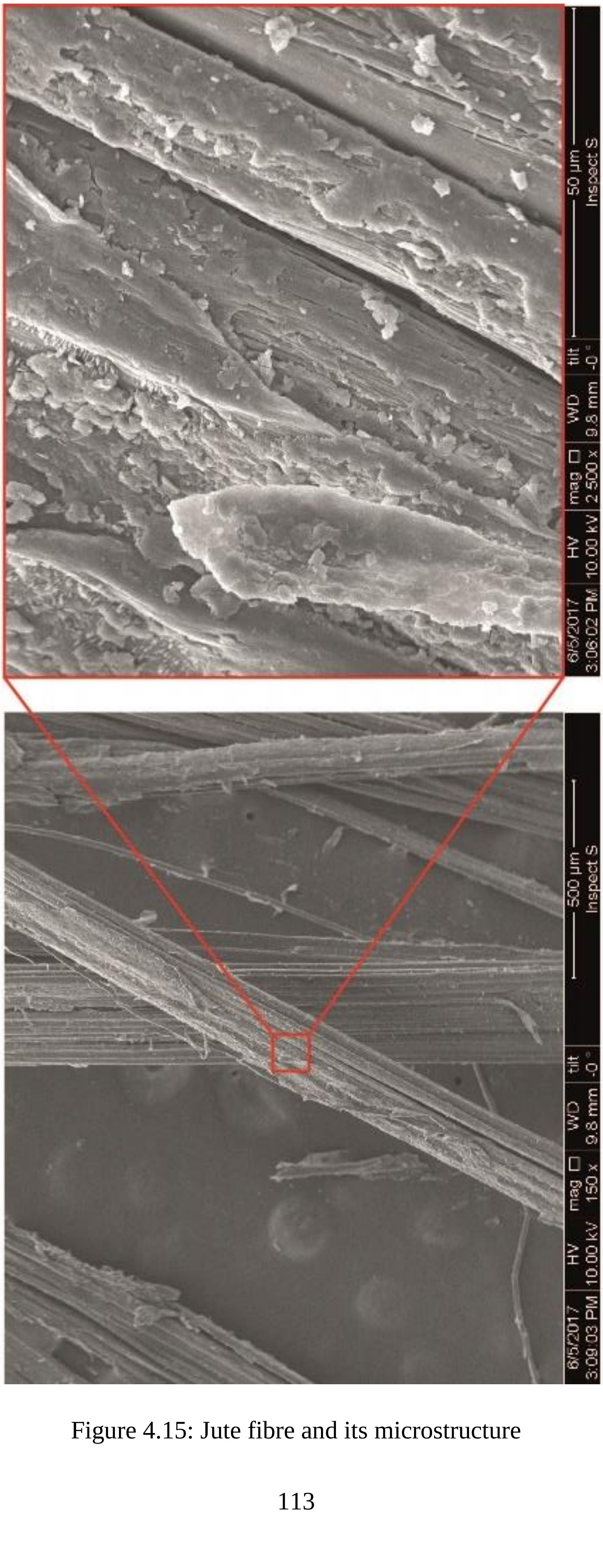


Figure 4.15: Jute fibre and its microstructure

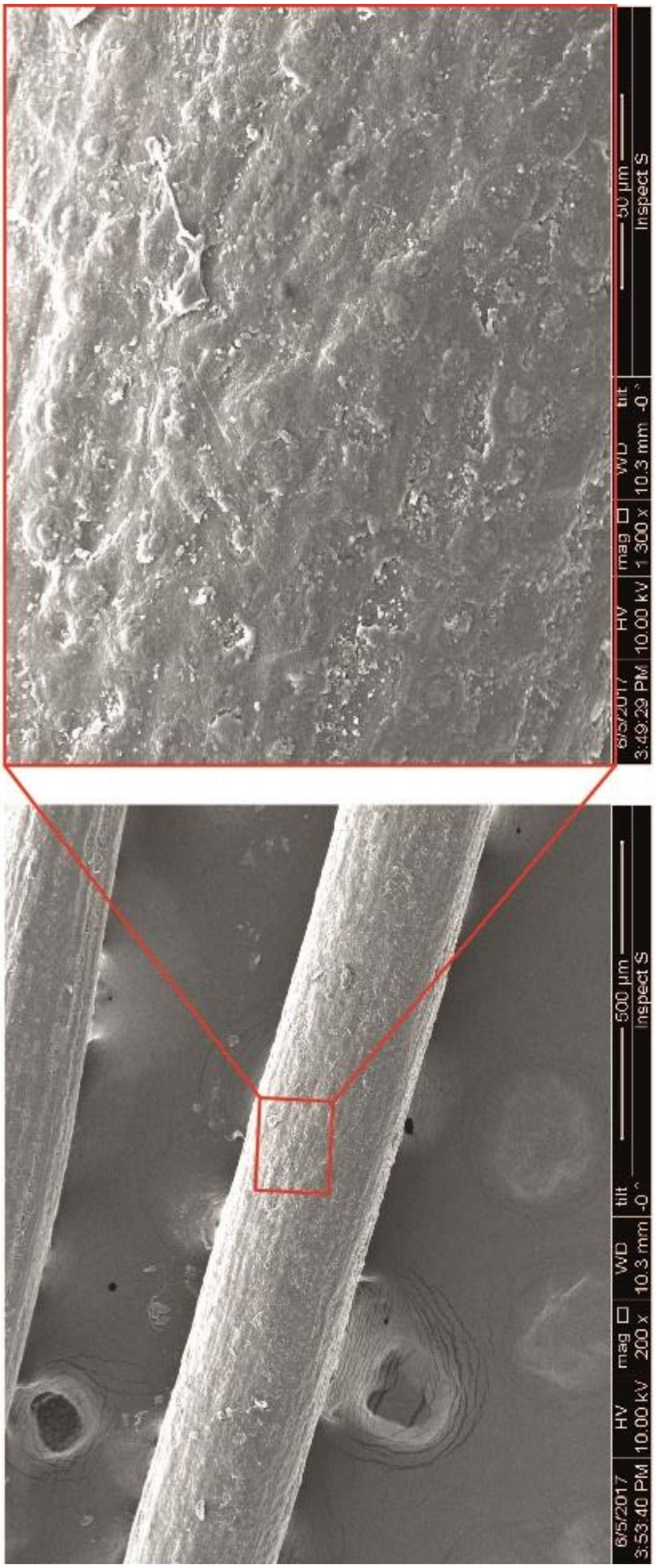


Figure 4.16: Coir fibre and its microstructure

4.6 Water Sensitivity

The evaluation of water damage is an important factor because of the direct effect on the performance and service life of flexible pavements (Vale, Casagrande and Soares, 2014; Sun, 2016a). More importantly, moisture susceptibility of bituminous materials is generally agreed among researchers as an indicative factor of predicting the durability of bituminous mixtures while in service. The existence of moisture in the bituminous mixtures is considered to develop stripping. The results of the water sensitivity test revealed that all the natural and synthetic fibres significantly improved the moisture resistance of the CBEMs. Figure 4.17 shows that the addition of fibres increased the value of *SMR*. The mixtures with glass and hemp fibres show *SMR* values approximately the same as HMA mixtures. The CBEMs with natural and synthetic fibres have better *SMR* values in comparison to the conventional CBEM. It is worth noting that the improved cohesion of the reinforced mixtures is the main reason for the improvement in performance against water action (Abtahi, Sheikhzadeh and Hejazi, 2010; Xu, Chen and Prozzi, 2010; Abiola et al, 2014; Ferrotti, Pasquini and Canestrari, 2014).

Higher percentages of retained reinforced stiffness modulus were observed in mixtures reinforced with fibres after undergoing the water sensitivity test. This indicates that in the case of emergency maintenance, cold mixtures can be applied in wet conditions.

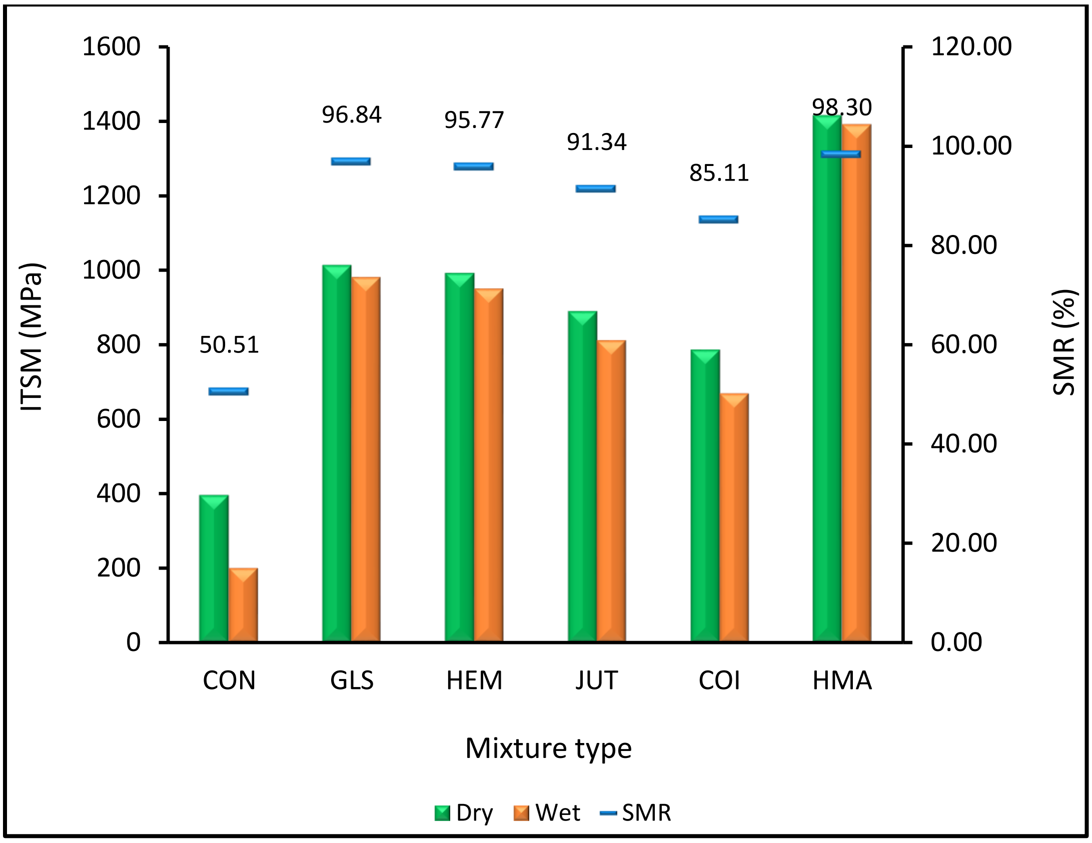


Figure 4.17: Water sensitivity results

4.7 Semi-circular Bending

The monotonic semi-circular bending (SCB) test was performed to determine the fracture toughness of the conventional CBEM, reinforced CBEM and HMA mixtures. It is shown in Figure 4.18 that all natural and synthetic fibres have improved the fracture toughness of the CBEMs. The fracture toughness of the mixtures reinforced with glass and hemp fibres have a superior performance in comparison to the others. The increasing in the fracture toughness ranged approximately from 11.5 to 20 $N/mm^{3/2}$ depend on the fibre types. For the mixtures reinforced with glass fibre, there was a considerable development of the fracture toughness and the increase was up to double compared to the value of the conventional CBEM. Such improvements in fracture toughness, in comparison to the conventional CBEM, is due to the fact that the conventional CBEM is more brittle and susceptible to material failure at low temperatures (Xu, Chen and Prozzi, 2010). Both the natural and synthetic fibres were found to be positively associated with the tensile strength of CBEMs in terms of their resistance to fracturing after crack initiation (Aliha et al, 2017). This test can be achieved using low and intermediate temperatures. At low temperatures, a crack propagates through the bitumen and aggregates and the fracture toughness (K_{IC}) is probably dependent on aggregate and bitumen properties (Somé et al, 2017). Also at low temperatures, the properties of the bitumen tend to be constant due to the elastic behaviour of the bitumen and the aggregate. Whilst, at intermediate temperatures, a crack propagates through the bitumen, which is more dependent on the test temperature due to the viscoelastic behaviour of the bitumen. Therefore, the decrease in the fracture toughness could be explained by the decrease in the specimen stiffness and especially the decrease in the bitumen stiffness when the temperature increases. This dependency of K_{IC} on the temperature reveals the need to take a viscoelastic behaviour into account (Somé et al, 2017). Accordingly, 5 °C was selected to determine the fracture toughness of HMA and CBEMs.

Figure 4.19 shows the load-displacement curve for both hot and cold mixtures. The load-displacement curves from the samples tested at 5 °C, show that the fracture behaviour of bituminous mixtures was linear under such conditions, due to the viscoelastic behaviour of bituminous mixtures at intermediate temperatures (Saeidi and Aghayan, 2016; Somé et al, 2017).

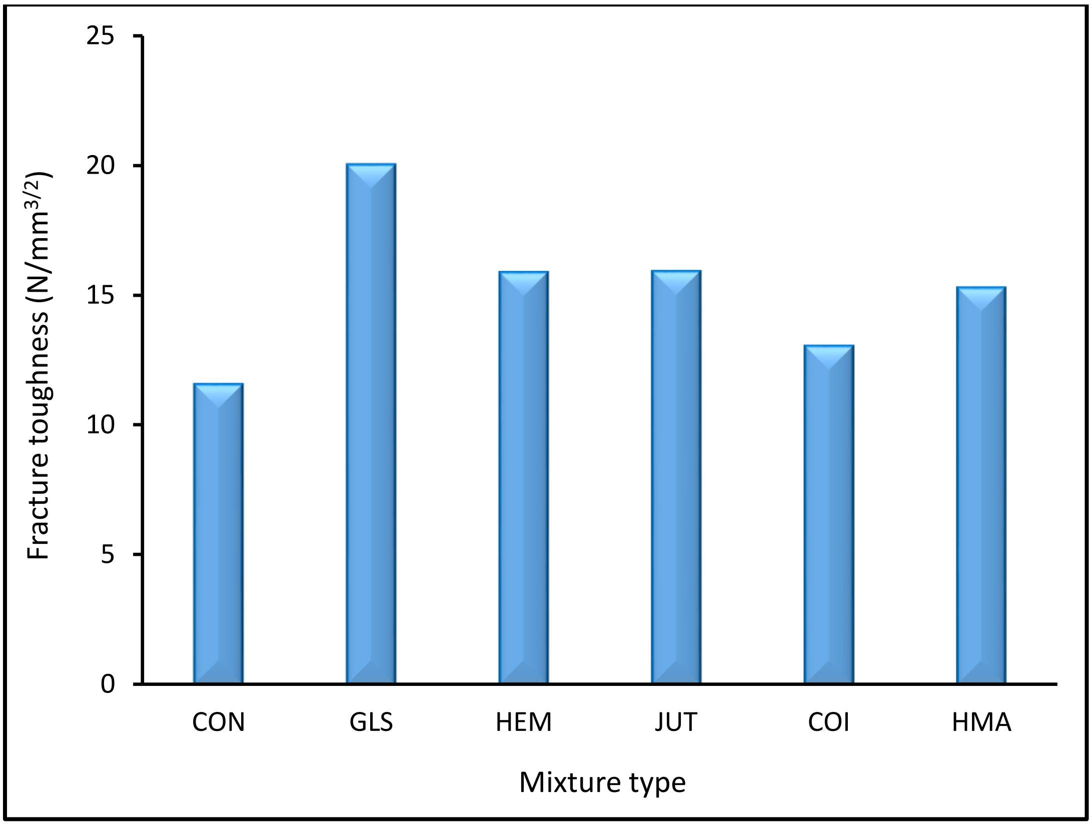


Figure 4.18: Effect of fibre-reinforced CBEM on fracture toughness

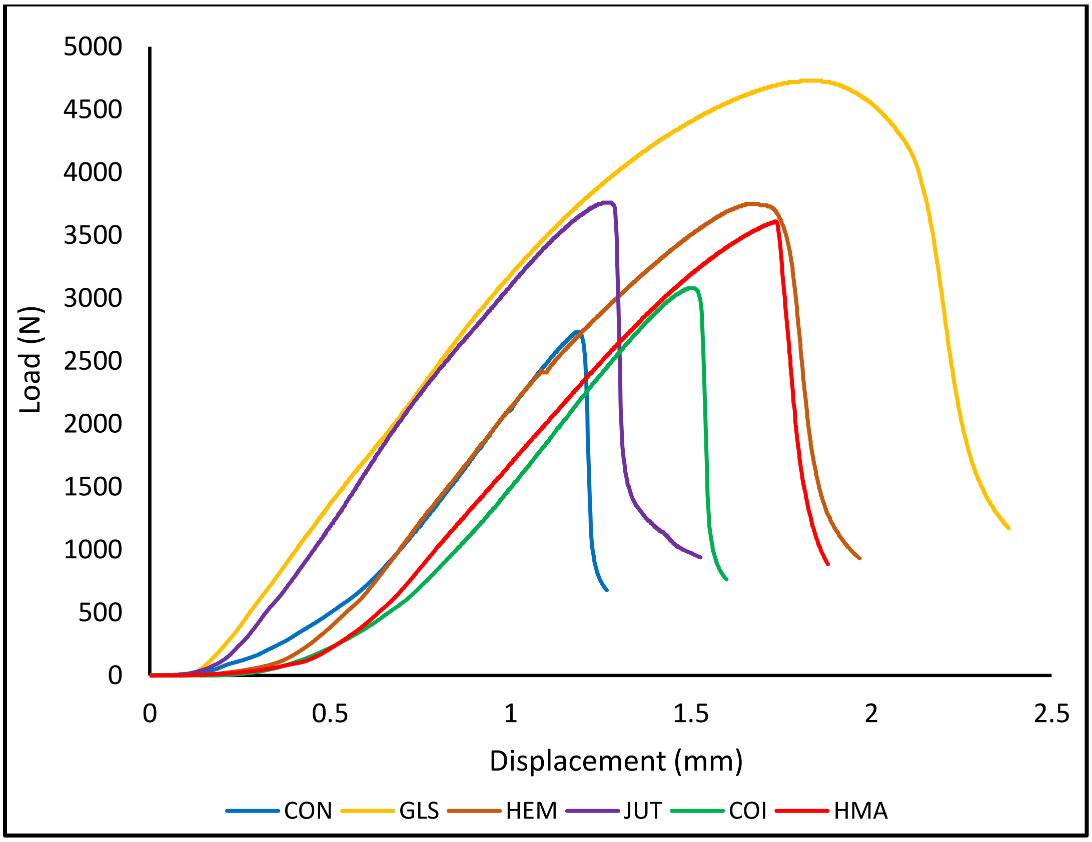


Figure 4.19: Typical load-displacement curves

4.8 Creep and Relaxation

This test, also known as unconfined creep test is normally conducted to evaluate the permanent deformation properties of bituminous mixtures. In the investigation conducted on CBEM and HMA mixtures in this work, a test temperature of 5 °C, 20 °C, 45 °C and 60 °C, and standard stress levels of 100 kPa were used. The strain of the tested specimens during the creep and relaxation stages was calculated for each mixture type. Figure 4.20 – 4.25 show the strain in one hour loading followed by one hour unloading conducted at a stress level of 100 kPa. All mixture types were tested to characterise their nonlinear behaviour for different temperatures. It can be clearly seen from these figures that the conventional CBEM and HMA mixtures have the worst creep resistance at the temperatures selected likely due to low values of stiffness, tensile and shear strength. These mixtures have larger strain and faster strain rates. Moreover, the good adhesion between the fibres and bituminous mixture helps to improve the creep resistance. Comparing the conventional CBEM and HMA mixtures and the reinforced CBEMs with different fibres, it shows that the fibres reinforcement strongly affects the accumulated strain at all temperatures selected. Therefore, when using a design of CBEM, the design should first consider how to ensure performance of asphalt pavements and its resistance to the deformation. In this test, when stress is applied (100 kPa), both the reinforced and unreinforced mixtures immediately produced transient elastic strain which continued to increase with time. The positive impact of using natural and synthetic fibres on the creep properties of CBEM, in comparison to the conventional CBEM and HMA mixtures, is demonstrated in Figure 4.20 – 4.25.

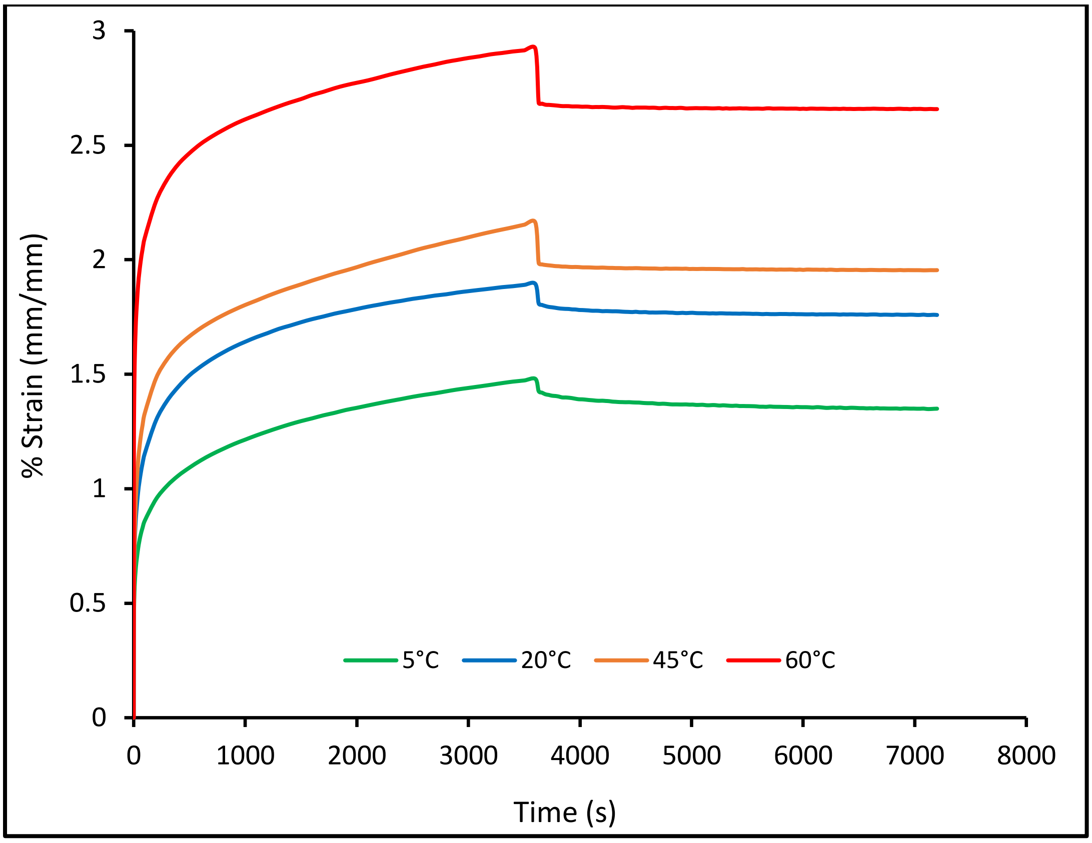


Figure 4.20: Accumulated strain versus loading time of CON mixture

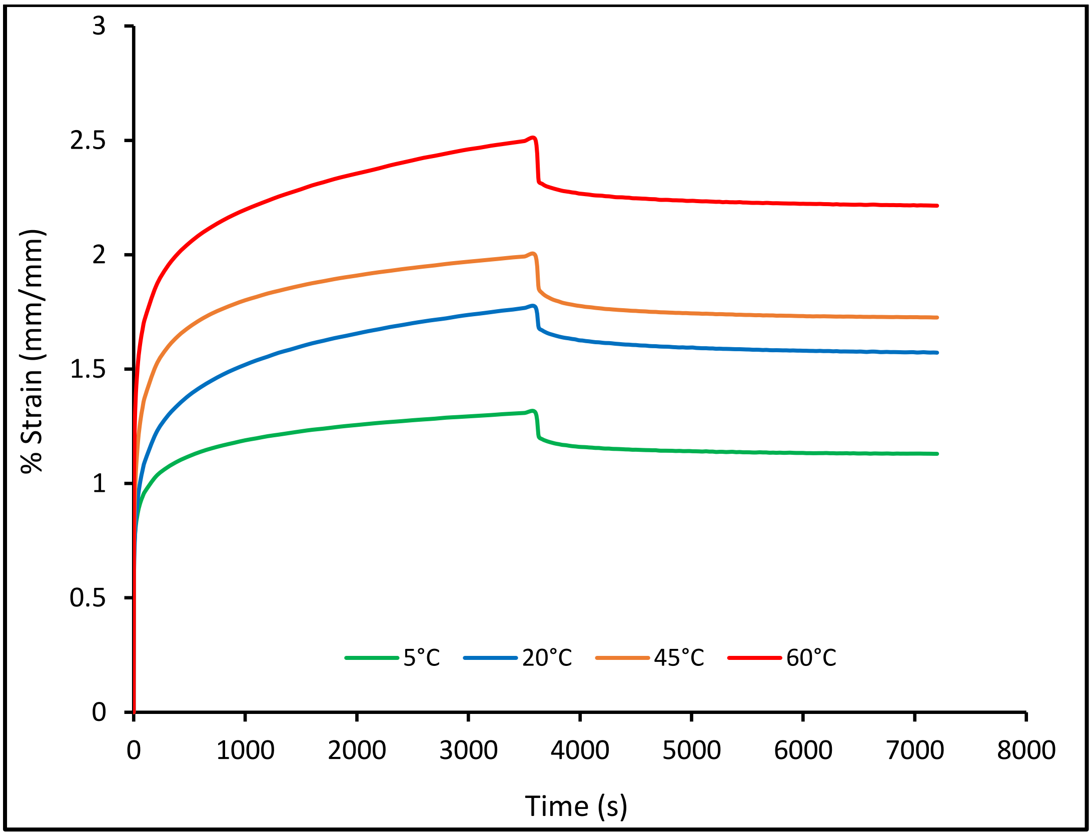


Figure 4.21: Accumulated strain versus loading time of HMA mixture

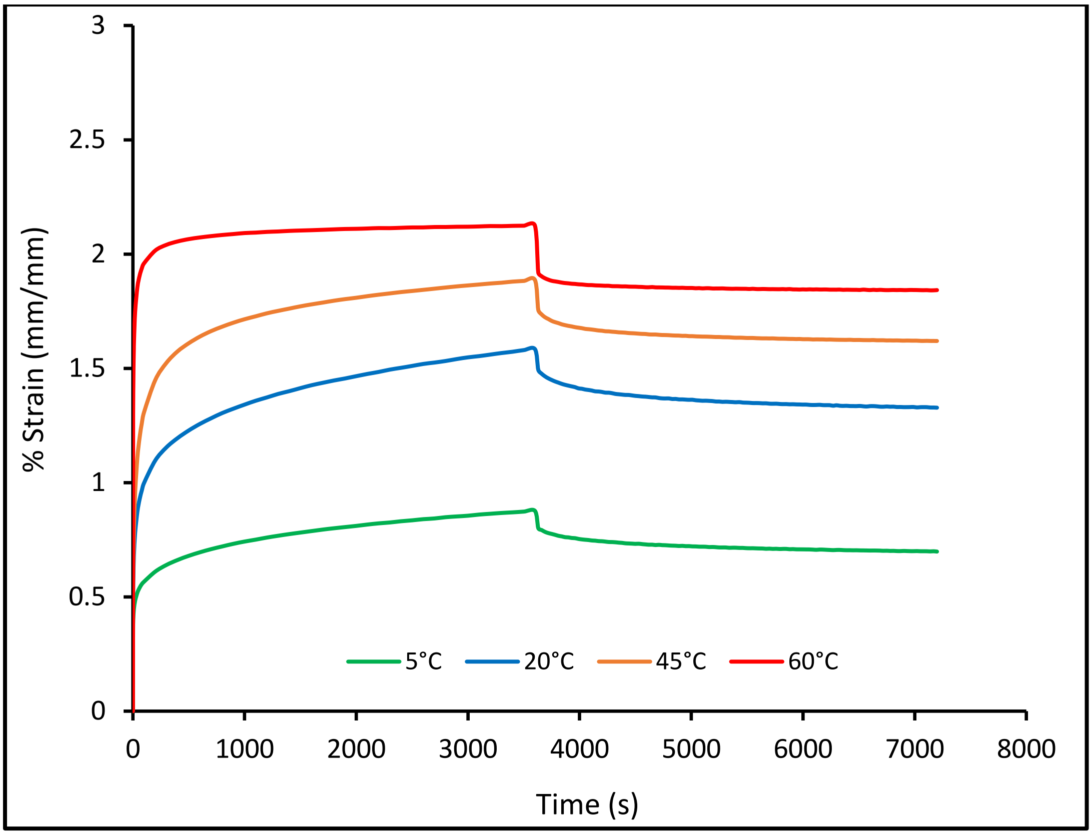


Figure 4.22: Accumulated strain versus loading time of COI mixture

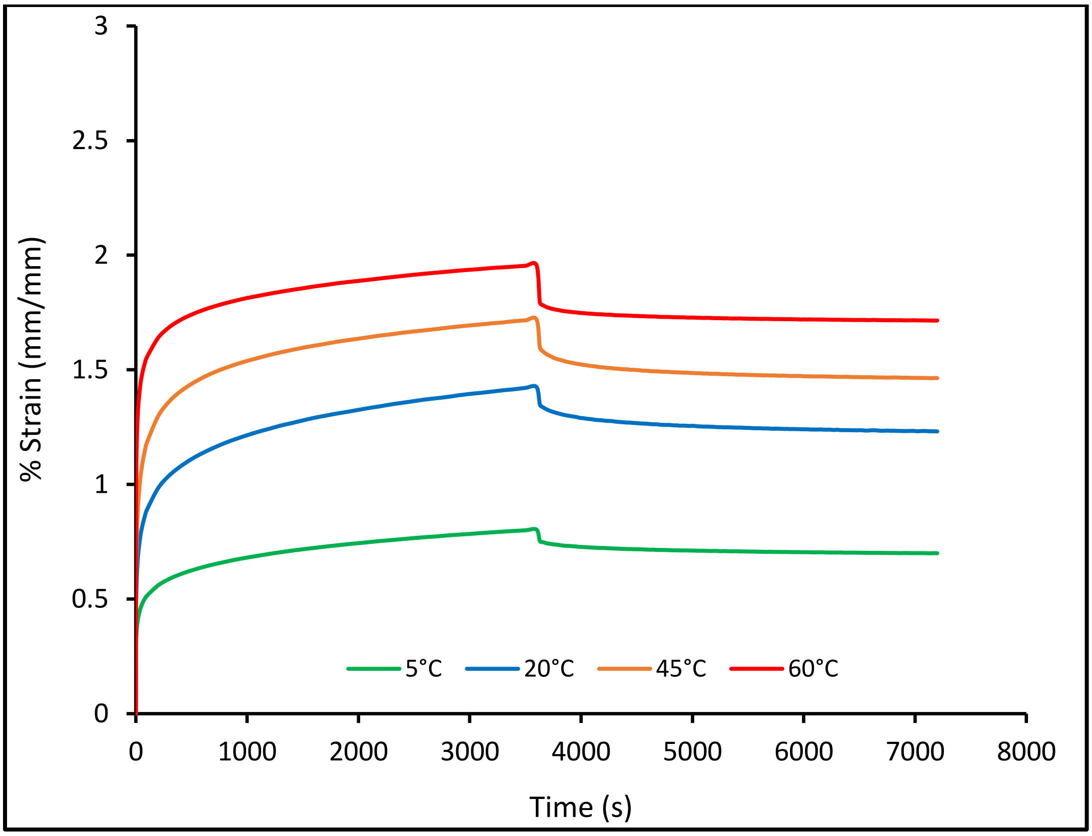


Figure 4.23: Accumulated strain versus loading time of JUT mixture

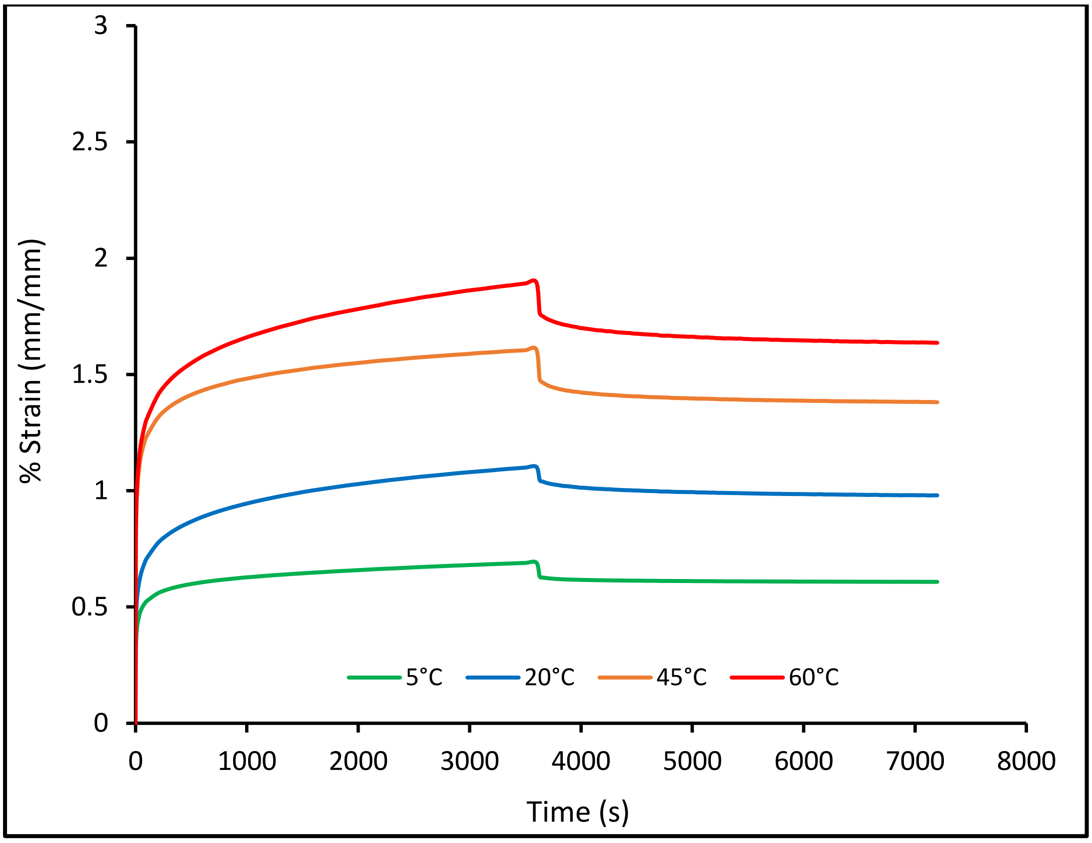


Figure 4.24: Accumulated strain versus loading time of HEM mixture

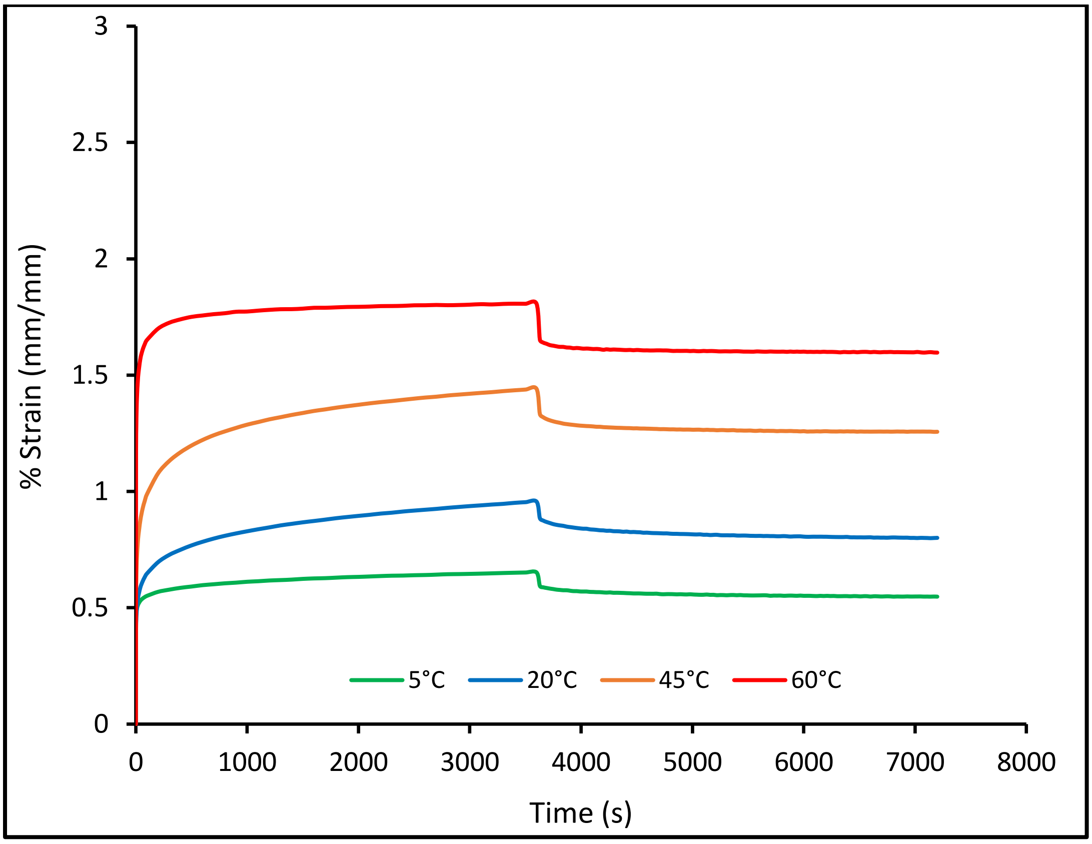


Figure 4.25: Accumulated strain versus loading time of GLS mixture

4.9 CBEM Behaviour

Contemporary flexible pavement designs assume that the pavements' response to traffic and environmental stressors is elastic. However, the validity of this assumption is limited to low temperature climate conditions and under rapidly applied vehicle loadings where the deformation of asphalt surfaces is not permanent, returning back to its original shape when the load is removed. At high temperatures, or under slow moving loads, flexible pavements are subjected to a plastic deformation associated with viscous behaviour. This is the main reason for the development of a FE model, which assists in simulating the mechanical response of the new reinforced cold and hot mix asphalt. This model is characterised by the elasticity required to simulate the immediate response of the pavement, viscosity to simulate the mechanical response of pavement, which depends on the strain rate in terms of loading time, and plasticity to simulate plastic flow in terms of permanent deformation.

The viscoplastic deformation of flexible pavements generally depends on the stress level, loading time, number of cycles and temperature. The constitutive law for flexible pavements can be stated in Equation 4.4 as (Uzarowski, 2006):

$$\varepsilon_{ij} = (\sigma_{ij}, t, M, T) \qquad 4.4$$

where:

ε_{ij} and σ_{ij} are the strain and stress components, respectively

t: time

M: loading cycles number

T: temperature

The creep and relaxation test is used in this research to characterise the viscoplastic behaviour of both cold and hot asphalt mixes. Four different types of strain develop in flexible pavements under vehicle moving load: elastic recoverable strain (ε_e) which is time independent; plastic irrecoverable strain (ε_p) which is time independent; viscoelastic recoverable strain (ε_{ve}) which is time dependent, and viscoplastic irrecoverable strain (ε_{vp}) which is time dependent (Sun, 2016b; Chen, Balieu and Kringos, 2017). The total strain (ε_t) can be expressed in Equation 4.5 as (Uzarowski, 2006):

$$\varepsilon_t(\sigma, t, M) = \varepsilon_e(\sigma) + \varepsilon_p(\sigma, M) + \varepsilon_{ve}(\sigma, t) + \varepsilon_{vp}(\sigma, t, M) \qquad 4.5$$

Responses to the above strains can be calculated from the creep and relaxation test. After applying the load, an instantaneous asphalt mixture response occurs comprising the elastic (ε_e) and plastic (ε_p) strains of the total strain, as shown in Figure 4.26. The elastic strain (ε_e) is the instantaneous reduction at the moment of unloading (relaxation). The plastic strain (ε_p) can be calculated by subtracting the elastic strain (ε_e) from the instantaneous loading strain (ε_e + ε_p). Both viscoelastic (ε_{ve}) and viscoplastic (ε_{vp}) strains are time dependent, occurring and overlapping during the loading time stage (ε_{ve} + ε_{vp}), as shown in Figure 4.26. Viscoelastic strain (ε_{ve}) is the delayed response during the unloading stage. The viscoplastic strain (ε_{vp}) can be determined by subtracting the elastic, plastic and viscoelastic strains from the total strain as shown in the Equation 4.6 below:

$$\varepsilon_{vp} = \varepsilon_t - \varepsilon_e - \varepsilon_p - \varepsilon_{ve} \qquad 4.6$$

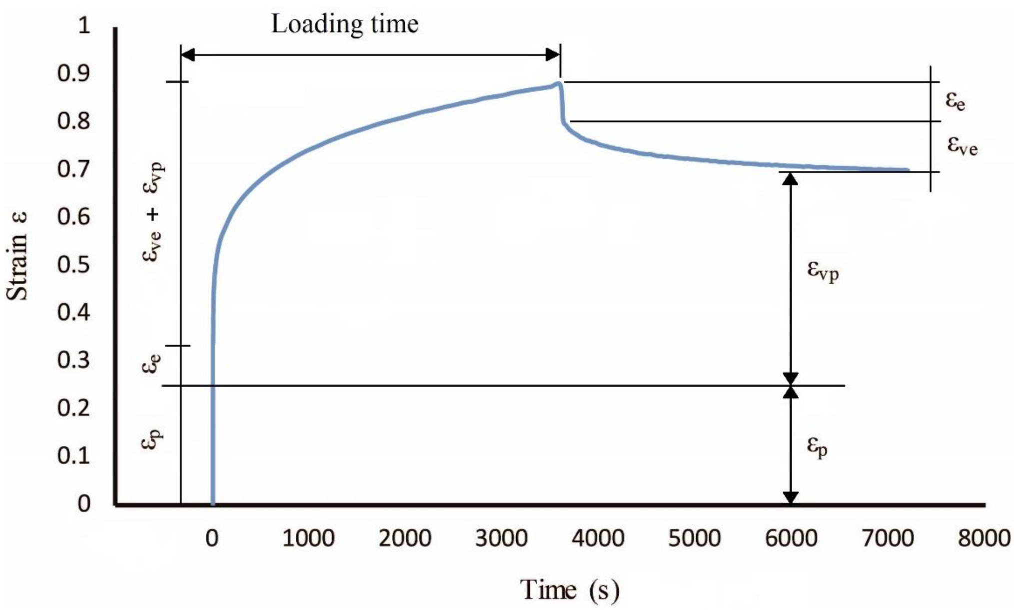


Figure 4.26: Elastic, plastic, viscoelastic and viscoplastic strains of CBEM at 100 kPa and 45 °C

Figure 4.27 illustrates the plastic and viscoplastic strains in the cold mix asphalt at 45 °C. From this figure, it can be seen that the cumulative viscoplastic strain curve increases with a constant steep slope, specifically after 1,000 seconds, while the plastic strain curve flattens horizontally with a constant value, as it is a time independent component. This indicates that the irrecoverable deformation of asphalt mixtures in the creep and relaxation test mainly depends on the viscoplastic strain component; plastic strain can be considered insignificant if loading occurs over a long time. This confirms the observations by Huang (2004).

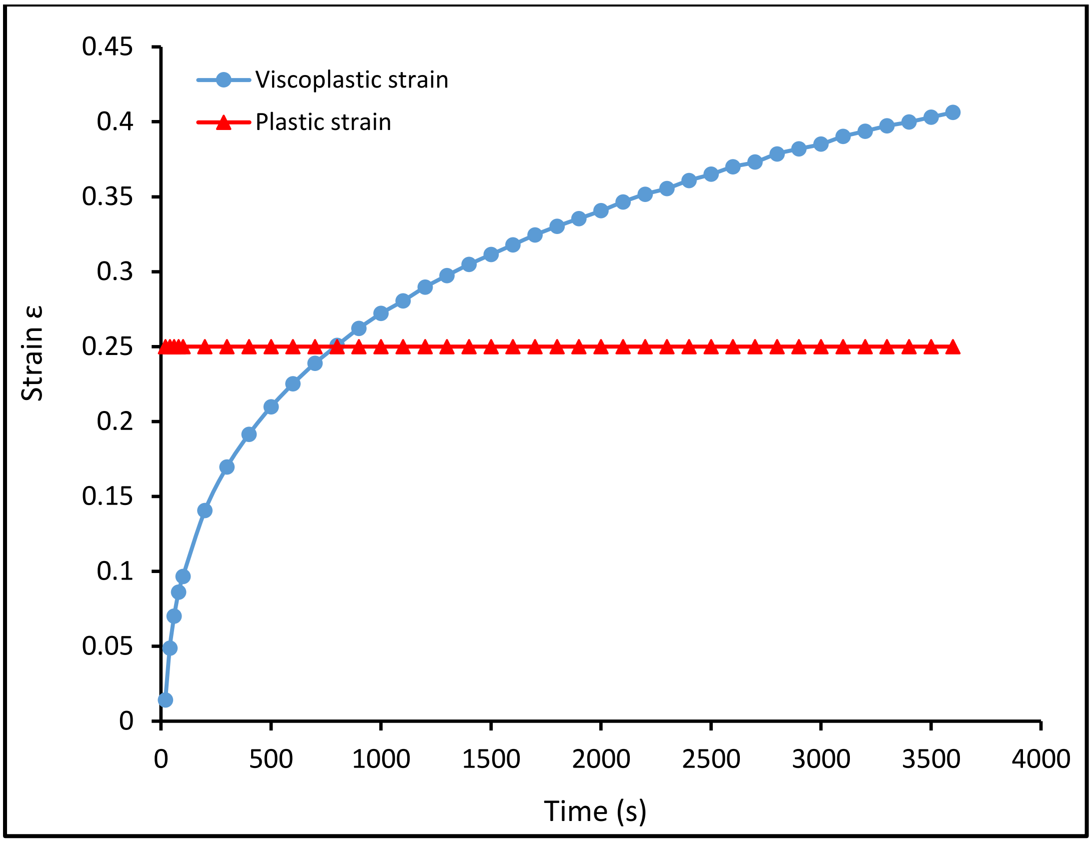


Figure 4.27: Plastic and viscoplastic strains in the CBEM at 100 kPa and 45 °C

A viscoplastic model of time-hardening is available in ABAQUS, using the creep power law to represent the nonlinear behaviour of asphalt mixtures. Equation 4.7 is expressed in a power law form and used to define the creep model (Huang, Mohammad and Rasoulian, 2001):

$$\varepsilon_{vp} = A\sigma^n t^m \qquad 4.7$$

where A, n and m are the creep power law parameters that relate to the material properties as:

A: Power law multiplier

n: Equation stress order

m: Time order

These parameters depend on bitumen viscosity, aggregate maximum size and aggregate angularity (Imaninasab, Bakhshi and Shirini, 2016). In this research, the values of the parameters for the conventional CBEM and HMA, and the reinforced CBEMs were determined according to the results obtained from the creep and relaxation test. It should be noted that if the creep power law is used to model the time-related behaviour of materials, repeated and continuous loadings result in the same estimation of creep strain on the condition that the total loading periods are the same as those of Imaninasab, Bakhshi and Shirini (2016).

4.10 Summary

Fibres play an important role in the performance of CBEMs. The establishment of the effect of natural and synthetic fibres on the mechanical properties of CBEMs was presented earlier in this chapter. The first main objective of this work was to optimise fibres' length and content to gain the best level of the mechanical properties of CBEMs, followed by the influence of other variables. Several CBEM and HMA specimens were prepared to study the effect of different fibres reinforcement on the ITSM of bituminous mixtures. Four fibres were used: glass as a synthetic fibre, and hemp, jute and coir as natural fibres. Different curing periods and testing temperatures were applied to study their impact on the performance of reinforced and unreinforced CBEM, and HMA for comparison purposes. Rutting behaviour of bituminous mixtures was also evaluated using the wheel tracking test. The main factor that was investigated is how the reinforced CBEMs under repeated loading with different temperatures improve the performance of the flexible pavements. Furthermore, the microstructure of the fibres used was evaluated using scanning electron microscopy to discover the rough surface area of the fibres. All reinforced CBEMs displayed a significant improvement in terms of water damage resistance in comparison to the conventional CBEM. In terms of fracture toughness behaviour, the results showed that there is a substantial enhancement in the reinforced mixtures in comparison to the others.

Chapter 5

Finite Element Modelling

5.1 Introduction

Laboratory tests of bituminous mixtures are increasingly able to predict performance in a road situation. However, there are still factors in this area that can be neither predicted nor replicated in the laboratory. It is necessary, therefore, to develop a numerical model to predict the effect of such factors on the pavement performance. The predicted results could provide valuable information regarding performance or highlight practical problems which may never be encountered in a laboratory situation. This chapter presents numerical procedures and techniques that are employed to simulate the rutting behaviour of the CBEMs under both moving and static loadings. The commercial finite element analysis code and ABAQUS/Standard software are used to develop numerical models to help understand the rutting performance and the structural behaviour of the conventional CBEM and HMA, and reinforced CBEM using natural and synthetic fibres under different loadings and temperature conditions. There are two different material behaviours considered to model the rutting phenomenon of bituminous mixtures, i.e. the viscoelasticity and viscoplasticity depend on the applied loads. The viscoelastic model was used to simulate the rutting behaviour when the deformation is small, typically at low temperatures and high speed. On the other hand, the viscoplastic model was adopted for undesirable loads and environmental conditions, where there are high temperatures and heavy traffic load. Subsequently, the finite element modelling results are also provided in this chapter. The numerical models were validated against the experimental data presented in Chapter 4, which will be further used to conduct parametric studies in this chapter. The comparison between the numerical and experimental time-displacement for the rutting of all mixtures with different temperatures is presented. The failure mode and deformation shape are also discussed.

5.2 Modelling of Rutting in Bituminous Mixtures

Different techniques are available to predict flexible pavement deformation such as multilayer elastic theory, boundary element methods, analytical methods, hybrid methods, finite difference methods and finite element methods (FEM) (Arabani, Jamshidi and Sadeghnejad, 2014). FEM has been used successfully for flexible pavement performance analysis and has been found suitable for application to the complex nonlinear behaviour of composite pavement materials (Bai, Yang and Zeng, 2016). Although, 2-D models are acceptable when calculating permanent deformation of flexible pavements, 3-D models are employed to determine more precise and realistic pavement responses (Imaninasab, Bakhshi and Shirini, 2016). A three-dimensional, finite element analysis of flexible pavement responses under repeated traffic loads was performed to study the mechanical properties of the reinforced and unreinforced CBEMs. The FEM gives numerical estimations to problems which are too complicated to be solved analytically. The problem is considered in this model under a repeated applied moving load and viscoelastic and viscoplastic material properties of the bituminous mixtures. The analytic model is a bituminous layer of 400 mm length, 305 mm width and 50 mm thickness, as illustrated in Figure 5.1. These dimensions were chosen to concur with the wheel tracking test specimens which were simulated in this study.

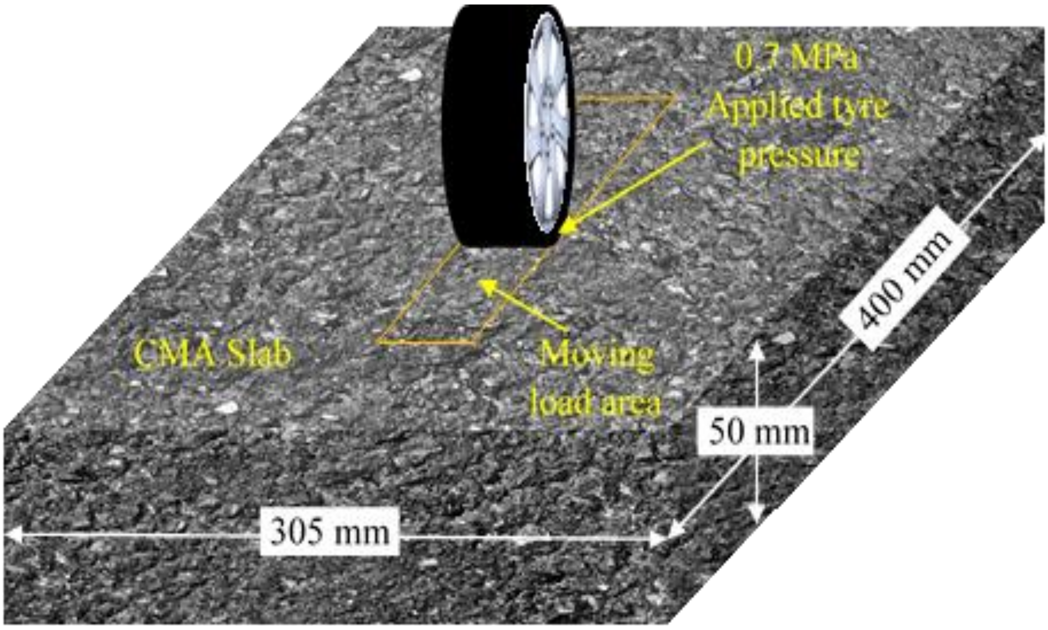


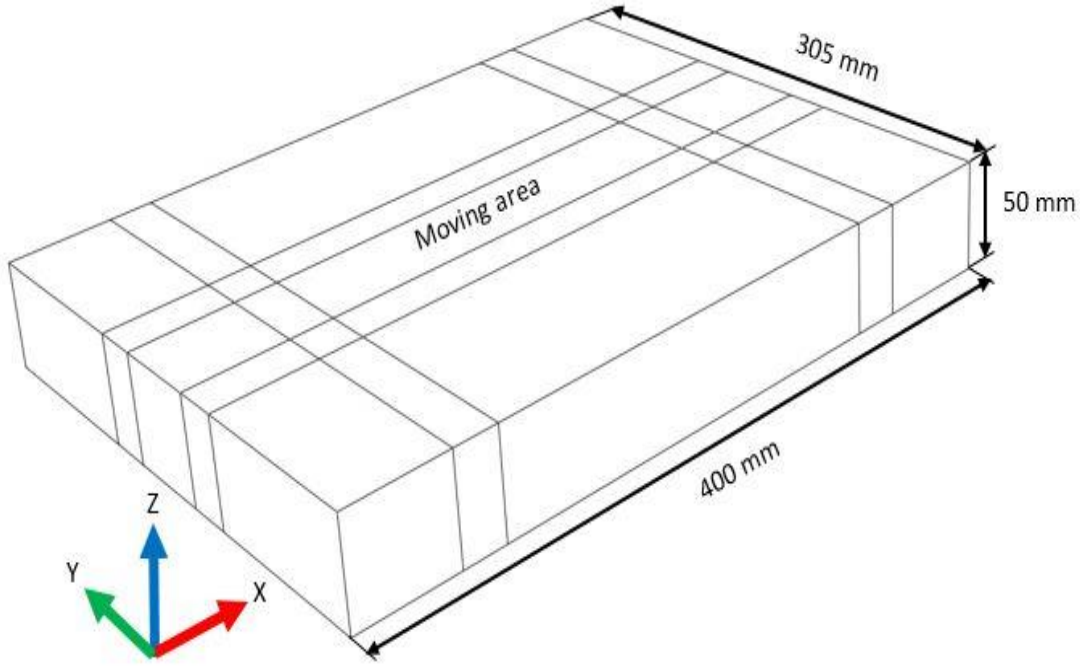
Figure 5.1: Three-dimensional slab modelling

5.2.1 Element Type and Mesh Size

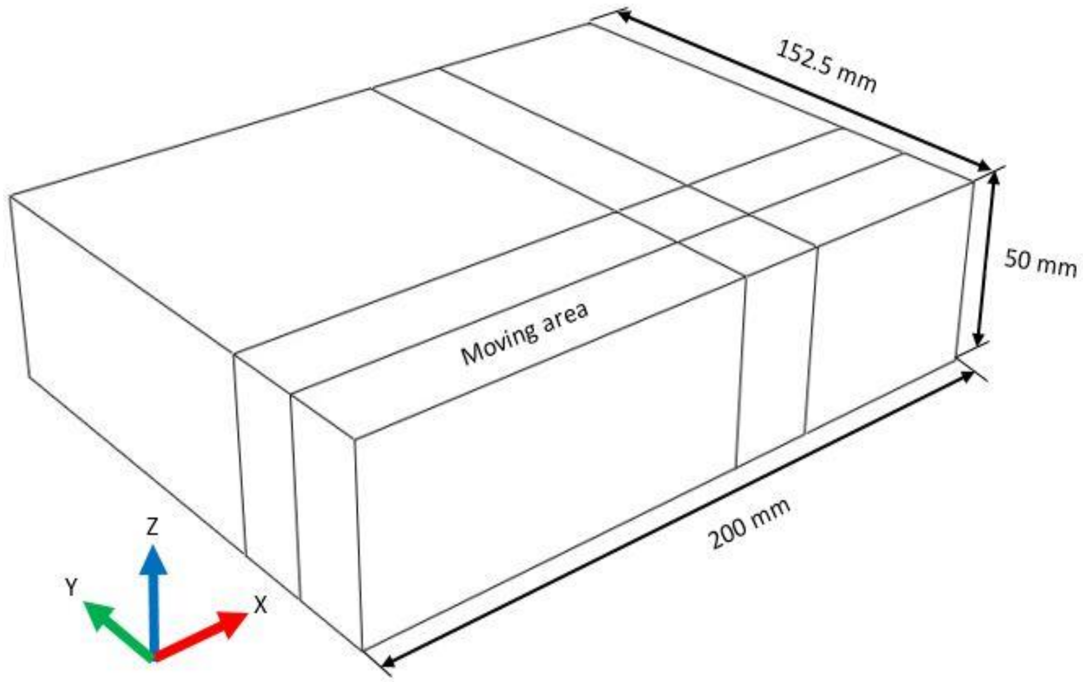
Full three-dimensional models were developed to simulate the rutting behaviour of all the reinforced and unreinforced mixtures with different temperatures and loading types. However, the slab specimens were modelled using a quarter model to reduce the computational time and cost by using the symmetry boundary conditions along the symmetry planes (Allou et al, 2015; Pérez, Medina and del Val, 2016; Gu et al, 2017), as shown in Figure 5.2-a and 5.2-b. The element behaviour can be defined using an element's formulation which refers to the mathematical theory.

In the finite element analysis, the numerical (full or reduced) integrations are used to find the stiffness and the mass of the element. The reduced integration, mainly used by ABAQUS/ Explicit (ABAQUS, 2015), means using lower order integration to form the element stiffness. Thus, the running time will be reduced, especially for the three dimensions elements. For example, the element assembly is about 3.5 times more costly for C3D8 (eight-node brick element) than that for C3D8R (eight-node brick element with reduced integration). In addition, with the reduced integration elements, the stresses and strains are found at the locations that provide optimal precision. The 8-node element is very active for solving the problems (Al-Husainy, 2017). In ABAQUS/Standard, both the full and reduced integration options are available. Many numerical studies used the linear elements with reduced integration to solve the structural problems (Zeinoddini, Harding and Parke, 2008; Al-Thairy, 2012). Thus, first order eight-node brick element with reduced integration elements (C3D8R) were used to mesh the bituminous slabs for all simulations, as shown in Figure 5.3. This figure shows the finite elements mesh for the model and moving load area on the pavement surface. The body was divided into many small, discrete, finite elements that are solved simultaneously. Shared nodes join these elements to each other. Each node of these elements has three translational degrees of freedom with the reduced integration to decrease the analysis time. The combination of nodes and elements forms a mesh. The mesh density is dependent on the number of elements used in a particular mesh. The mesh size under the loading area was refined to 1.5 mm, where there is large stresses and strains are present, and gradually increased along the horizontal directions to ensure accurate results (Chen et al, 2016; Shanbara et al, 2016).

The element size for the bituminous slabs was found based on a mesh sensitivity study. Figure 5.4 shows that the numerical model of the conventional CBEM at 45 °C with element size of 3 mm exhibited weak behaviour with the rutting depth and more total displacement than the corresponding experimental results. By reducing the element size, the precision of the model was enhanced. The mesh with element size of 1.5 mm demonstrated a reasonably good agreement with the experimental data. However, reducing the element size to 1 mm did not effectively improve the accuracy of the numerical results. In addition, the computational time increased when decreasing the element size, as expected. Therefore, the element size of 1.5 mm was adopted in this study for the bituminous slabs.



(a) The whole geometry



(b) The quarter geometry

Figure 5.2: Geometric conditions of the wheel tracking slab

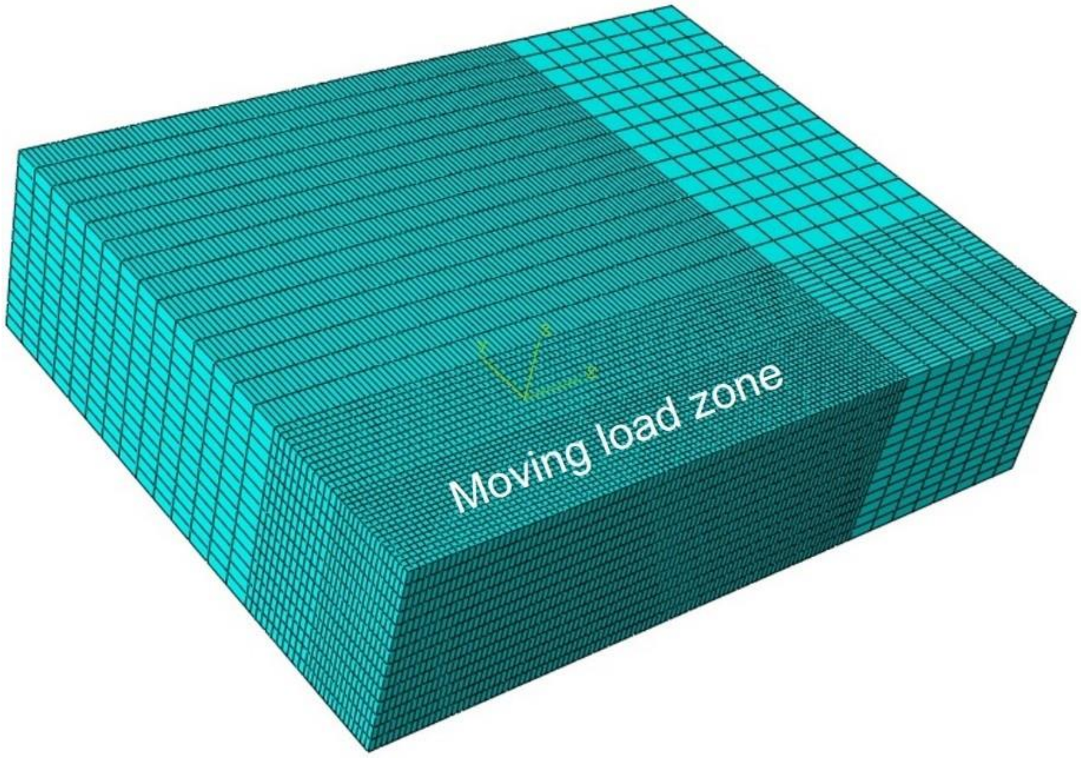


Figure 5.3: 3-D finite element mesh for pavement simulation

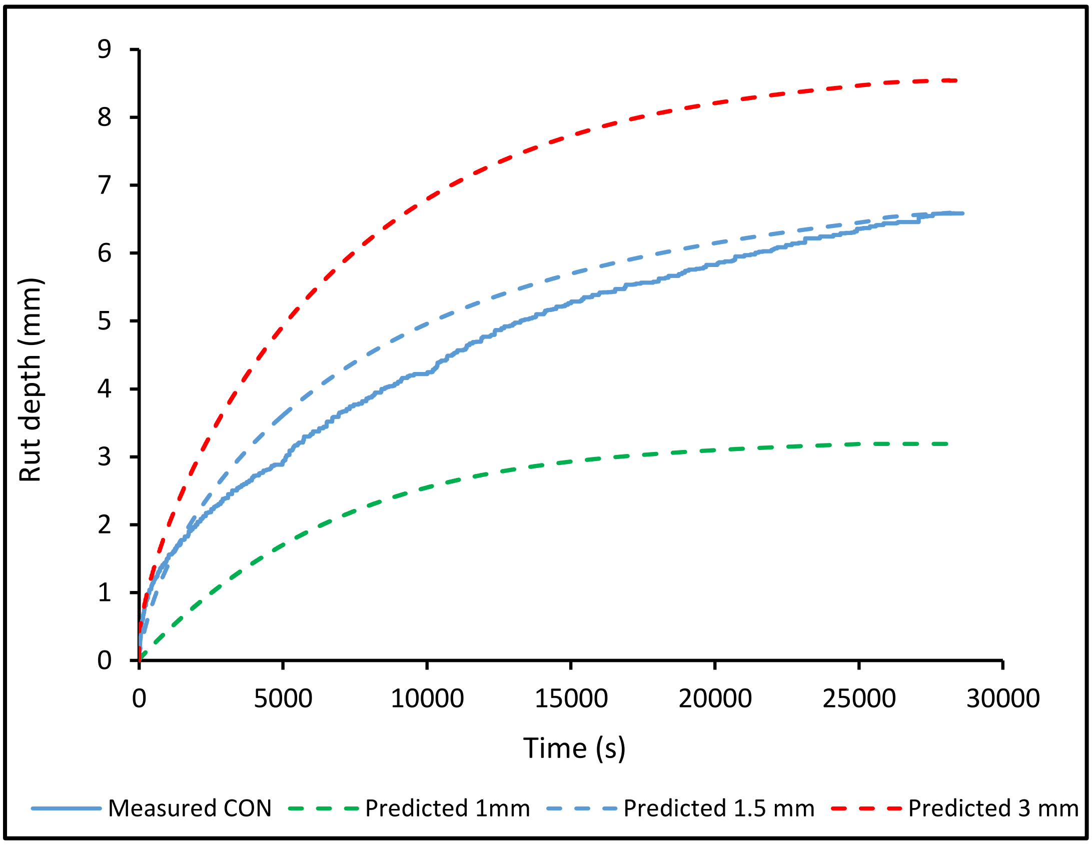
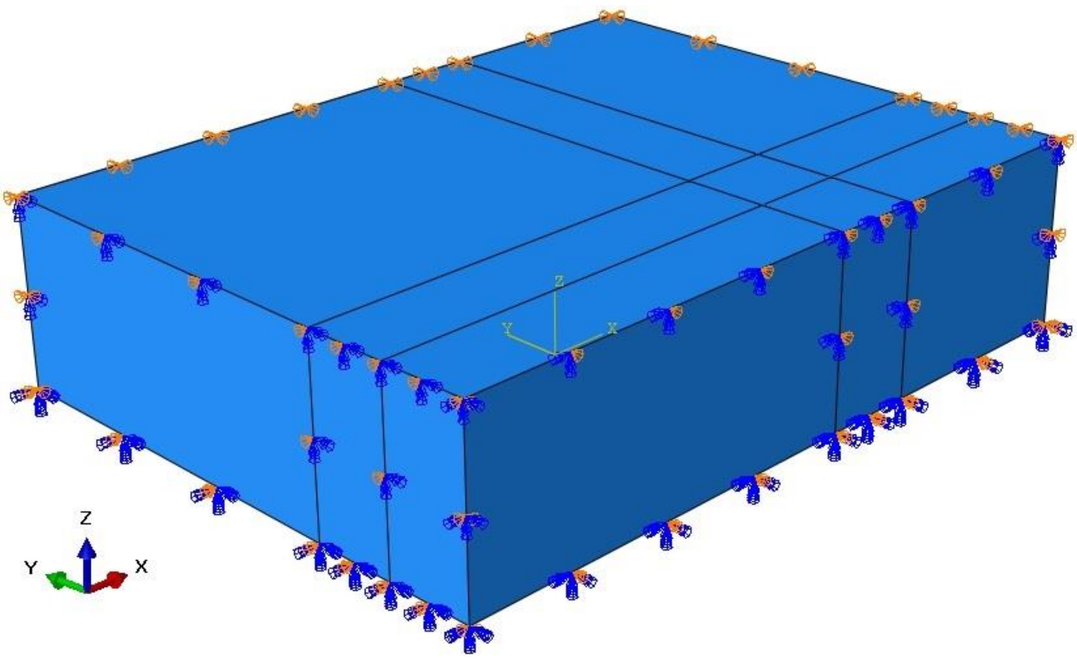


Figure 5.4: Element size effect on the precision of the numerical model

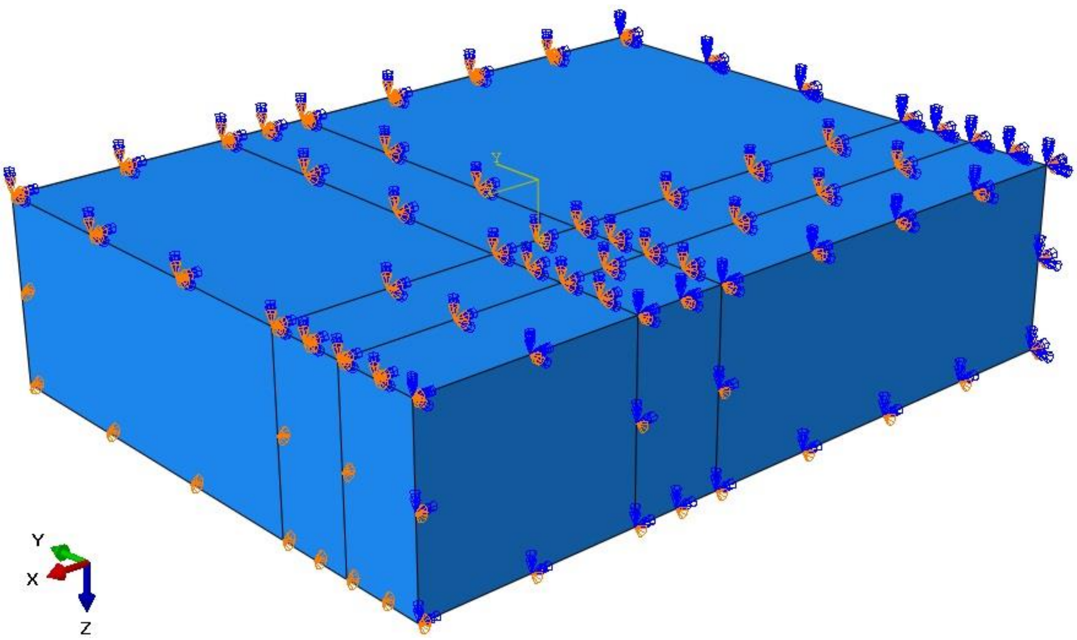
5.2.2 Boundary Conditions and Loading

To simulate the experimental test conditions, the bottom faces of the bituminous slabs were restrained in all directions to provide a fully fixed end that mimics the experimental conditions, while the surface was free, as shown in Figure 5.5. Displacements of the layer edges were also restrained in horizontal directions. As mentioned earlier, only a quarter of the wheel tracking slabs were modelled. Thus, the slabs were restrained in the x-z plane and y-z plane as symmetric conditions, as shown in Figure 5.6.

A vertical uniform tyre pressure of 700 kPa was applied as a moving load on the pavement surface with a rectangular loading footprint of 50 mm in length and 30 mm in width, to meet the wheel tracking test requirements. The load transfers to the pavement surface through contact pressure between the tyre and pavement surface. This contact pressure is equal to the pressure from a tyre on a road surface (National Cooperative Highway Research Program, 2002), simplified as a rectangular, uniformly distributed, surface load (Huang et al, 2011; Wu, Liang and Adhikari, 2014). The moving wheel load zone (Figure 5.7-a) was divided into several small rectangles, which have the same width as the tyre footprint (50 mm) and one-third of its length (10 mm). The wheel load occupies three rectangular areas as shown in Figure 5.7-a. When the load gradually moves forwards and backwards, a series of load application steps are performed. At the end of each load application step, the whole load moves forward to a small rectangular area, for example, at the end of the first load application step, the load occupies areas 2, 3 and 4. In order to avoid any impact, the applications load of area 4 increases gradually to reach the maximum (700 kPa), at the same time it decreases gradually in area 1, as shown in Figure 5.7-b. Tyre pressure is applied repeatedly on the pavement surface over a large number of cycles; during each cycle (1.43 s) the load is applied to each element for 0.18 s to simulate a vehicle speed of approximately 0.6 km/h. The load is then removed as shown in Figure 5.7-b.



(a) Boundary conditions of the surface and sides



(b) Boundary conditions of the bottom and sides

Figure 5.5: The boundary conditions of the wheel tracking slab

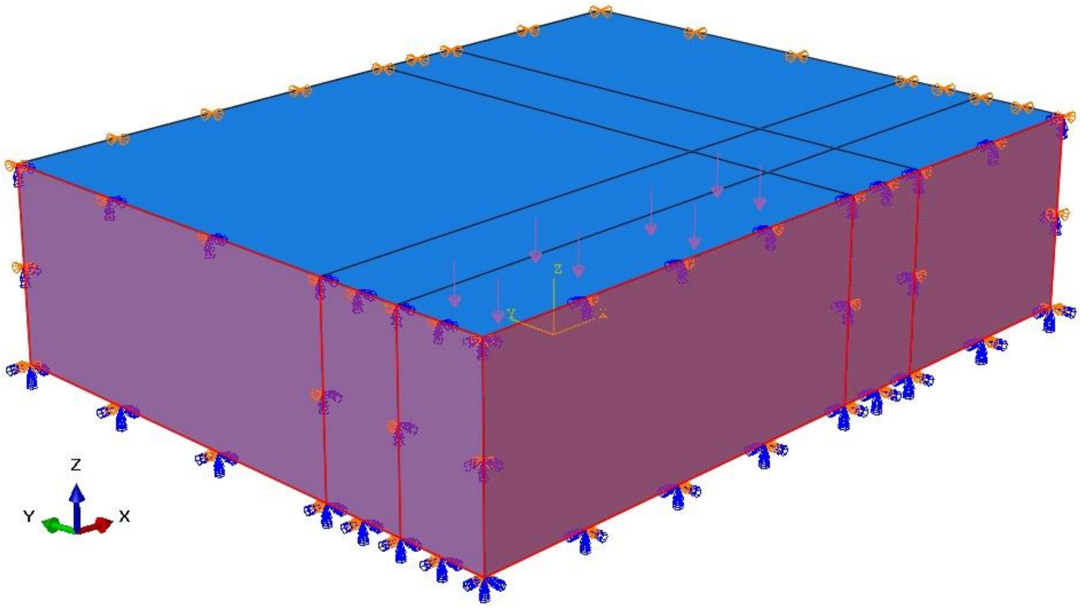


Figure 5.6: The symmetrical boundary conditions planes of the wheel tracking slab

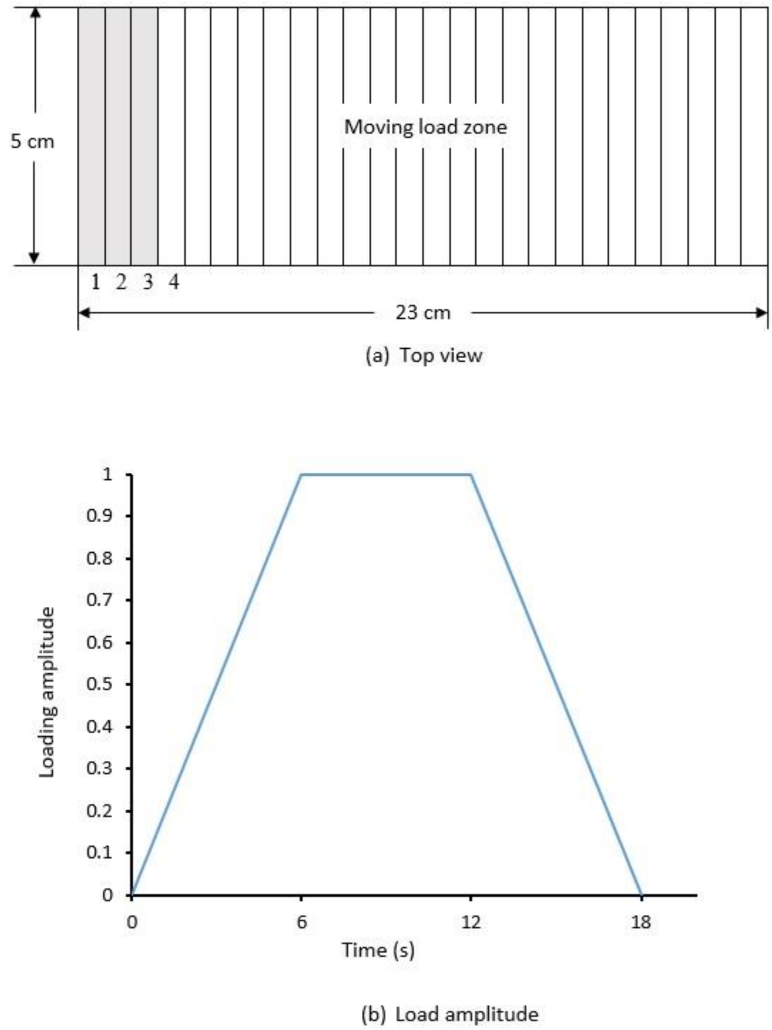


Figure 5.7: Moving load zone and loading amplitude

5.2.3 Material Properties

Theoretically, the most common methodologies used to predict rutting in flexible pavements are the 'layer-strain' method and methods based on viscoelastic theory. Methods using the layer-strain approach consider rutting in all pavement layers by assuming either a linear or a non-linear relationship between the elastic stress and the vertical permanent deformation in each layer. The permanent deformation properties of the flexible pavement materials are determined usually using triaxial and creep testing. These methods account for the fact that rutting is only dependent on the elastic material properties and is independent of the material viscosity and plasticity. The main disadvantage of this type of modelling is the assumption that bituminous mixtures behave as a linear elastic material. It can be seen from the results presented in Chapter 4 that the behaviour of the bituminous mixtures is non-linear at higher stress levels. However, implementation of a non-linear constitutive law to calculate permanent deformation properties is required to be used in the finite element modelling. Rutting models that are based on the viscoelastic and viscoplastic material properties directly incorporate time-dependent response and repeated applied moving wheel loads. These types of modelling consider that rutting forms primarily by shear flow of the bituminous pavement materials. Additionally, in these types, permanent deformation is assumed to be dependent on the elastic, viscous and plastic properties of the bituminous mixtures. Typically, the viscoelastic and viscoplastic properties of the bituminous materials are determined from the creep and relaxation testing.

The success of the viscoelastic and viscoplastic models relies on the ability to consider the elastic, viscous and plastic material properties that are necessary to be supplied to such models. The following sections describe the procedure used to determine the viscoelastic and viscoplastic parameters based on the results from the creep and relaxation tests on the bituminous mixtures.

5.2.3.1 Viscoelastic Materials

The ABAQUS software used in this research is efficient in analysing complex time rate dependent and viscoelastic problems. For the viscoelastic analysis of bituminous materials, shear *G(t)* and/or bulk *K(t)* moduli are required in most finite element modelling as viscoelastic material properties inputs. These properties can be calculated from the creep test at certain temperatures using the Prony series. This is a mechanical representation of the viscoelastic material behaviour of flexible pavements (Souza and Castro, 2012). Flexible pavement material is homogeneous and isotropic and the Poisson's ratio does not change with time (Chun et al, 2015). Therefore, Poisson's ratio has been considered as a constant of (0.35). This is the most suitable assumption for bituminous mixtures as it provides reasonable and accurate time and rate dependent responses of viscoelastic materials (Kim, Lee and Kim, 2010). Elastic modulus of different CBEMs and the conventional HMA mixture at different temperatures were measured using the ITSM test. The Prony series parameters and moduli of elasticity were successfully calculated based on the experimental results, as given in Table 5.1, after 14 days of curing time for the CBEMs.

Table 5.1: Elastic and viscoelastic properties of different CBEM and HMA mixtures at different temperature

		Viscoelastic material coefficients											
		Temperatures (°C)											
		60						45					
		D_i (1/kPa)						D_i (1/kPa)					
i	τ_i (s)	CON	GLS	HEM	JUT	COI	HMA	CON	GLS	HEM	JUT	COI	HMA
1	0.1	6.91×10^{-6}	4.49×10^{-6}	5.12×10^{-6}	4.86×10^{-6}	4.65×10^{-6}	6.33×10^{-6}	1.14×10^{-5}	7.33×10^{-6}	5.50×10^{-6}	2.75×10^{-6}	2.69×10^{-5}	3.77×10^{-5}
2	1	6.12×10^{-5}	5.63×10^{-5}	5.03×10^{-5}	3.36×10^{-5}	4.41×10^{-5}	3.71×10^{-5}	1.90×10^{-5}	3.58×10^{-5}	6.81×10^{-5}	2.14×10^{-5}	4.05×10^{-5}	1.76×10^{-5}
3	10	1.54×10^{-4}	4.47×10^{-5}	5.65×10^{-5}	8.52×10^{-5}	1.04×10^{-4}	1.92×10^{-4}	4.08×10^{-5}	2.08×10^{-4}	1.80×10^{-5}	6.71×10^{-5}	8.03×10^{-5}	5.19×10^{-4}
4	100	2.09×10^{-4}	1.06×10^{-4}	3.34×10^{-4}	1.39×10^{-4}	1.27×10^{-4}	2.49×10^{-4}	7.43×10^{-5}	3.25×10^{-4}	5.39×10^{-4}	8.67×10^{-5}	1.31×10^{-4}	6.66×10^{-5}
5	1000	2.62×10^{-4}	4.52×10^{-4}	3.23×10^{-4}	1.74×10^{-4}	1.42×10^{-4}	2.02×10^{-4}	1.08×10^{-4}	4.05×10^{-4}	2.00×10^{-4}	1.15×10^{-4}	1.72×10^{-4}	3.33×10^{-4}
Modulus of elasticity E (MPa)		35	604	529	311	255	550	100	789	713	417	324	835

		Viscoelastic material coefficients											
		Temperatures (°C)											
		20						5					
		D_i (1/kPa)						D_i (1/kPa)					
i	τ_i (s)	CON	GLS	HEM	JUT	COI	HMA	CON	GLS	HEM	JUT	COI	HMA
1	0.1	3.66×10^{-6}	2.42×10^{-6}	7.56×10^{-6}	1.10×10^{-6}	6.30×10^{-6}	5.31×10^{-6}	8.81×10^{-6}	2.73×10^{-6}	4.47×10^{-6}	7.68×10^{-6}	9.11×10^{-6}	8.53×10^{-6}
2	1	5.18×10^{-6}	2.04×10^{-6}	8.63×10^{-5}	1.52×10^{-6}	1.69×10^{-5}	3.11×10^{-5}	7.24×10^{-5}	7.19×10^{-6}	3.05×10^{-6}	4.34×10^{-5}	5.53×10^{-5}	2.28×10^{-6}
3	10	3.90×10^{-5}	1.16×10^{-5}	7.99×10^{-5}	3.05×10^{-5}	3.69×10^{-5}	2.38×10^{-6}	9.63×10^{-5}	1.84×10^{-5}	2.11×10^{-6}	6.02×10^{-5}	8.78×10^{-5}	5.54×10^{-5}
4	100	5.67×10^{-5}	7.30×10^{-4}	2.12×10^{-4}	5.08×10^{-5}	5.16×10^{-5}	5.86×10^{-4}	5.16×10^{-4}	5.67×10^{-5}	2.37×10^{-5}	9.79×10^{-5}	4.33×10^{-4}	9.14×10^{-4}
5	1000	7.40×10^{-5}	2.25×10^{-4}	8.36×10^{-4}	5.21×10^{-5}	6.28×10^{-5}	4.77×10^{-5}	8.25×10^{-4}	4.47×10^{-4}	6.72×10^{-4}	2.95×10^{-4}	8.19×10^{-4}	4.11×10^{-5}
Modulus of elasticity E (MPa)		464	1152	1100	1021	890	1420	581	2267	2047	1876	1634	4138

5.2.3.2 Viscoplastic Materials

In this study, viscoplastic models were developed for the bituminous layers (CBEM) containing natural or synthetic fibres as a reinforcing material and conventional CBEM and HMA mixtures since the main aim of this study was to qualitatively compare the rutting resistance of different CBEMs under very heavy stresses. The fibres used provide random three-dimensional reinforcements, which improve the tensile and shear strength of the asphalt layer. The main variations in the mixtures were the elastic modulus, and creep power law parameters. However, temperature is considered as an important factor that affects the rutting resistance of all mixtures. The elastic modulus and creep power law of different mixtures corresponding to different temperatures were obtained from the experimental results and a constant Poisson’s ratio of 0.35 was assumed. All the flexible pavement material properties are presented in Table 5.2, after 14 days of curing time for the CBEMs.

Table 5.2: Elastic and viscoplastic properties of different CBEM and HMA mixtures at different temperatures

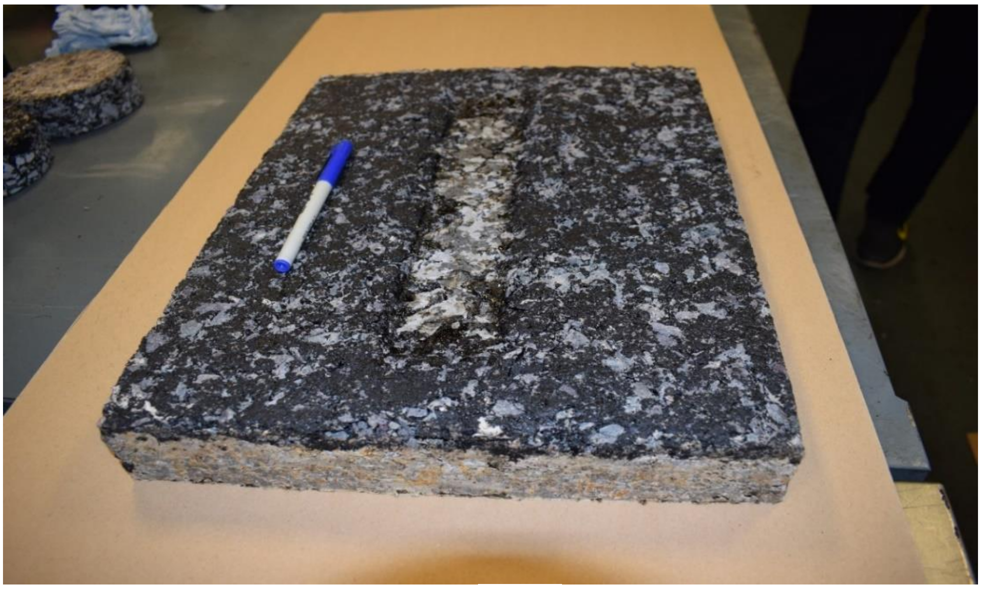
Mixture type	Temperature (°C)	A	n	m	E (MPa)
CON	60	1.01×10^{-3}	1.721	-0.0058	35
	45	1.00×10^{-3}	1.648	-0.0011	100
	20	1.91×10^{-3}	1.494	-0.0072	464
	5	9.46×10^{-4}	1.602	-0.0139	581
GLS	60	6.38×10^{-4}	1.716	-0.0096	604
	45	5.06×10^{-4}	1.721	-0.0137	789
	20	3.23×10^{-4}	1.737	-0.0224	1152
	5	2.17×10^{-4}	1.736	-0.0195	2267
HEM	60	6.81×10^{-4}	1.640	-0.0127	529
	45	5.74×10^{-4}	1.652	-0.0147	713
	20	4.11×10^{-4}	1.668	-0.0152	1100
	5	2.88×10^{-4}	1.655	-0.0149	2047
JUT	60	7.15×10^{-4}	1.634	-0.0118	311
	45	6.86×10^{-4}	1.639	-0.0135	417
	20	5.01×10^{-4}	1.625	-0.0144	1021
	5	2.97×10^{-4}	1.618	-0.0110	1876
COI	60	7.56×10^{-4}	1.696	-0.0079	225
	45	5.99×10^{-4}	1.706	-0.0089	324
	20	3.43×10^{-4}	1.709	-0.0124	890
	5	2.51×10^{-4}	1.683	-0.0138	1634
HMA	60	9.76×10^{-4}	1.756	-0.0093	550
	45	8.19×10^{-4}	1.758	-0.0123	835
	20	6.97×10^{-4}	1.747	-0.0149	1420
	5	5.33×10^{-4}	1.737	-0.0163	4138

5.3 Validation of the Finite Element Models

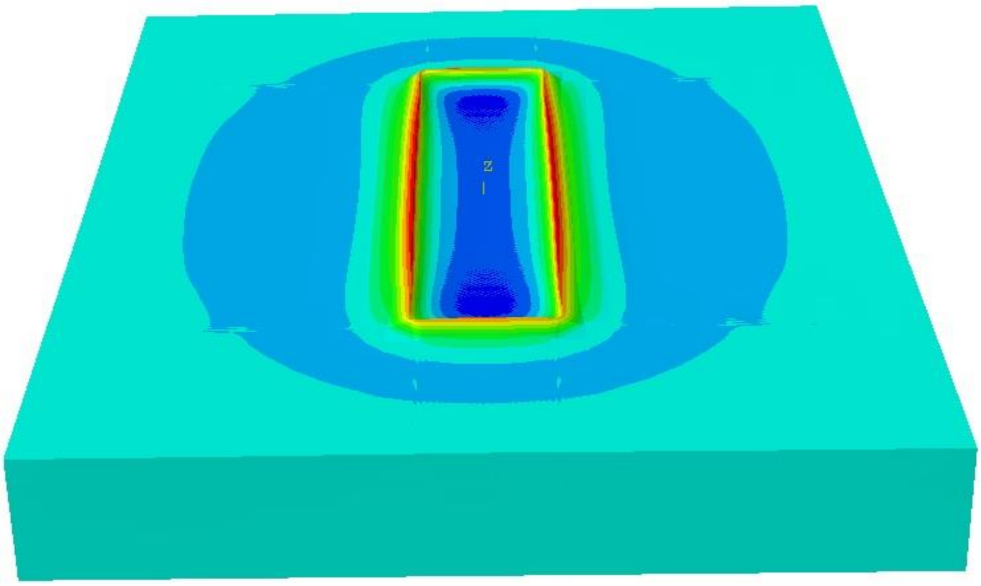
In order to validate the finite element model, a validation process was carried out by comparing the experimental results with the finite element modelling output data. A similar set of experiments had been conducted using wheel tracking tests to compare the actual measurements of rutting (permanent deformation) with the rutting values obtained from the model. The experimental set-up consisted of an asphalt mix slab with dimensions of 50 mm thickness, 305 mm width and 400 mm length, over a fixed rigid steel plate. Initially, the slabs were kept in the oven for 14 days at 40 °C after compaction in order to reach the final curing condition stage (Dulaimi et al, 2016).

During the test, the slabs were subjected to a repeated moving tyre pressure of 700 kPa. The total travelling distance of the tyre on the slab is 230 mm at a speed of 0.6 km/h. Six types of cold and hot asphalt mixtures were prepared to make the slabs. These mixtures are conventional CBEM and HMA, and reinforced CBEMs with glass (GLS) as a synthetic fibre, hemp (HEM), jute (JUT) and coir (COI) as natural fibres. Each slab was then wheel track tested at two different temperatures; 45 °C and 60 °C. The wheel tracking tests were carried out to measure the rut depth on the asphalt pavements surface along and under the wheel path, after 3,472 cycles (5,000 s) for the viscoelastic model and 20,000 cycles (28,600 s) for the viscoplastic model.

A very slight modification of the model was required to simulate the repeated moving load as it needs to use a repeated moving surface load to simulate the moving wheel load. Whilst, other modelling features remained the same, including the loading and unloading time, wheel speed, the total number of load repetitions, boundary conditions and temperature. The total number of load cycles applied on the pavement surface was deemed to be sufficient to distort these pavements. The vertical strain results (rut depth) and the deformation shapes produced on the surface of the asphalt pavement samples using this model were compared with the pavement strain results, which were performed using the wheel tracking test as shown in the Figure 5.8. Based on the comparison of peak deformation and transverse surface deformation, it can be seen that the FEM-simulated-CBEM response is close to the lab response.



(a)



(b)

Figure 5.8: Deformed shape of CON at 45 °C (a) measured, (b) predicted

5.3.1 Viscoelastic Model Validation

Viscoelasticity describes the time dependent stress-strain behaviour. It is well known that bituminous mixtures are loading-rate and temperature dependent exhibiting elastic and viscous behaviour under moderate traffic loads and temperature. To capture the time-dependent behaviour, a viscoelastic model is required. The creep test at a certain temperature using the Prony series parameters was introduced to capture the time-dependent properties of the bituminous mixtures.

5.3.1.1 Rutting in CBEMs

This model was developed to simulate rutting of bituminous mixtures that were subjected to moderate stress level as 3,472 repeated wheel loads during 5,000 seconds were applied on the slabs surface of CBEM and HMA mixtures with different temperatures. Viscoelastic material properties were used to define the bituminous mixtures in this model. Figure 5.9 – 5.12 show the numerical rutting curves, together with experimental ones for the conventional CBEM and HMA, and reinforced CBEMs subjected to two different temperatures (45 °C and 60 °C). Clearly, the predicted traces of the accumulated rutting correlated reasonably well to the corresponding experimental results. After 5,000 s of repeated applied wheel load with speed of 0.6 km/h, the predicted rutting for both conventional mixtures (CBEM and HMA) are comparatively lower than the measured one by a range of 12% to 48%, while the experimental and numerical rutting for the reinforced CBEMs match relatively well. This proves that the viscoelastic model can accurately predict rutting for the moderate stresses, such as the reinforced mixtures due to the viscoelastic properties of such mixtures. However, the rutting of the conventional CBEM and HMA was not well predicted, which might be attributed to the fact that the simulation considered the material properties as viscoelastic, whilst in the reality these properties may not be the same due to more possible permanent deformation.

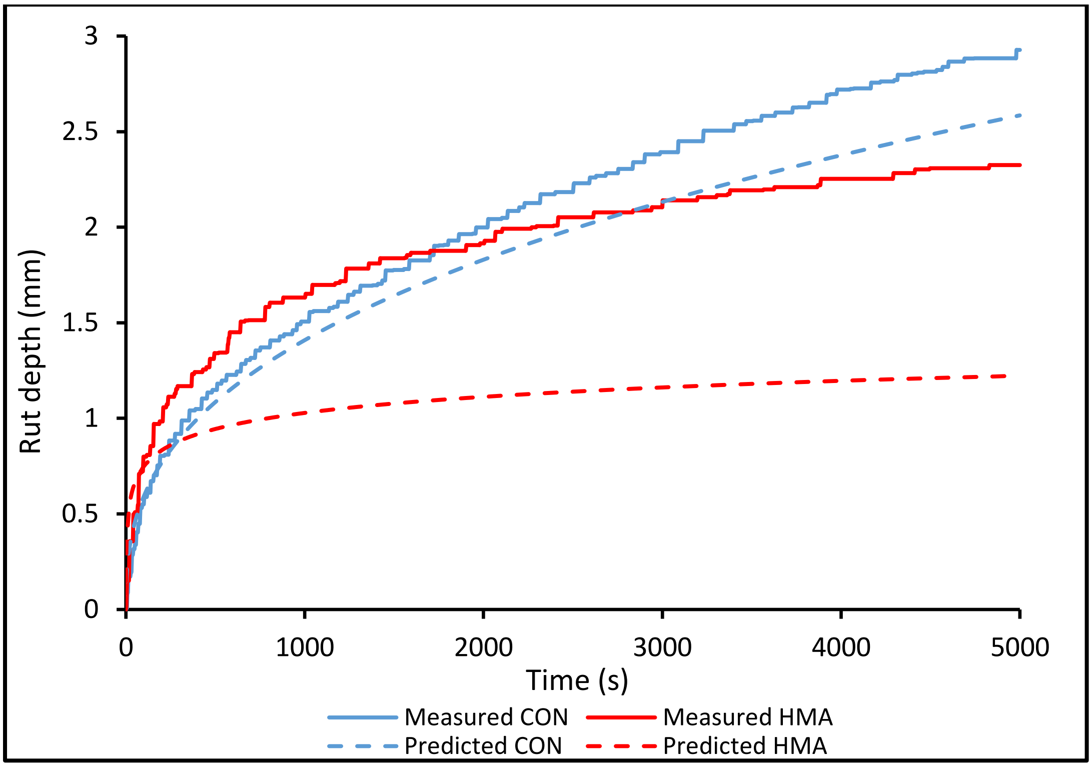


Figure 5.9: Rutting of viscoelastic model for conventional mixtures at 45 °C

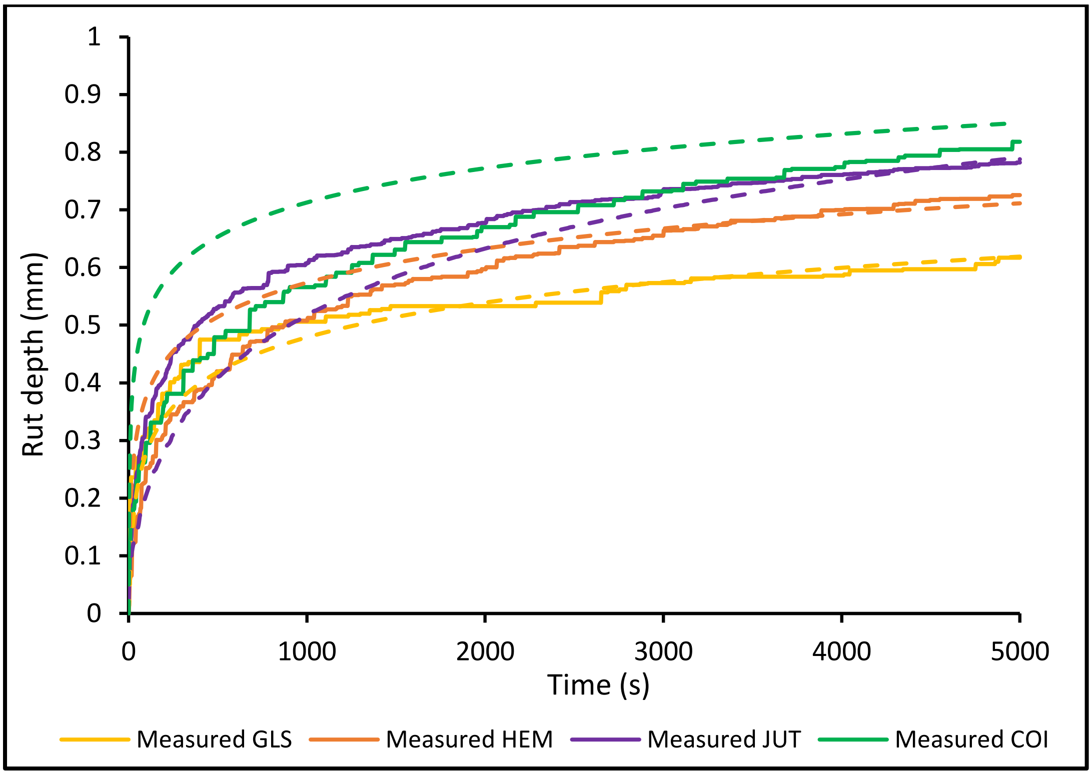


Figure 5.10: Rutting of viscoelastic model for reinforced mixtures at 45 °C

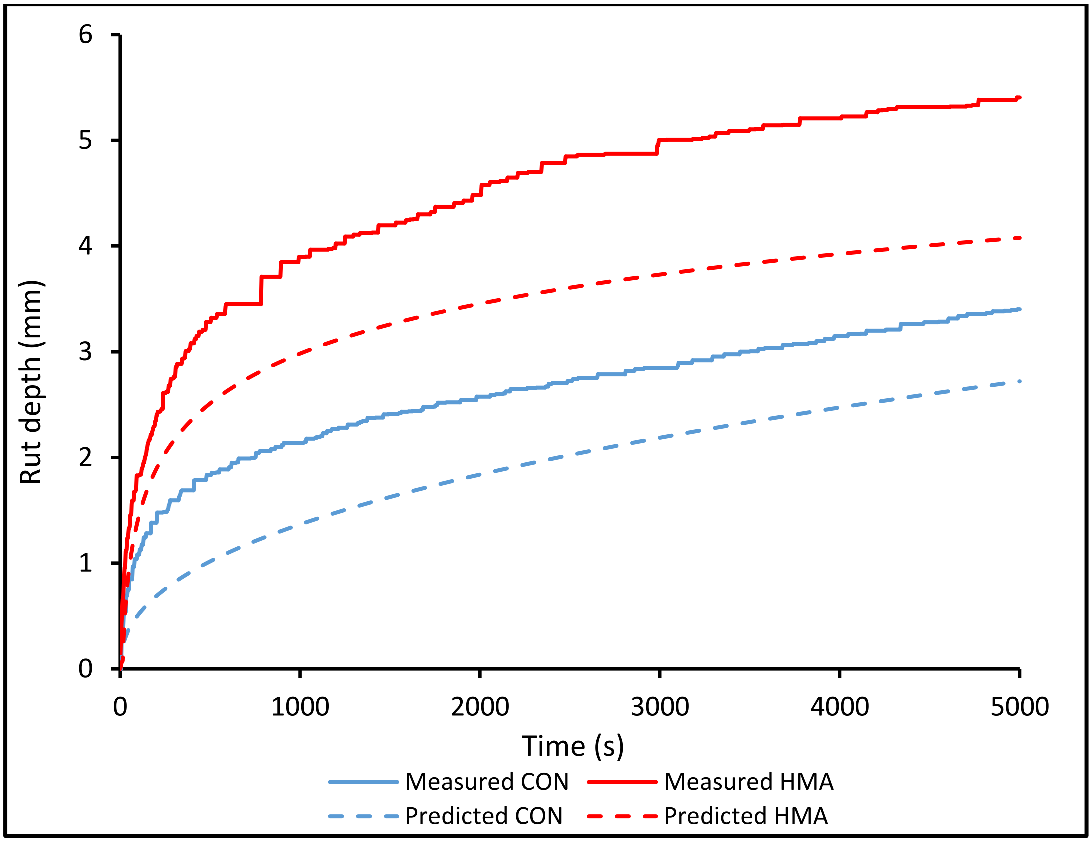


Figure 5.11: Rutting of viscoelastic model for conventional mixtures at 60 °C

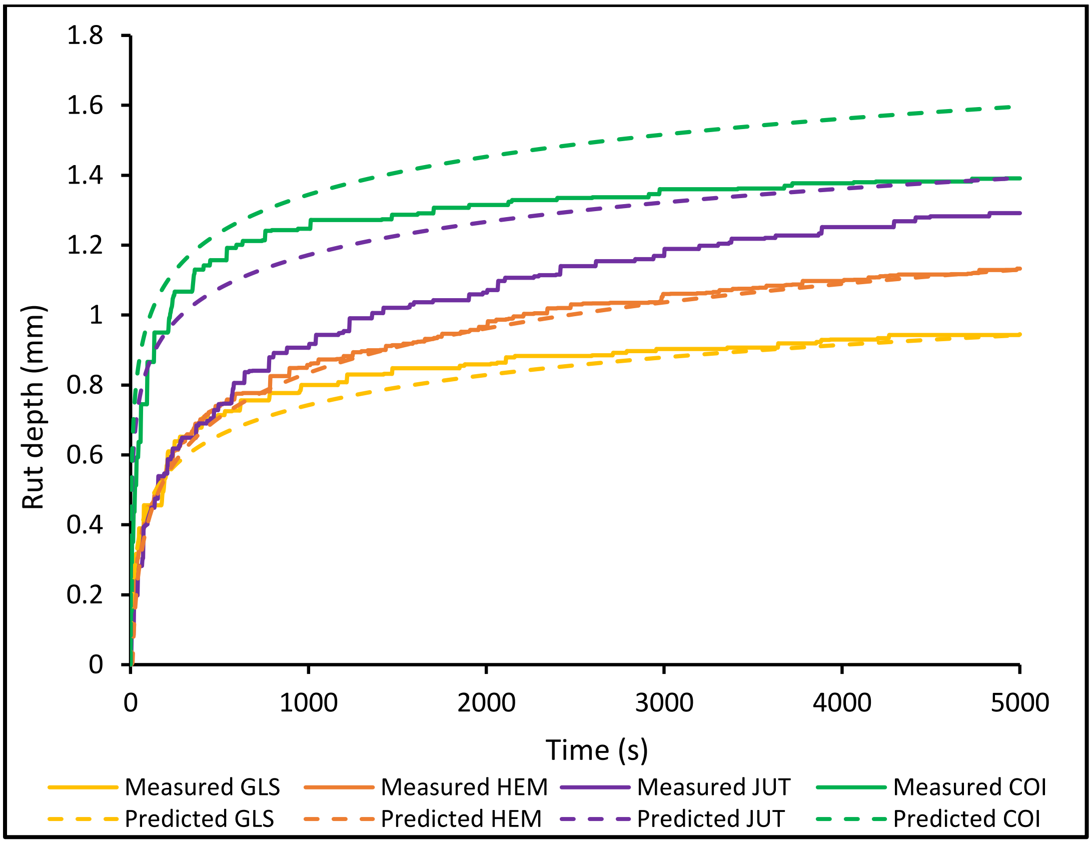


Figure 5.12: Rutting of viscoelastic model for reinforced mixtures at 60 °C

5.3.1.2 Permanent Deformation Shape

Twelve bituminous slabs were modelled for six different mixtures with different temperatures to predict the permanent deformation shape. These mixtures are conventional CBEM and HMA mixtures, and four reinforced CBEMs with glass, hemp, jute and coir fibres. This section presents the results of the predicted permanent deformation shape of the viscoelastic pavement materials and compares these predicted results to the wheel tracking deformation shape. The reasonable agreement between the predicted and measured deformations confirms the argument that the permanent deformation can be predicted from the viscoelastic properties of the material for moderate stress levels. Two temperatures were selected, 45 °C and 60 °C for all six mixtures. The permanent deformation shapes of the different mixtures, after 3,472 repeated applied wheel loads (about 5,000 s), are illustrated in Figure 5.13 – 5.24. The viscoelastic models indicate that increasing the temperature leads to an increase in the rutting and the total permanent deformation, as expected. For both temperature conditions, the mixtures followed the same order of permanent deformation resistance. The CBEMs reinforced with glass, have the smallest rut depth followed by the hemp fibre mix. The conventional CBEMs have the maximum rut depth. Because the elastic modulus of conventional CBEM is less than the modulus of the reinforced CBEMs, its rut depth is greater. The elastic modulus and viscoelastic properties of different CBEMs (as shown in Table 5.1) have a significant effect on the permanent deformation shape.

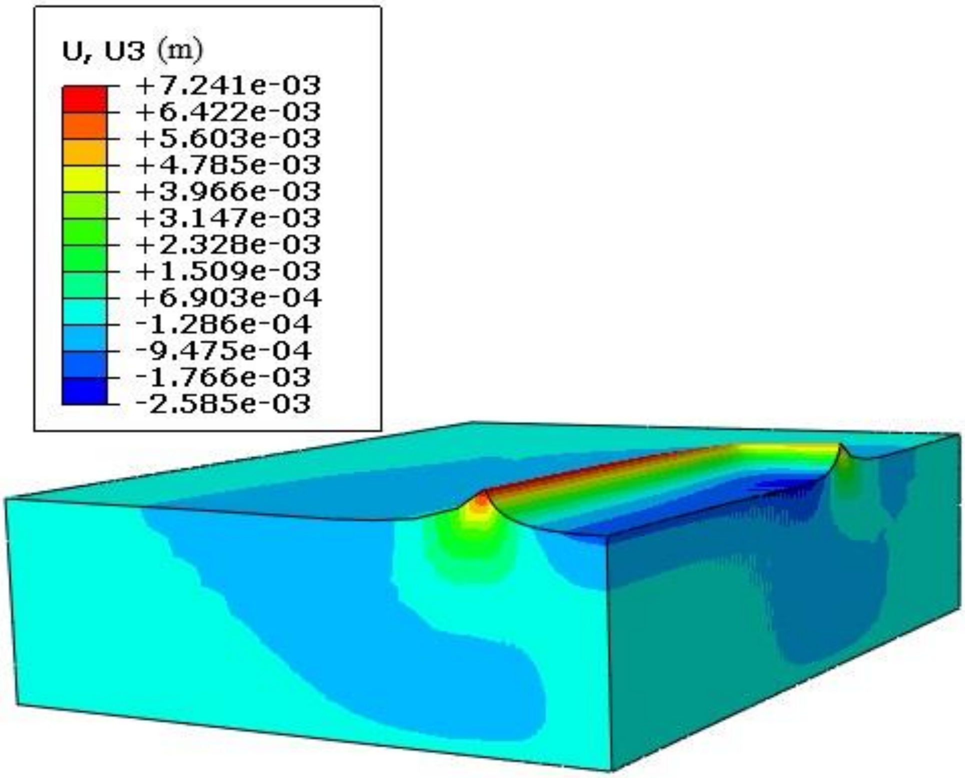


Figure 5.13: Permanent deformation shape of CON at 45 °C under repeated moving loading condition

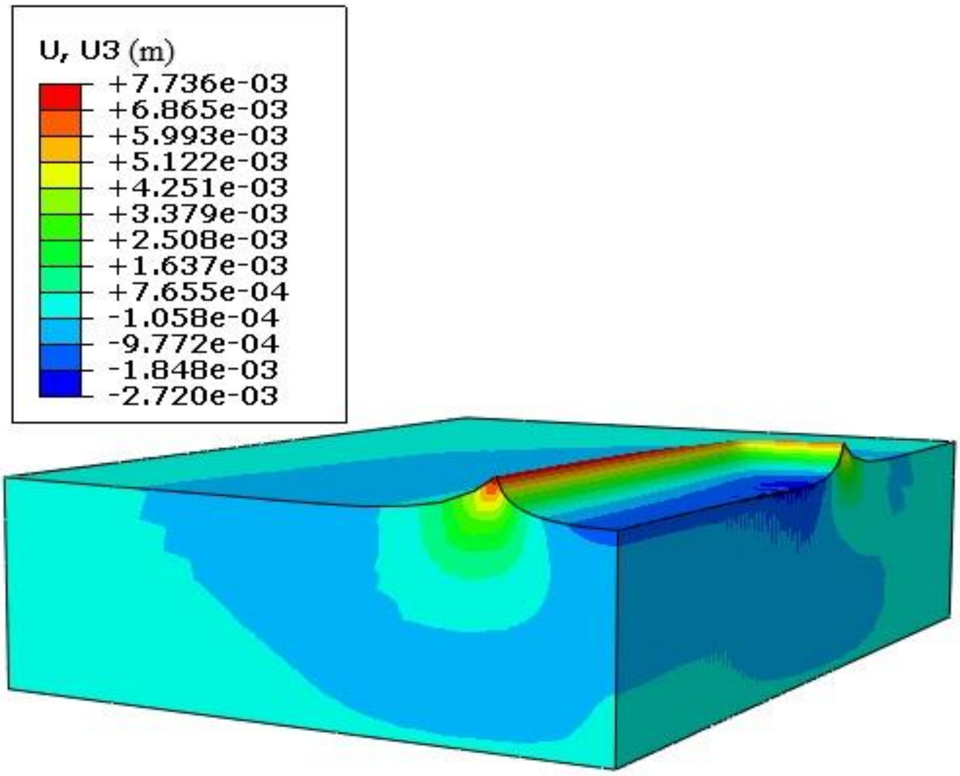


Figure 5.14: Permanent deformation shape of CON at 60 °C under repeated moving loading condition

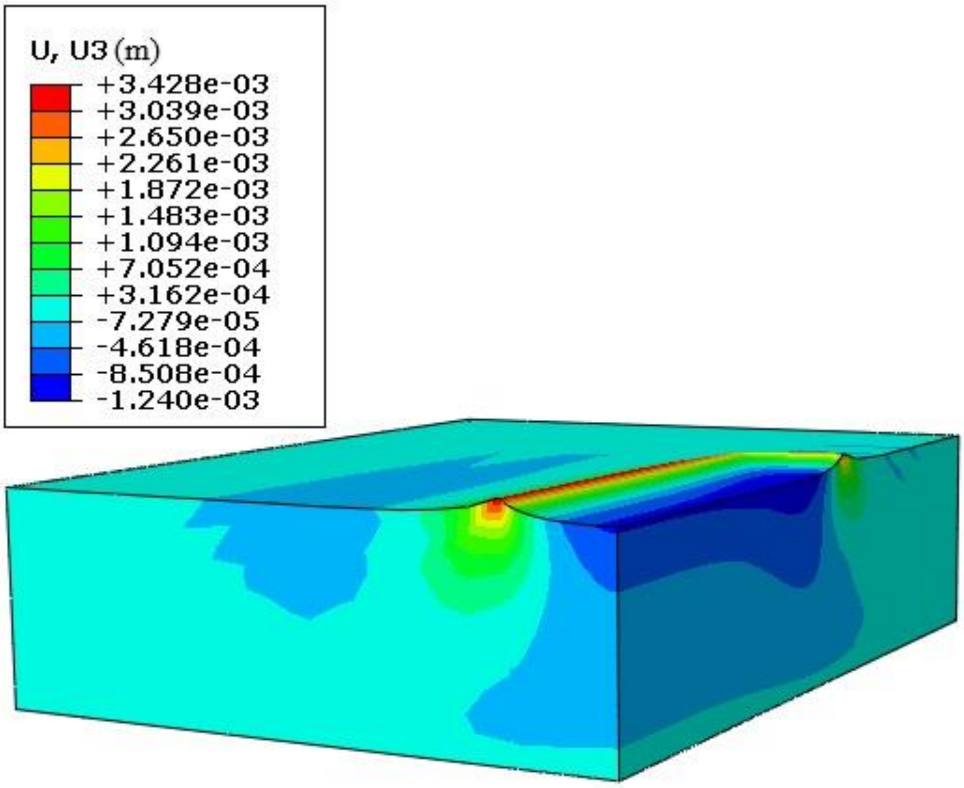


Figure 5.15: Permanent deformation shape of HMA at 45 °C under repeated moving loading condition

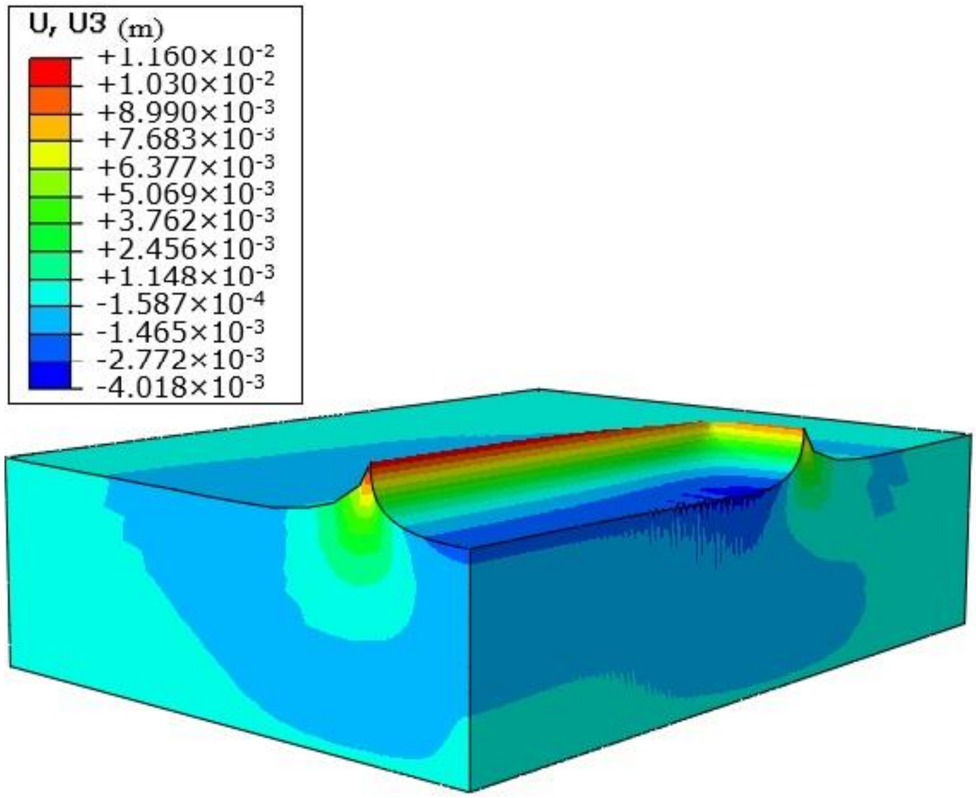


Figure 5.16: Permanent deformation shape of HMA at 60 °C under repeated moving loading condition

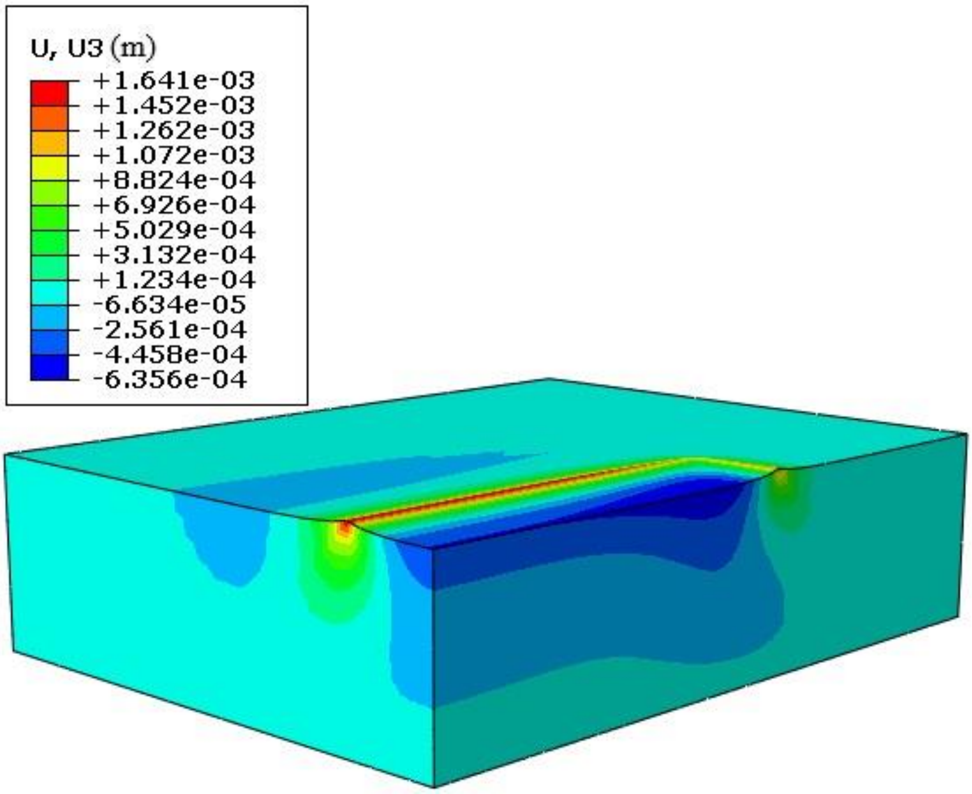


Figure 5.17: Permanent deformation shape of GLS at 45 °C under repeated moving loading condition

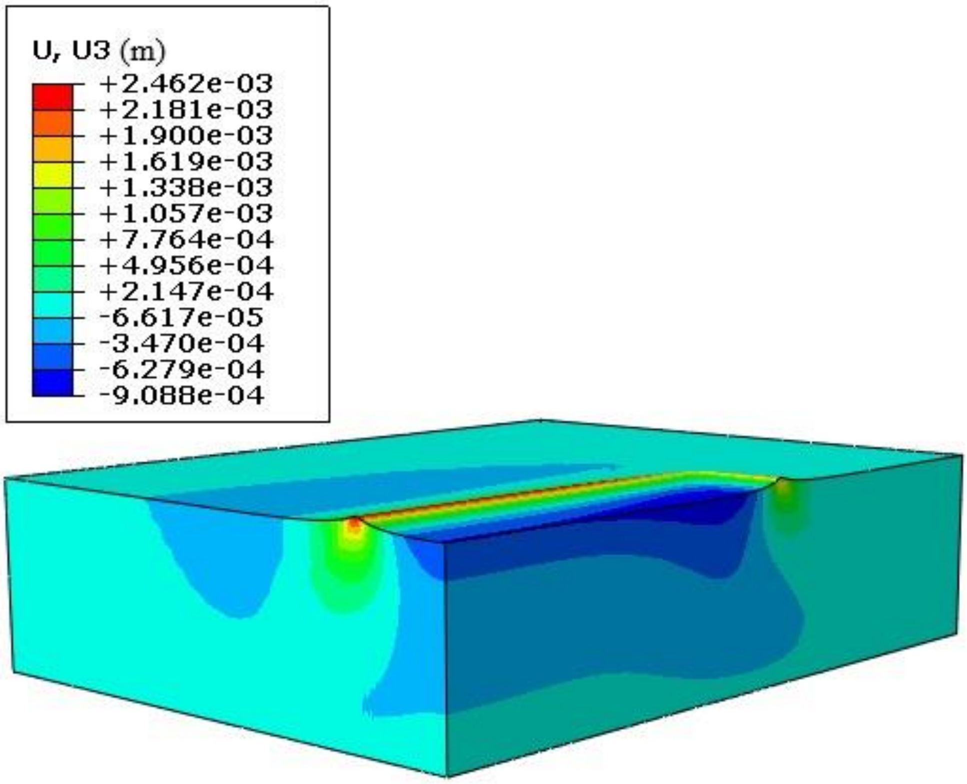


Figure 5.18: Permanent deformation shape of GLS at 60 °C under repeated moving loading condition

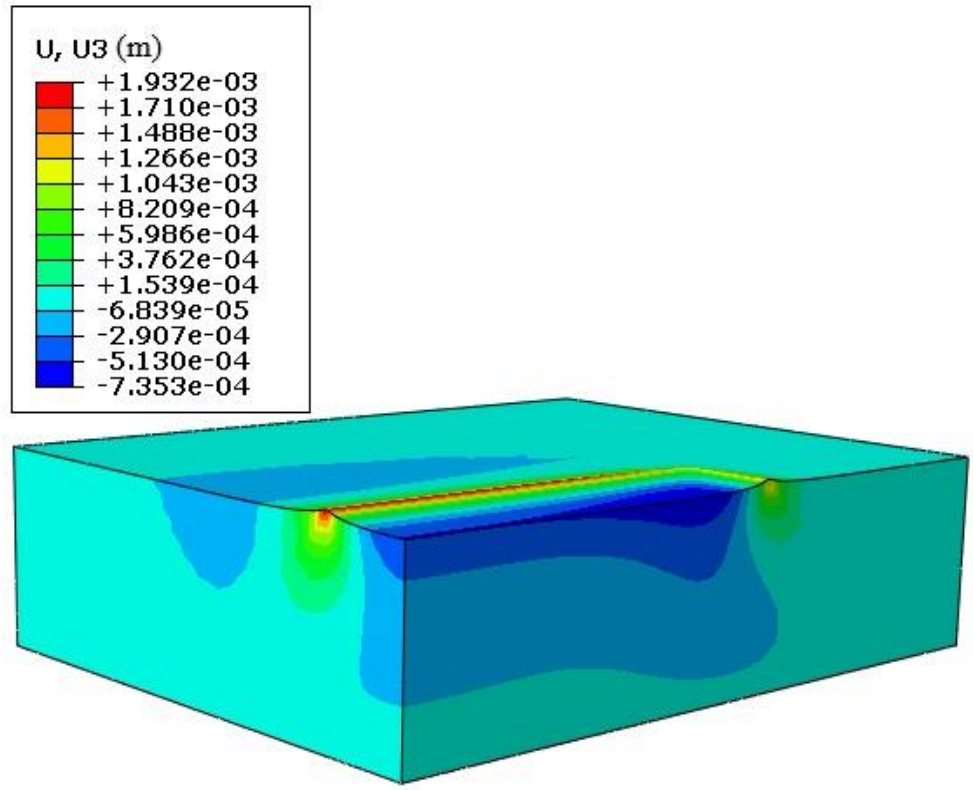


Figure 5.19: Permanent deformation shape of HEM at 45 °C under repeated moving loading condition

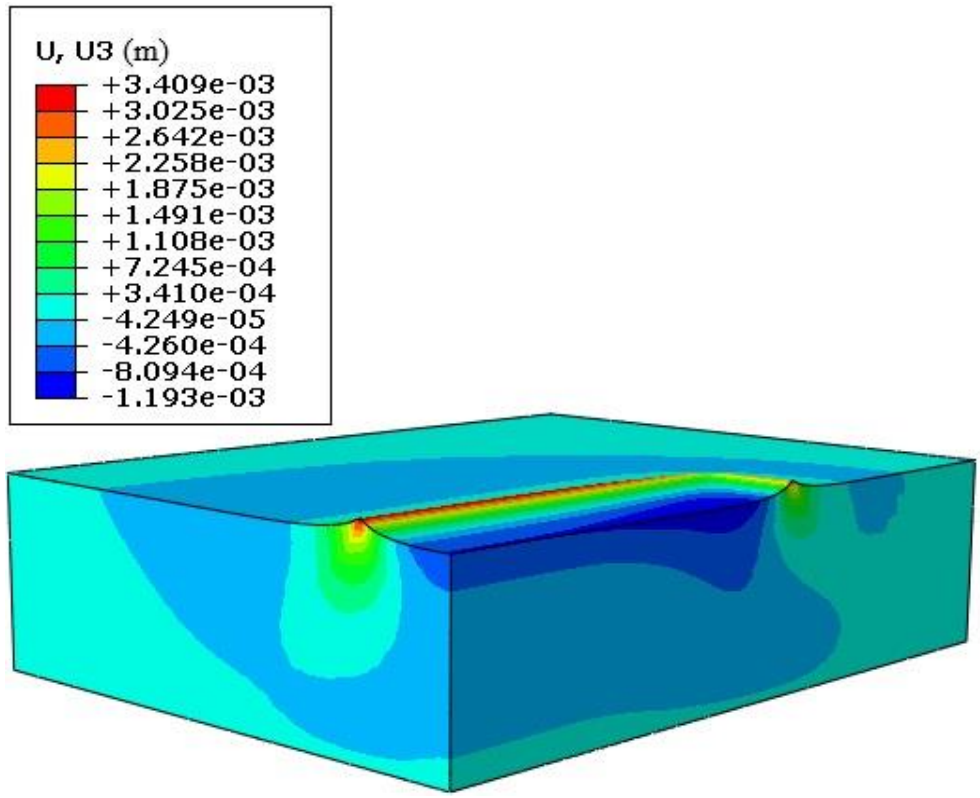


Figure 5.20: Permanent deformation shape of HEM at 60 °C under repeated moving loading condition

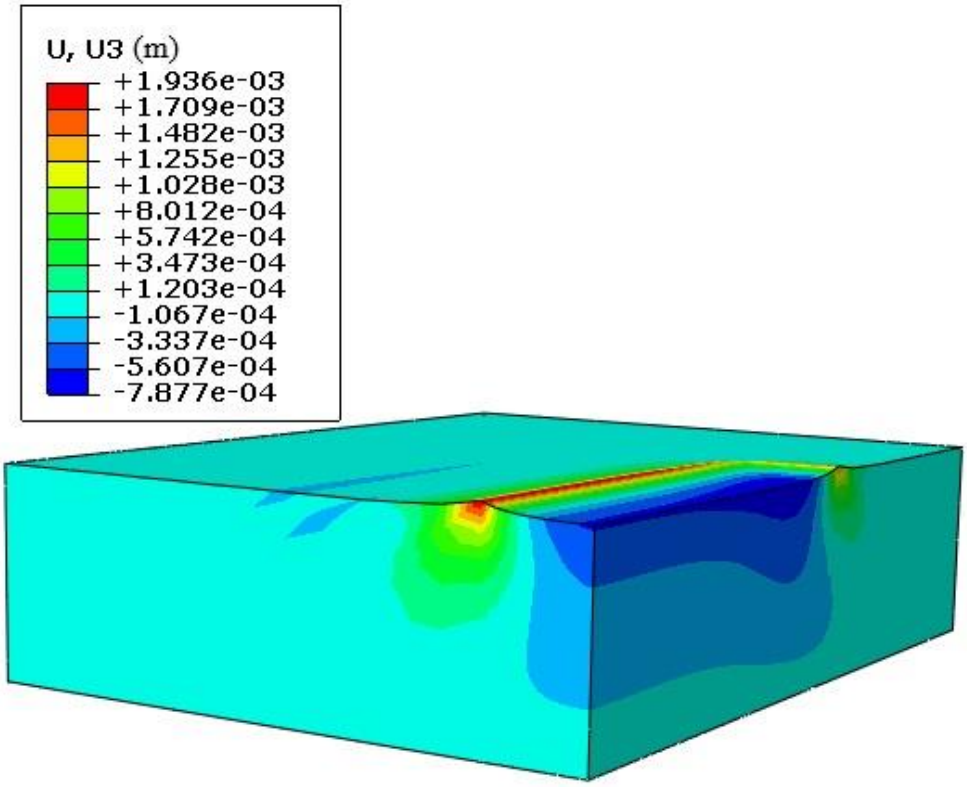


Figure 5.21: Permanent deformation shape of JUT at 45 °C under repeated moving loading condition

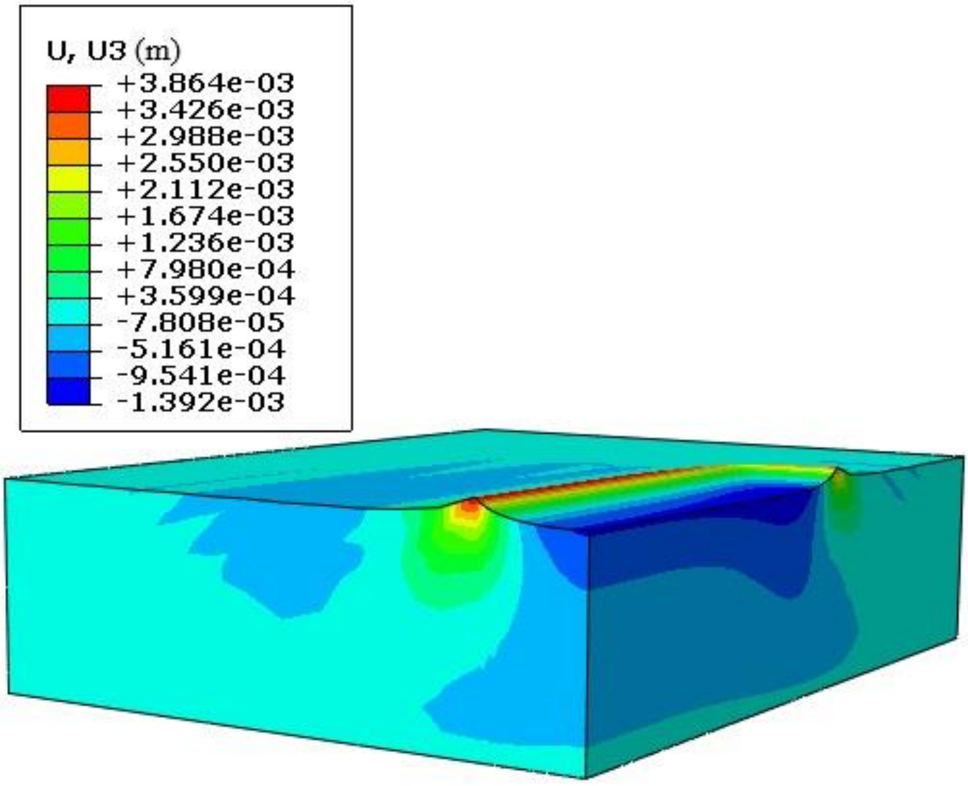


Figure 5.22: Permanent deformation shape of JUT at 60 °C under repeated moving loading condition

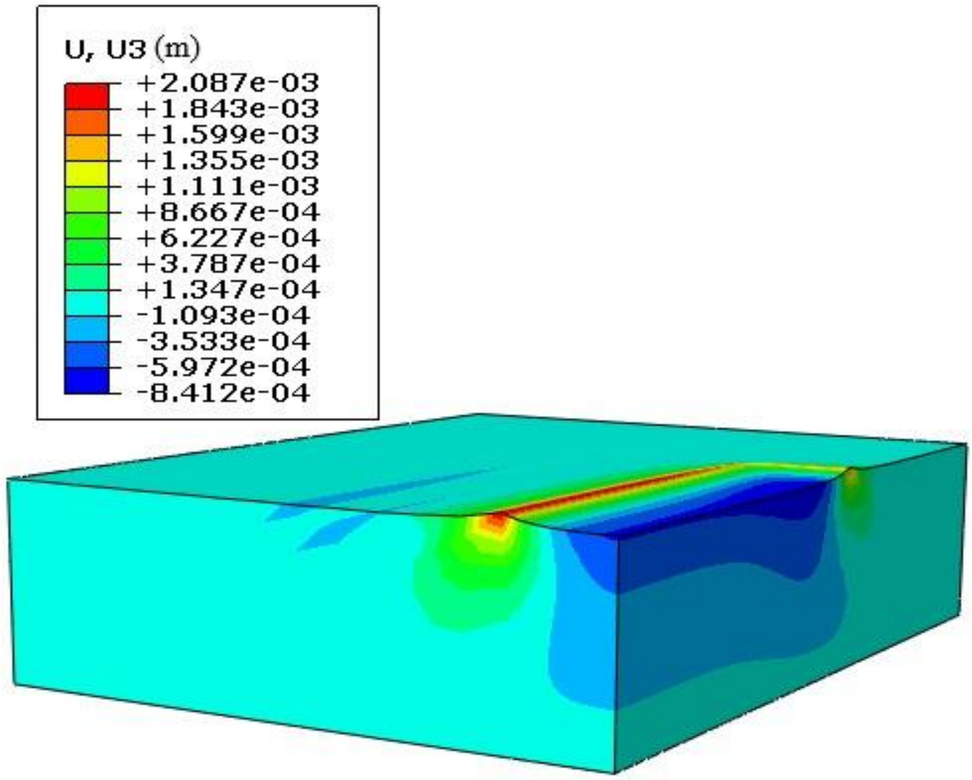


Figure 5.23: Permanent deformation shape of COI at 45 °C under repeated moving loading condition

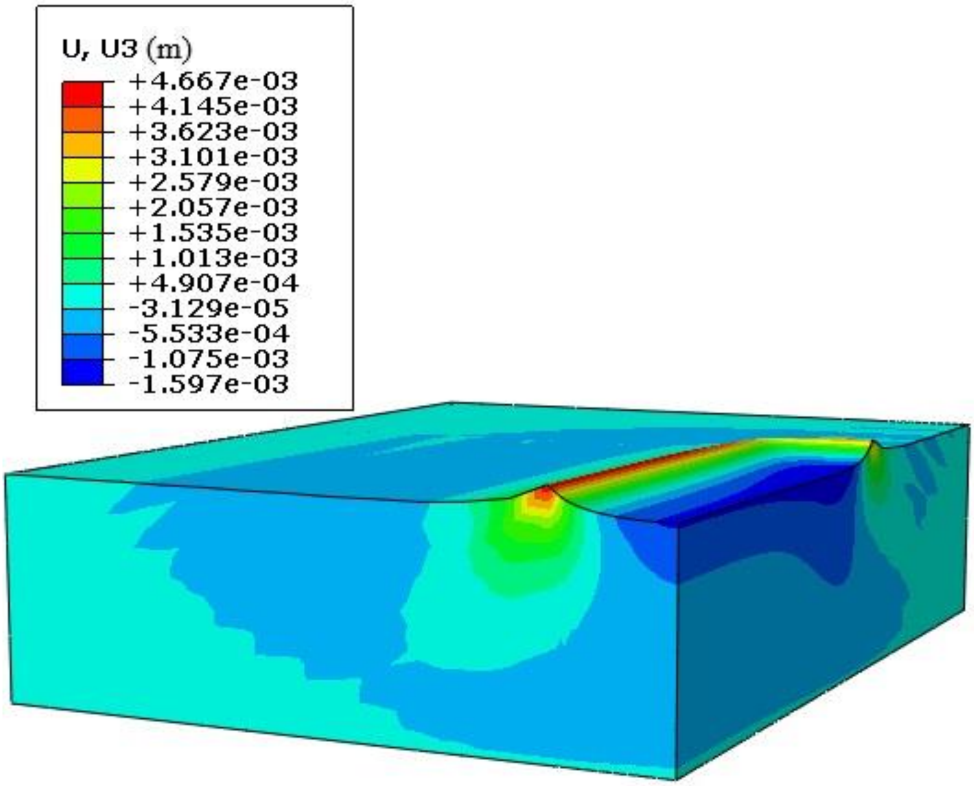


Figure 5.24: Permanent deformation shape of COI at 60 °C under repeated moving loading condition

5.3.2 Viscoplastic Model Validation

In this study, the behaviour of the bituminous mixtures is indicated to be largely controlled by the plastic with viscous deformation behaviour of the bitumen over a wide range of temperatures, stress levels and strain rates. Results from the wheel tracking tests (Chapter 4) have shown that rutting in the bituminous mixtures is non-linear. This section introduces a finite element model based on the theory of viscoplasticity which is used to simulate the measured non-linear rutting in the wheel tracking test using data from creep and relaxation testing. The model was validated by comparison with measured results from the wheel tracking tests.

5.3.2.1 Rutting in CBEMs

The viscoplastic model was developed to predict rutting in CBEMs under very heavy stress conditions. Accordingly, 20,000 repeated applied loads were performed on the bituminous slab surfaces with viscoplastic material properties. The magnitude of permanent deformation at the surface of the CBEM layer is the most significant factor characterizing the rutting performance of flexible pavements. Rutting transfer functions are the functions of shear and tensile strain at the surface of the bituminous layer under repeated applied wheel loads. It is, therefore, imperative to accurately predict deformation response characteristics at the surface of the CBEM layer for more appropriate evaluation of pavement rutting. Different rut depth measurements were obtained for the CBEM and HMA mixtures at 45 °C and 60 °C from the finite element model to be compared with experimental data. Figure 5.25 – 5.28 present these comparisons. These figures show the rutting measured on the surface of the CBEM layer under the centre of the moving wheel path, and those predicted by the viscoplastic model for both reinforced (by glass, hemp, jute and coir fibres) and conventional (no treatment) CBEM and HMA mixtures at two different temperatures

(45 °C and 60 °C). The predicted rutting matches well with the measured ruts, even though some variations were observed (between the predicted and measured rutting) between mixture types and temperatures. This small variation between the predicted and measured rutting is because the model assumes that the material properties are uniform and homogenous, whilst in reality the mixtures include some voids and different aggregate interlocks. Also, in reality, the temperature and viscosity of the mixtures cannot be distributed equally for the whole mixture and this is so hard to model because of the difficulty of setting different temperatures and viscosities for each particle of the mixture. However, these discrepancies do not affect the validation of the FE model. It can clearly be seen from the Figure 5.25 – 5.28 that there is good agreement on rut depth measurements between the model and the test results. It is interesting to note the distinctive difference in the rutting due to the different fibres used. The measured and predicted permanent deformation of the bituminous layer that occurs along the moving area under the wheel path is calculated as the average deformation along and under the wheel path. The results clearly show that the CBEM with natural and synthetic fibres induces reduced rutting on the bituminous surface layer, this positively affects the rutting resistance of flexible pavements.

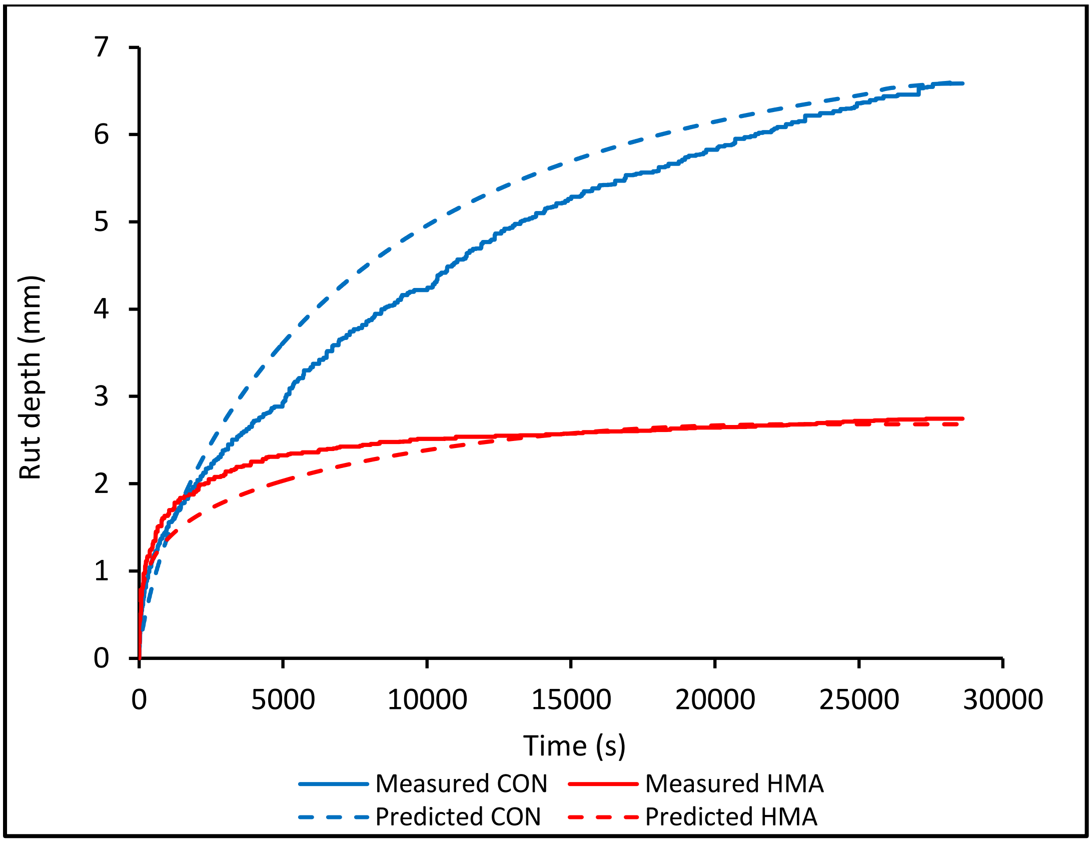


Figure 5.25: Rutting of viscoplastic model for conventional mixtures at 45 °C

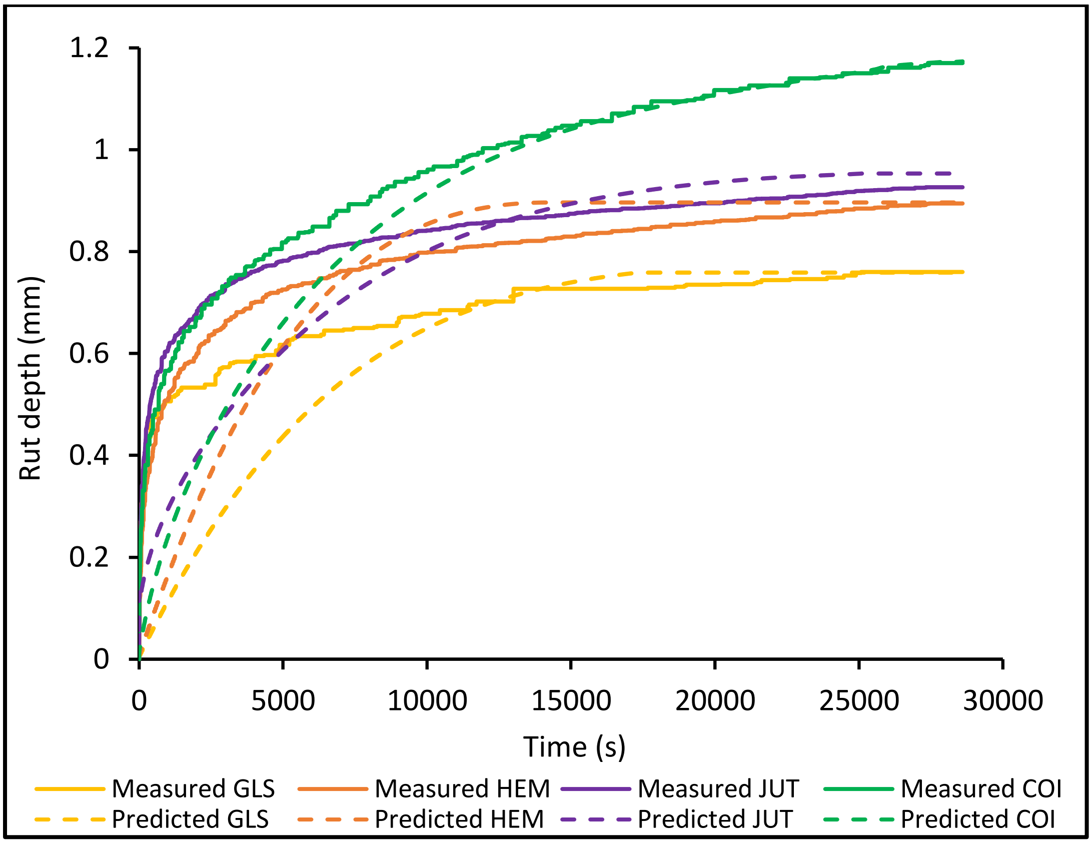


Figure 5.26: Rutting of viscoplastic model for reinforced mixtures at 45 °C

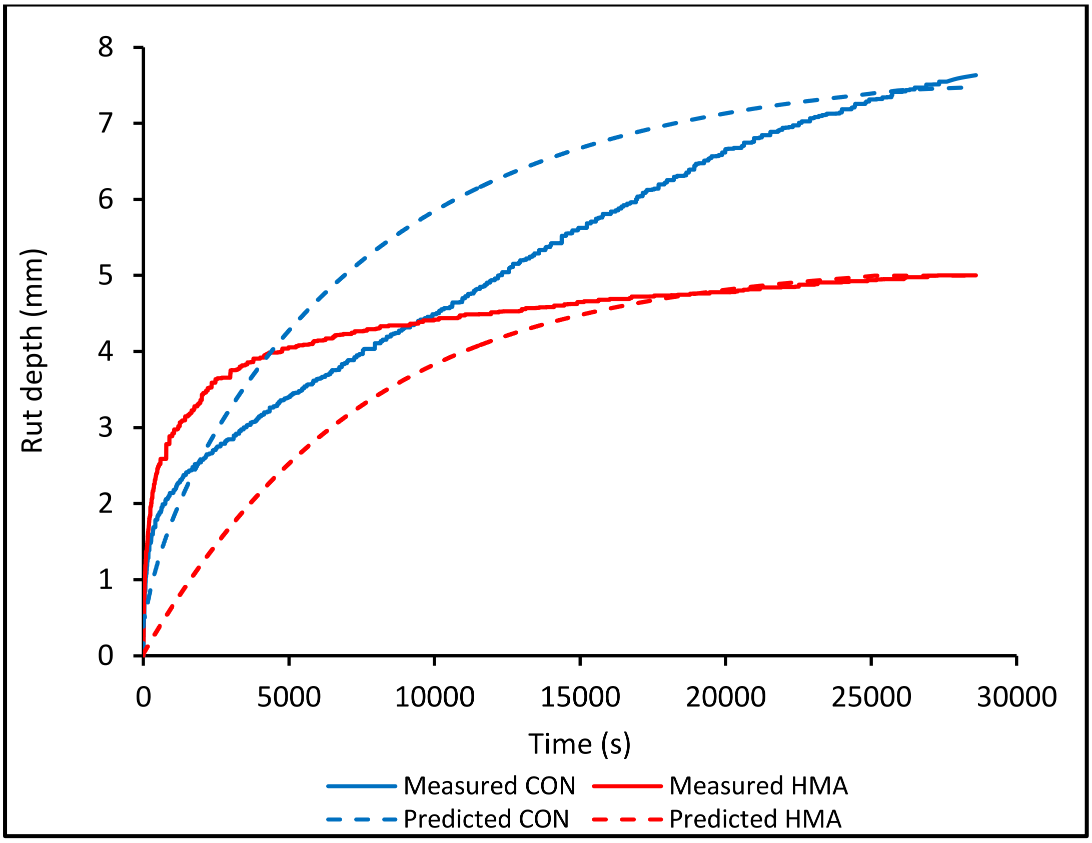


Figure 5.27: Rutting of viscoplastic model for conventional mixtures at 60 °C

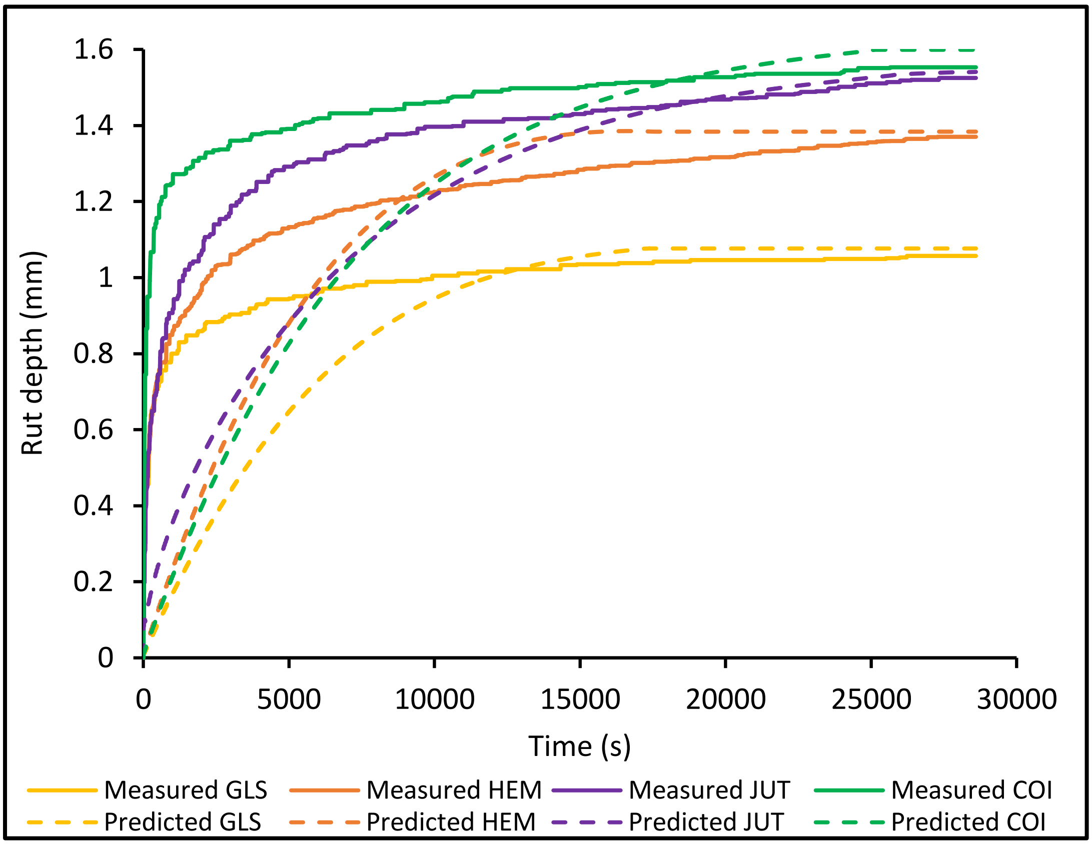


Figure 5.28: Rutting of viscoplastic model for reinforced mixtures at 60 °C

5.3.2.2 Transverse Rut Profile of CBEMs

In this section, six types of bituminous mixtures were simulated using the viscoplastic model to compare quantitatively and qualitatively the predicted rutting of such mixtures with those measured in the lab. Figure 5.29 – 5.40 present the transverse rut profile of different bituminous mixtures for both measured and predicted deformation. Rutting consists of depression underneath the moving wheel load and heave outside and perpendicular to the loaded area. In this case, the stresses start to develop on the surface layer mainly under the edge of the tyre. The stresses developed (shear stresses) are the cause of viscoplastic flow in the direction from the load centre towards the edge of the tyre. Hence, substantial heave developed at the edges of the wheel paths. In addition, it can be noticed that there is a permanent deformation underneath the moving wheel load. The reinforced CBEMs with natural and synthetic fibres produced less permanent deformation than the conventional CBEM and HMA mixtures, both in terms of depression and heave. This is likely due to the higher shear and tensile strength of the reinforced mixtures that were improved by using fibres as reinforcing material in CBEM.

The transverse rut profile of the simulated slabs follow the same trend as the slabs that were utilised in the lab using the wheel tracking tests. In both cases, good correlation was obtained between the numerical prediction and experimental response. The simulated trace for all mixtures accurately captures the upheaval along the sides of the rut and the surface depression under the wheel path. Qualitative comparisons of the measured and predicted CBEM and HMA responses prove that the finite element model is capable of predicting rutting based on the correct assumed material properties of the material, corresponding to the assumptions of repeated load with different temperatures.

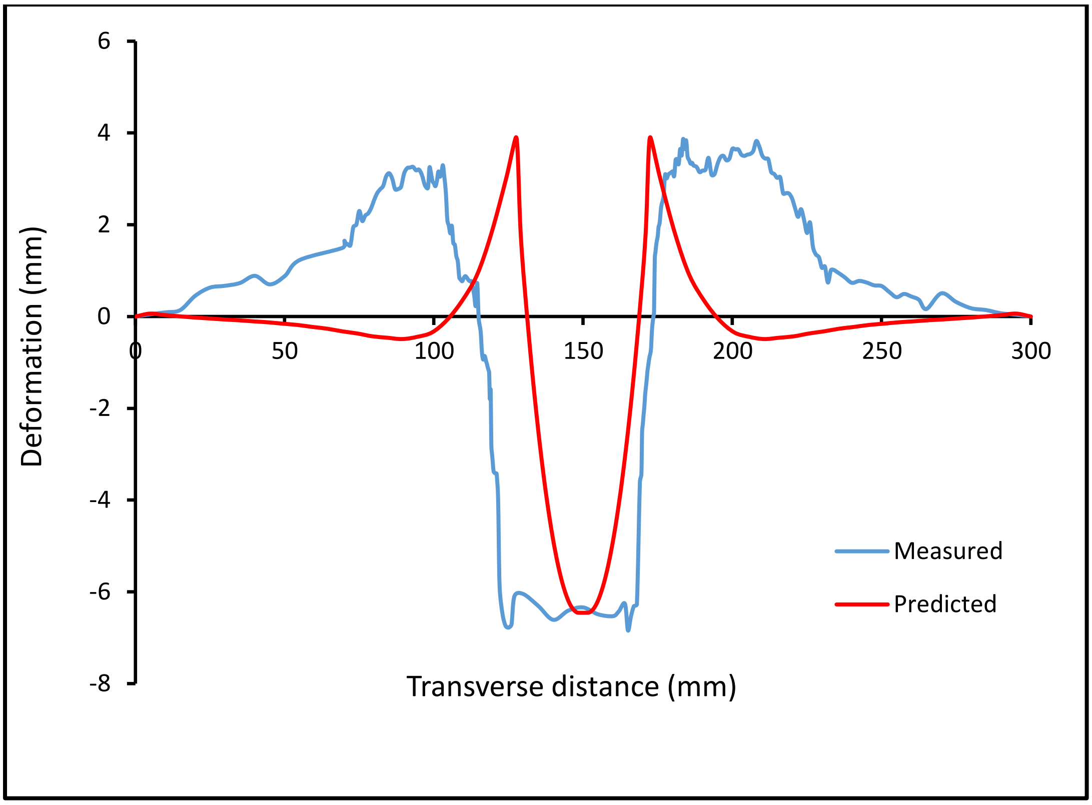


Figure 5.29: Measured vs predicted transverse rut profile of CON at 45 °C

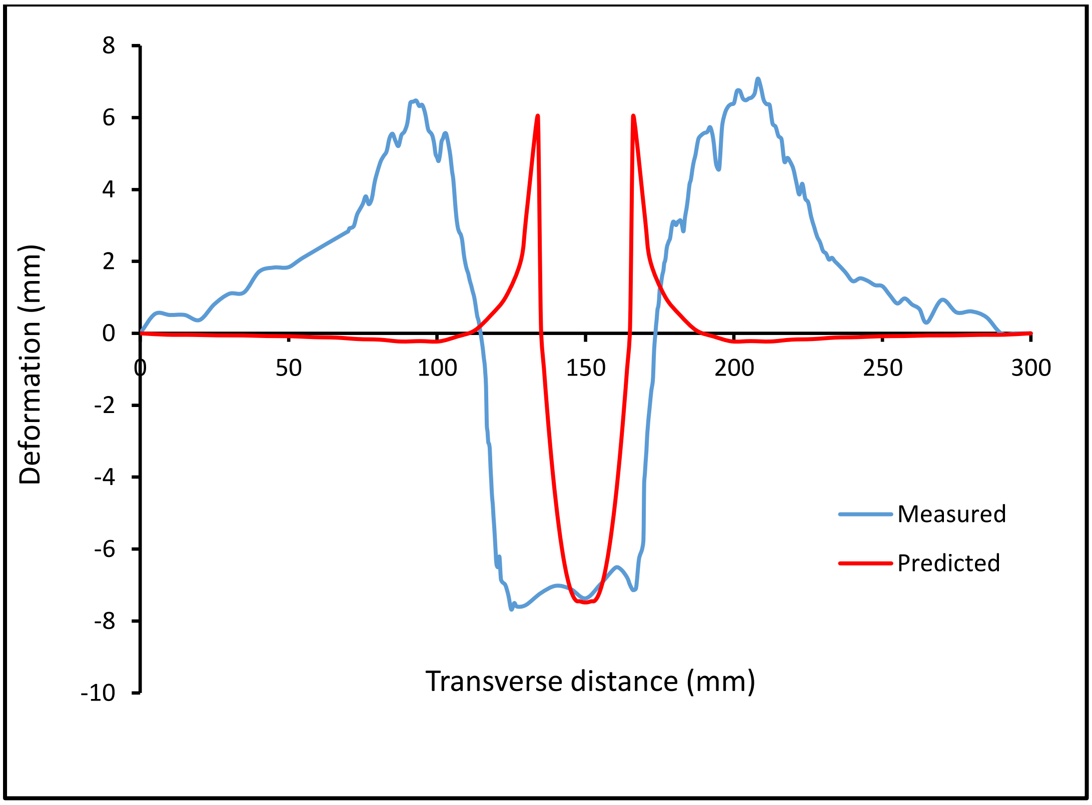


Figure 5.30: Measured vs predicted transverse rut profile of CON at 60 °C

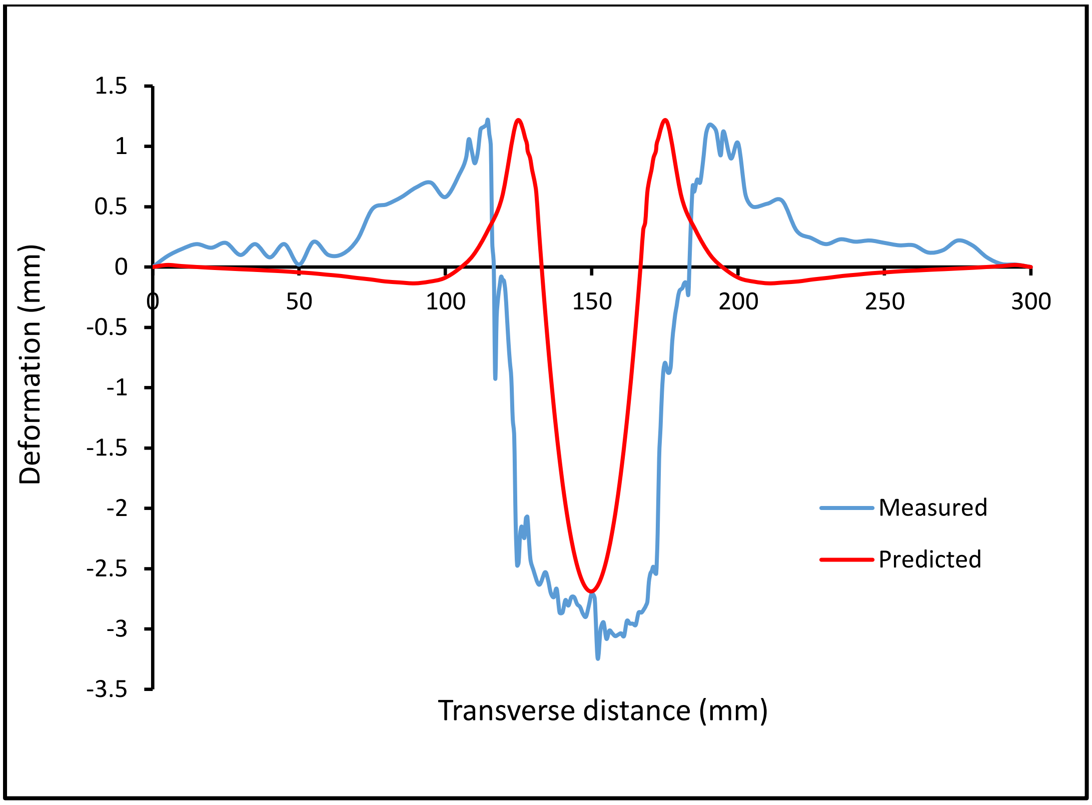


Figure 5.31: Measured vs predicted transverse rut profile of HMA at 45 °C

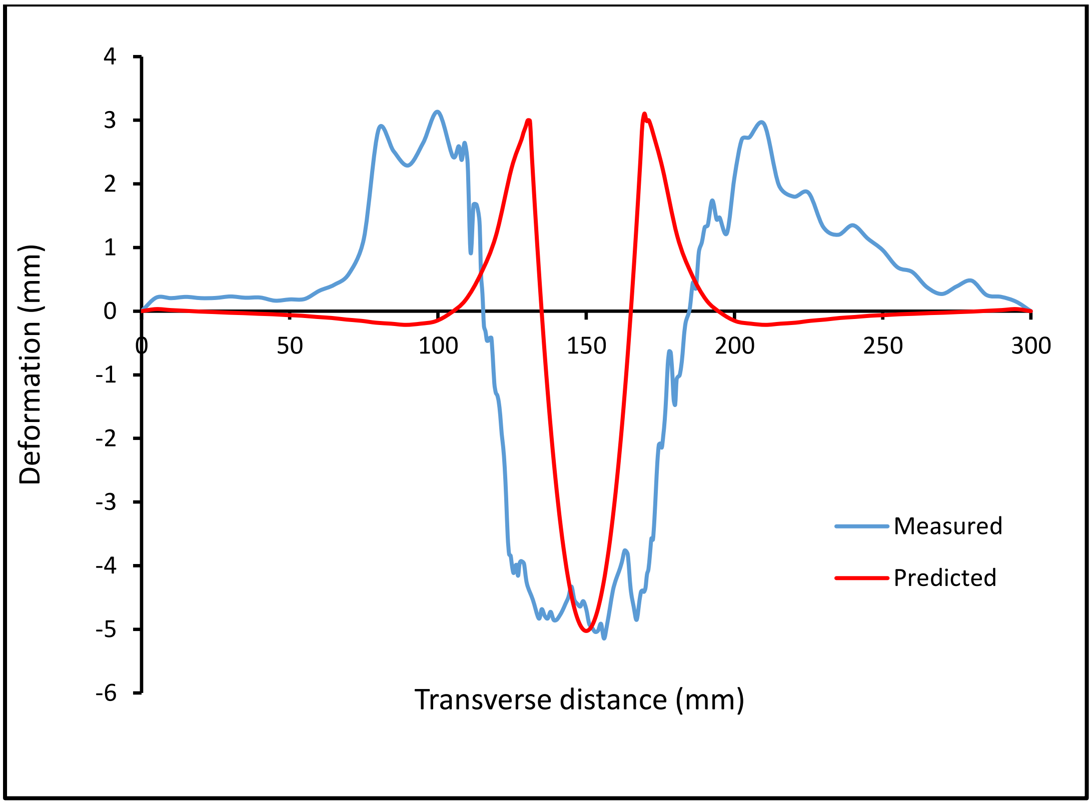


Figure 5.32: Measured vs predicted transverse rut profile of HMA at 60 °C

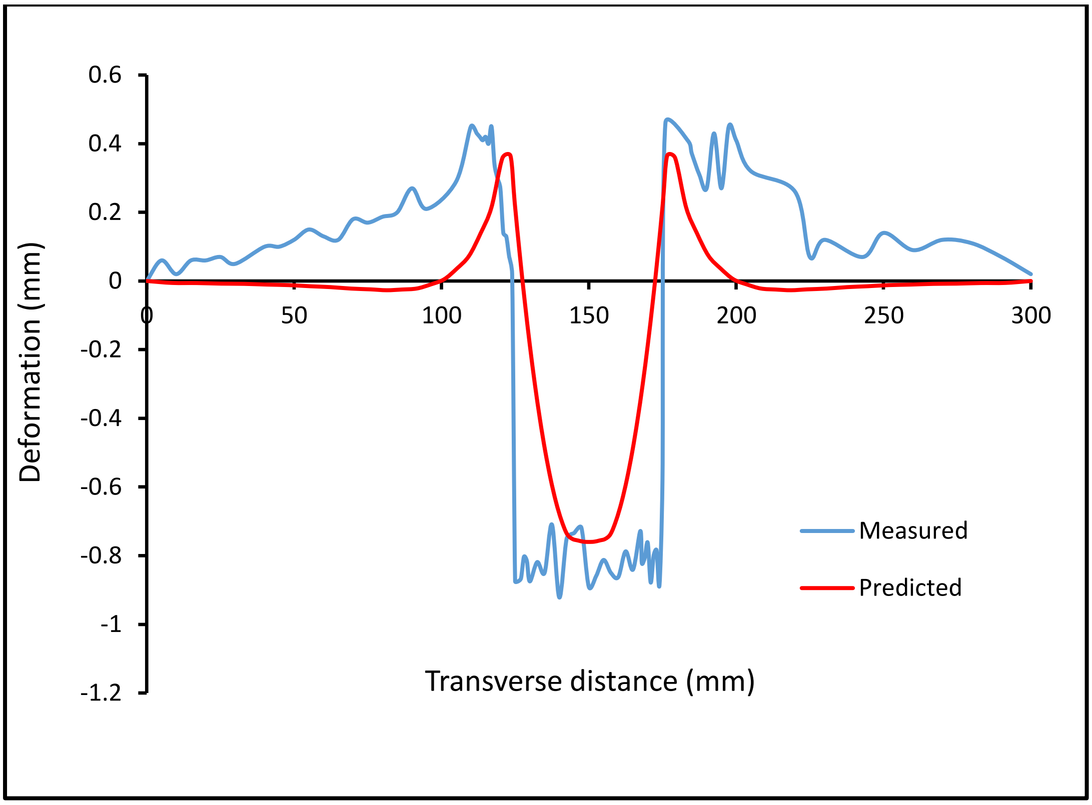


Figure 5.33: Measured vs predicted transverse rut profile of reinforced GLS at 45 °C

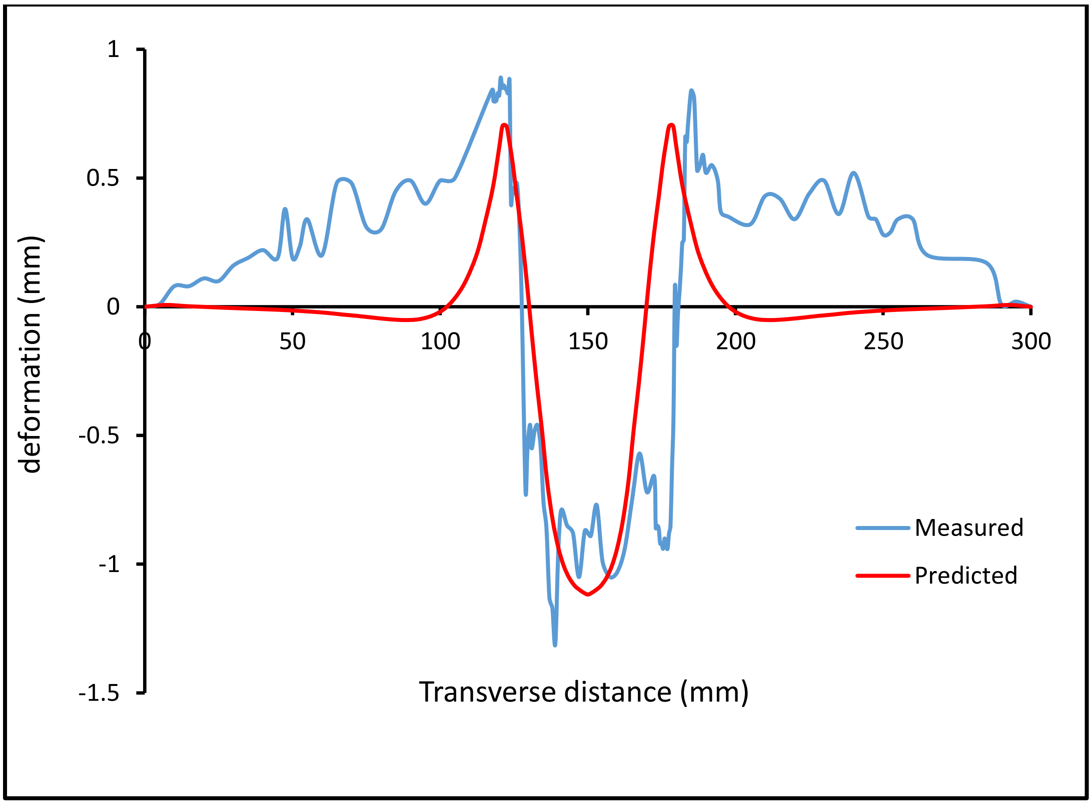


Figure 5.34: Measured vs predicted transverse rut profile of reinforced GLS at 60 °C

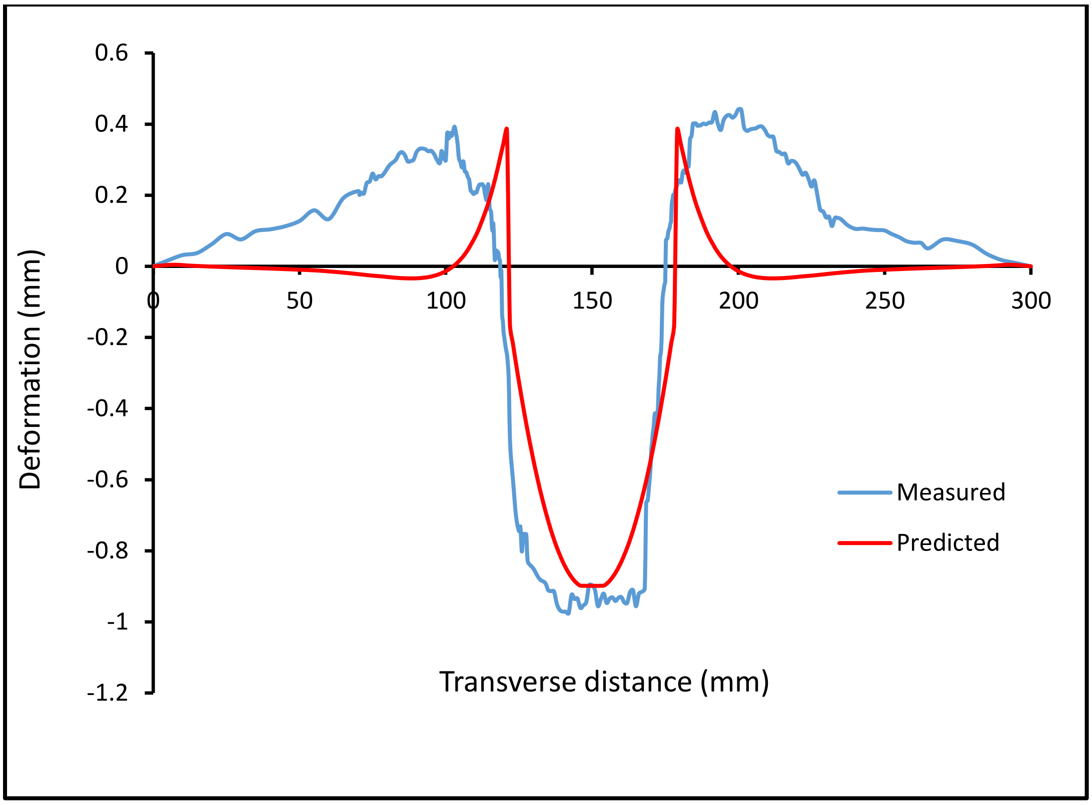


Figure 5.35:Measured vs predicted transverse rut profile of reinforced HEM at 45 °C

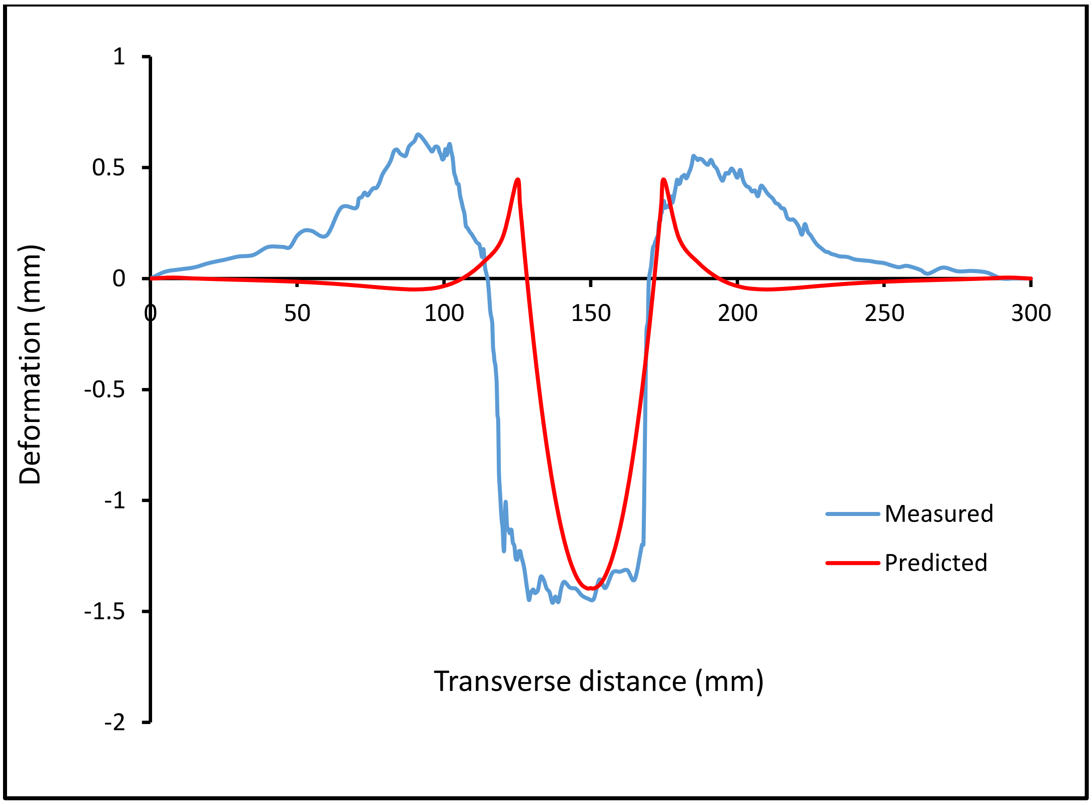


Figure 5.36:Measured vs predicted transverse rut profile of reinforced HEM at 60 °C

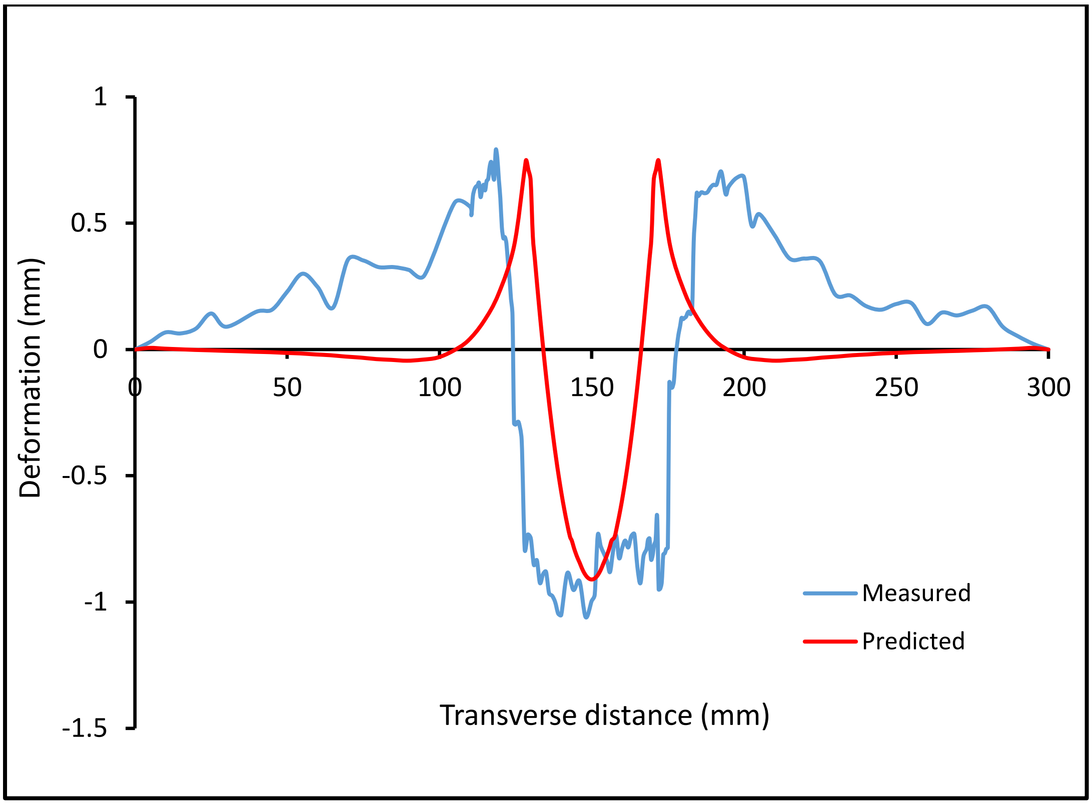


Figure 5.37: Measured vs predicted transverse rut profile of reinforced JUT at 45 °C

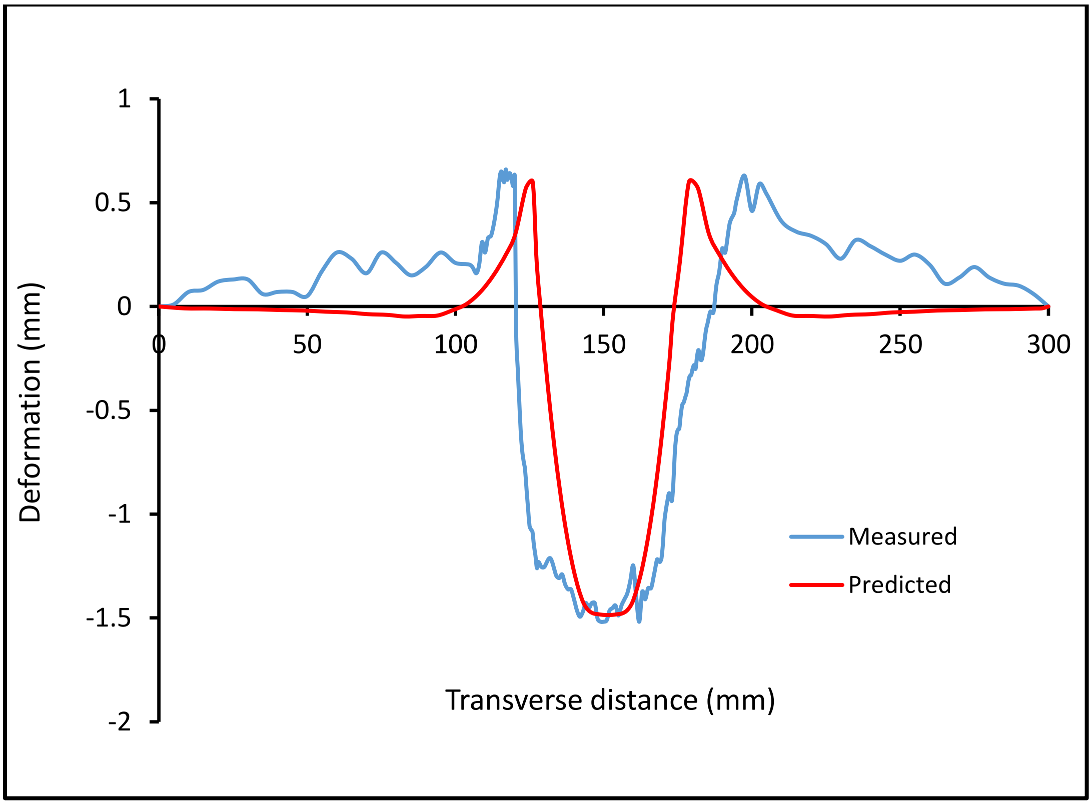


Figure 5.38: Measured vs predicted transverse rut profile of reinforced JUT at 60 °C

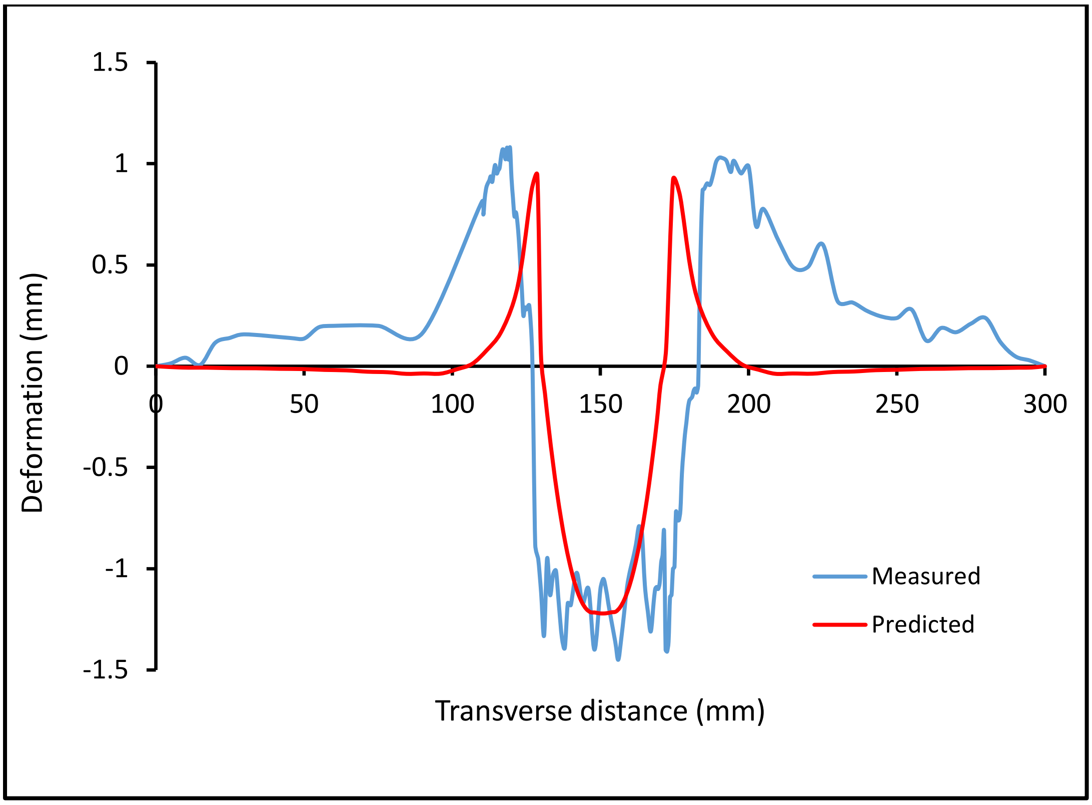


Figure 5.39: Measured vs predicted transverse rut profile of reinforced COI at 45 °C

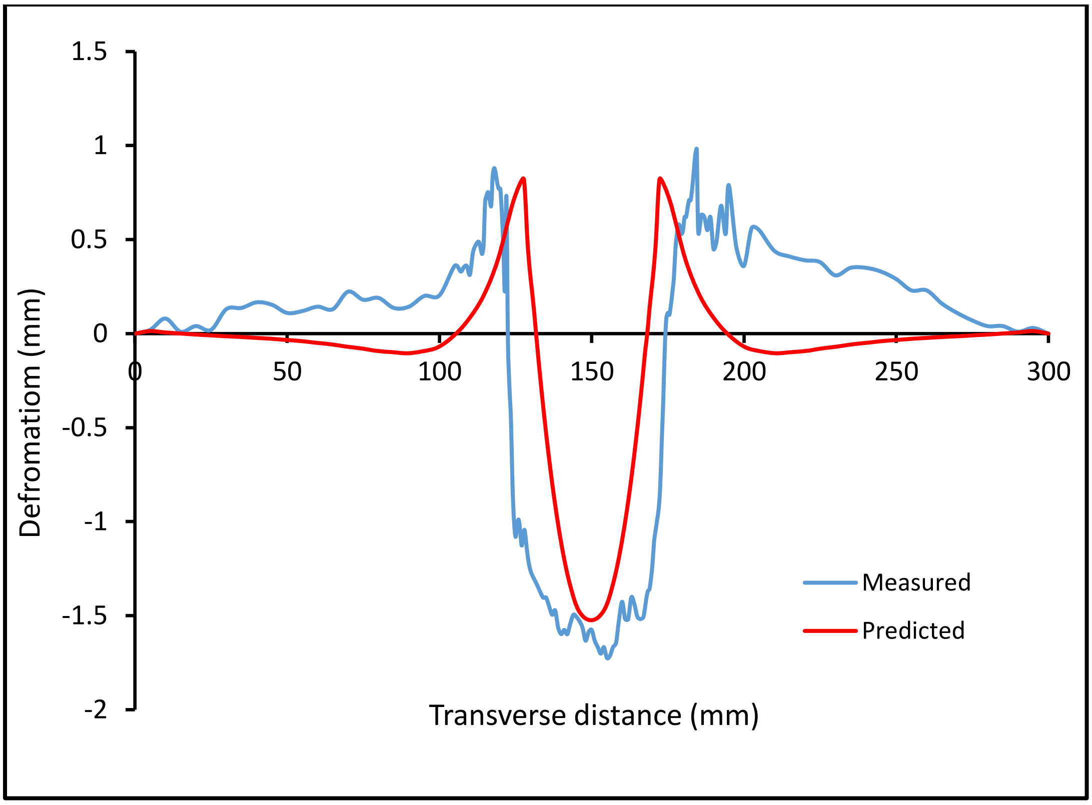


Figure 5.40: Measured vs predicted transverse rut profile of reinforced COI at 60 °C

5.4 Parametric Study Based on the FE Models

The validated numerical models presented in Section 5.3 were used to carry out parametric studies in order to investigate the effect of other parameters on the rutting behaviour of the CBEM, which were not covered. The parametric studies are divided into four parts, which are the static loading attribute, temperature effects, repeated applied wheel load speed in addition to investigating the effect of different stress distributions. These parts present the results of parametric studies, which were conducted to investigate the effects of the material properties (viscoelastic and viscoplastic) on the rutting response of the bituminous mixtures. The results of the studies are presented to examine the influence of the natural and synthetic fibres as reinforcing materials in CBEM on the behaviour of such mixtures to resist rutting.

5.4.1 Static Loading Attributes

The permanent deformation of the different CBEMs, after 3,472 repeated applied moving loads (about 5,000 s), were illustrated in Section 5.3.1. The results of the equivalent static loading condition (5,000 s loading) on the same viscoelastic models are also presented in Figure 5.41 – 5.52. The permanent deformation found in the static loading condition is greater than that of the repeated moving loading condition for all mixture types because there is no rest interval to let mixtures recover (viscoelastic properties) in the static loading condition (Shanbara, Ruddock and Atherton, 2018b).

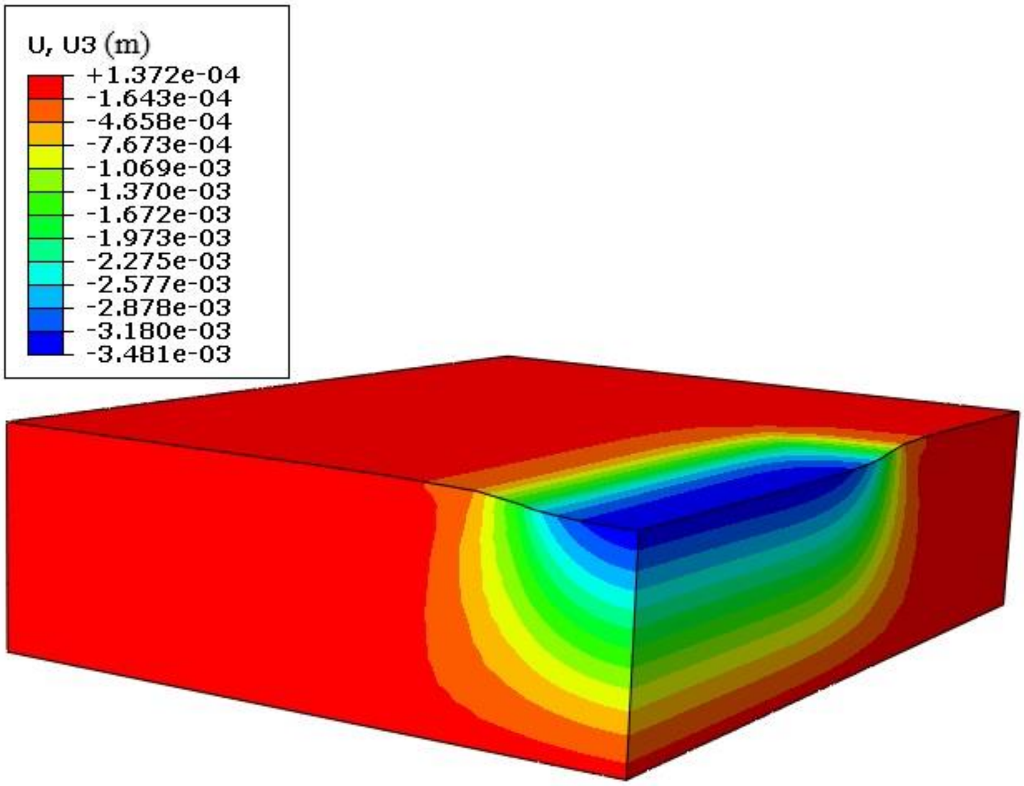


Figure 5.41: Permanent deformation shape of CON at 45 °C under static loading condition

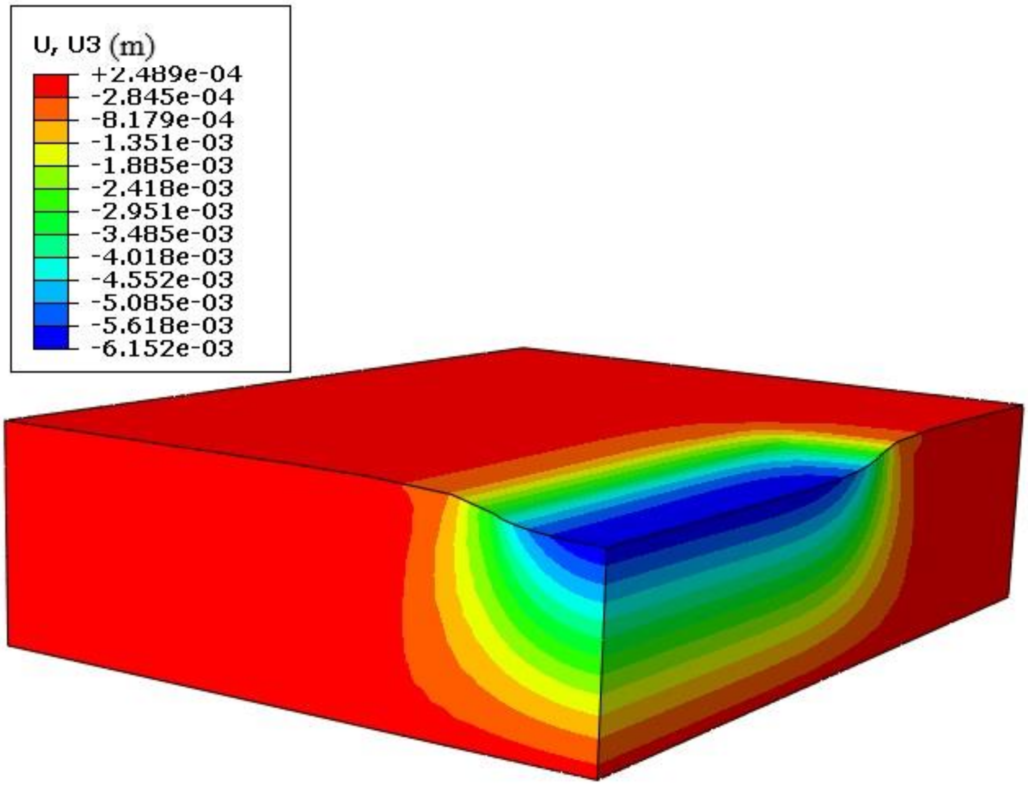


Figure 5.42: Permanent deformation shape of CON at 60 °C under static loading condition

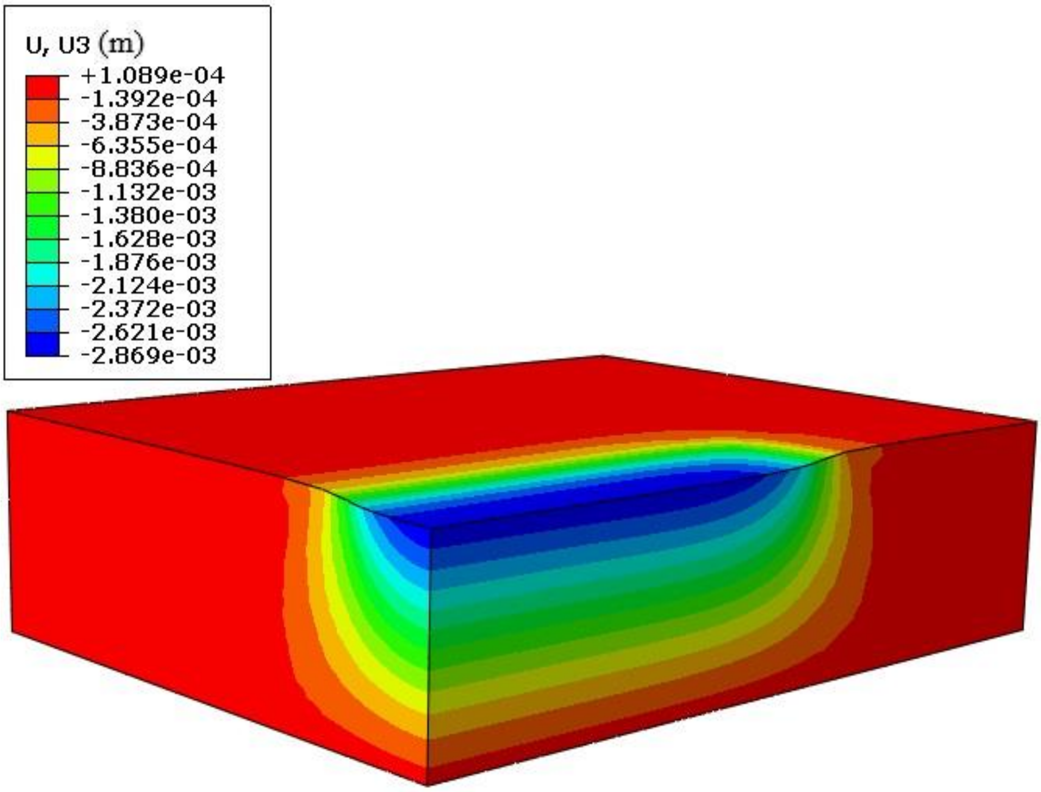


Figure 5.43: Permanent deformation shape of HMA at 45 °C under static loading condition

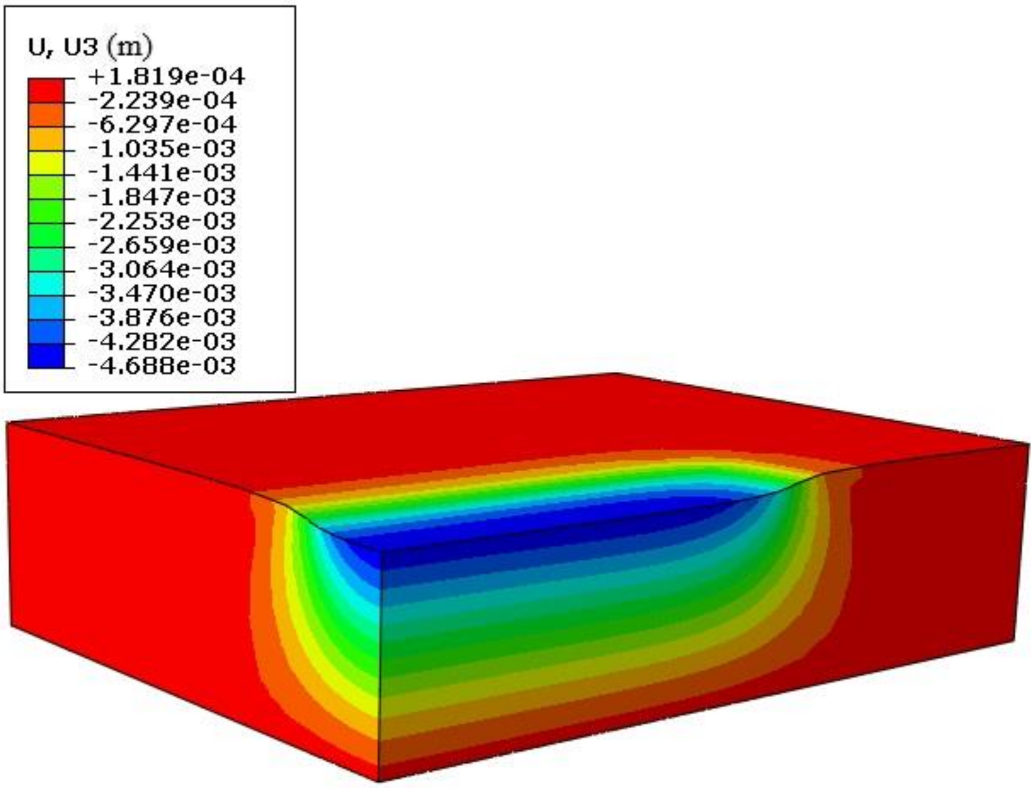


Figure 5.44: Permanent deformation shape of HMA at 60 °C under static loading condition

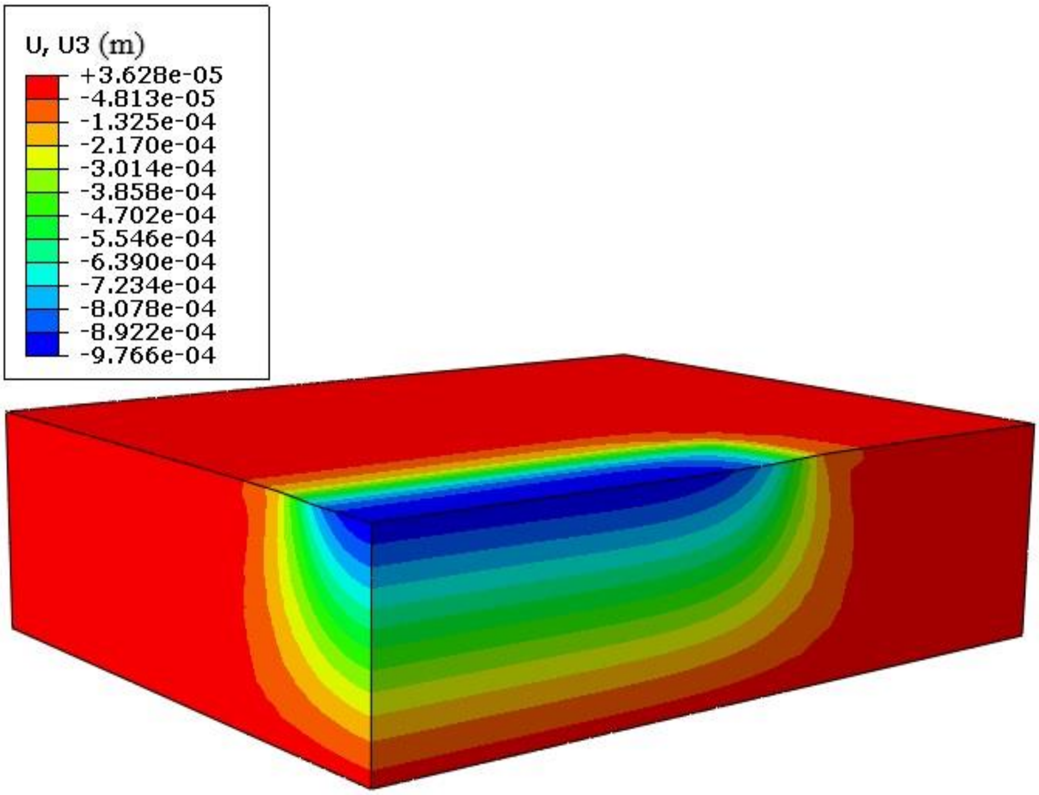


Figure 5.45: Permanent deformation shape of GLS at 45 °C under static loading condition

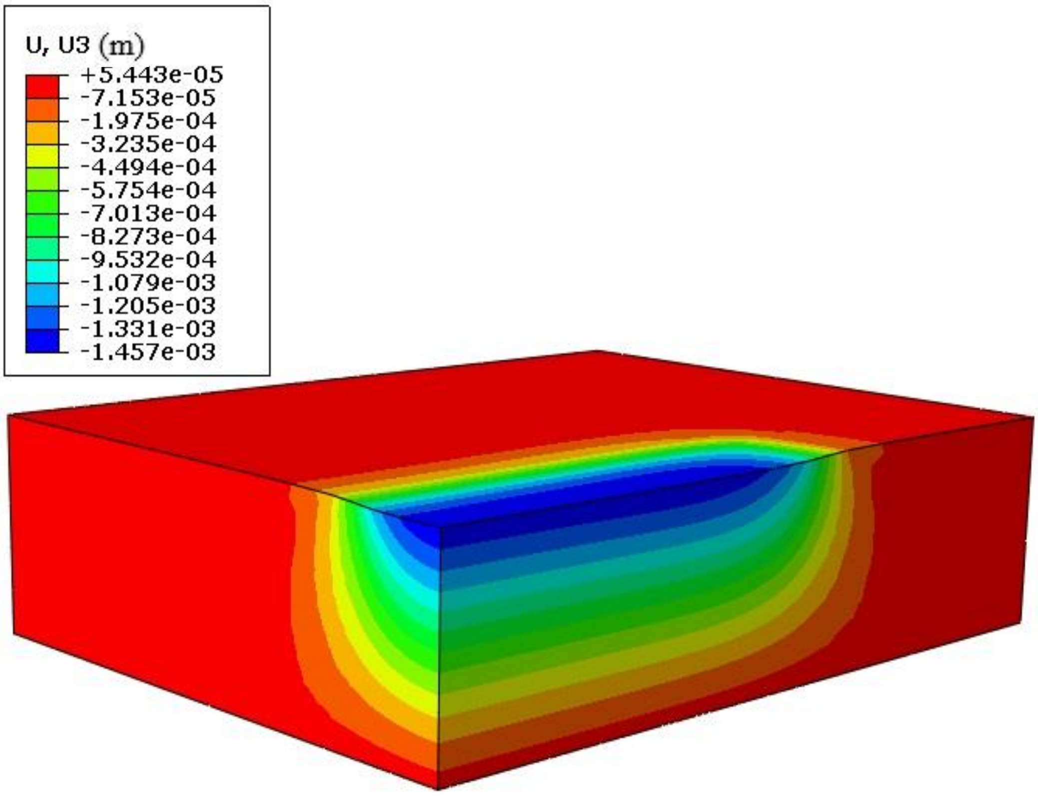


Figure 5.46: Permanent deformation shape of GLS at 60 °C under static loading condition

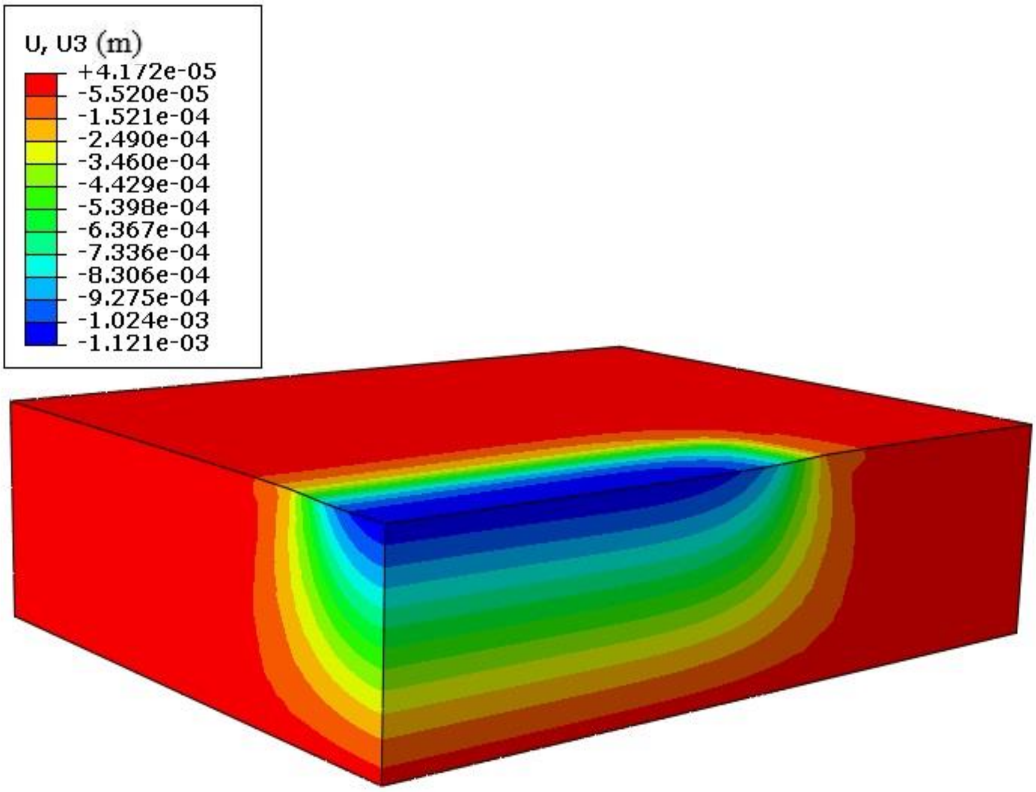


Figure 5.47: Permanent deformation shape of HEM at 45 °C under static loading condition

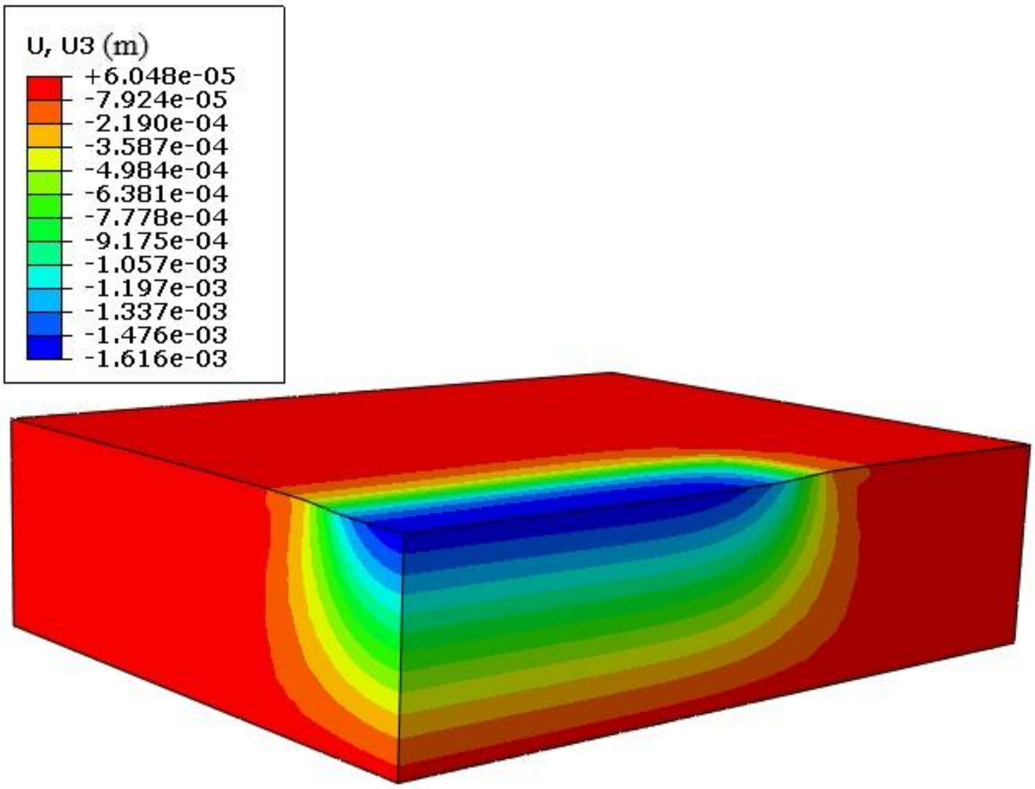


Figure 5.48: Permanent deformation shape of HEM at 60 °C under static loading condition

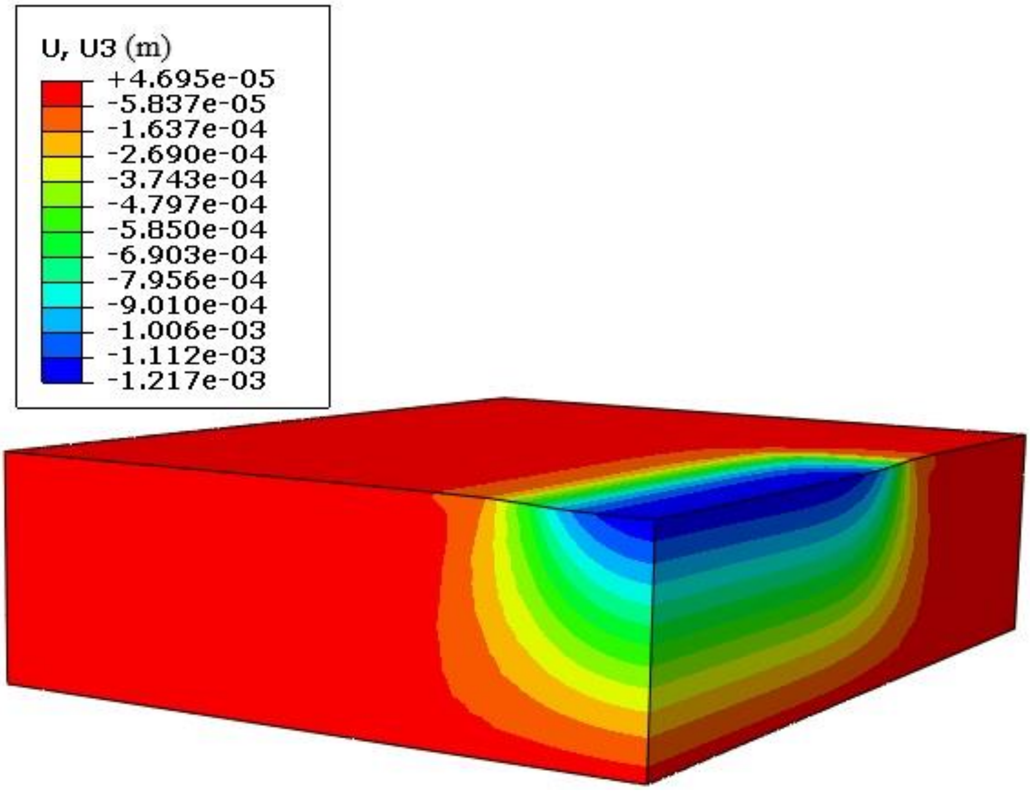


Figure 5.49: Permanent deformation shape of JUT at 45 °C under static loading condition

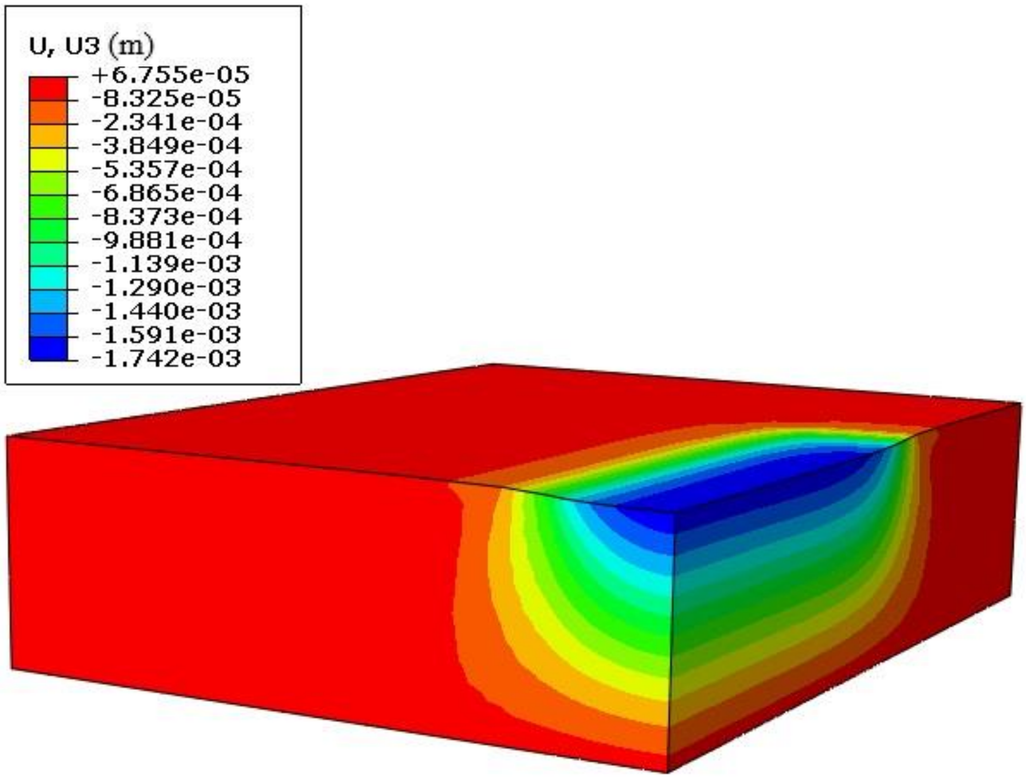


Figure 5.50: Permanent deformation shape of JUT at 60 °C under static loading condition

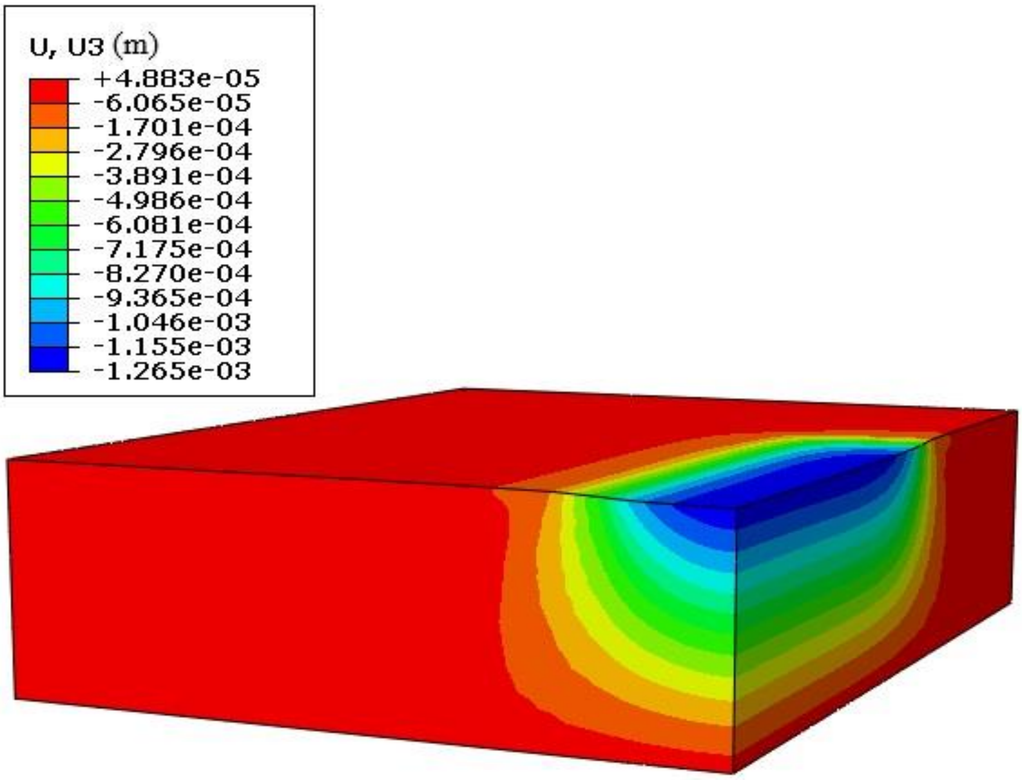


Figure 5.51: Permanent deformation shape of COI at 45 °C under static loading condition

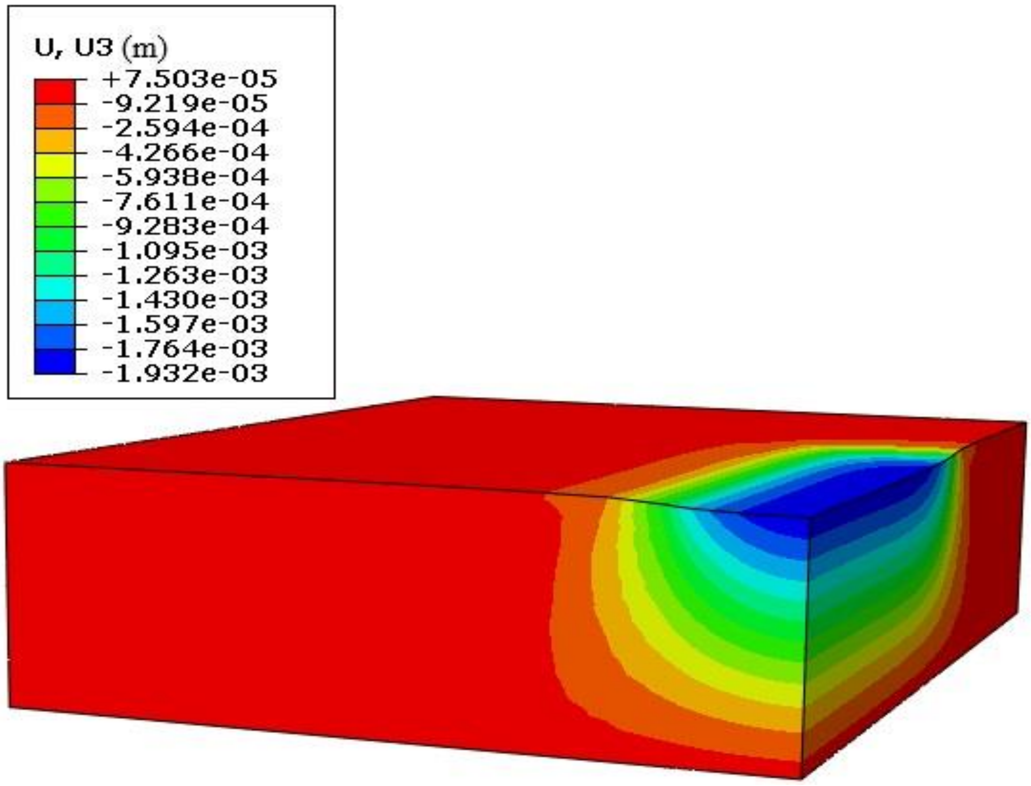


Figure 5.52: Permanent deformation shape of COI at 60 °C under static loading condition

To examine the effect of the static loading on the permanent deformation of the reinforced and unreinforced CBEM and HMA mixtures, one loading step with loading time of 28,600 seconds was applied on the surface of the bituminous mixtures. The viscoplastic properties of the materials at certain temperatures were used in this model to define the bituminous materials. Figure 5.53 and 5.54 show the predicted rutting depth for different mixtures at different temperatures. Clearly, the static load has more influence on the permanent deformation than the moving load with the rutting depth being increased up to 45%. However, the rutting pattern under the static load seems to be different from that under the moving load. This could be attributed to the absence of the rest interval when the static load is applied, which prevents the mixtures from recovering (Shanbara, Ruddock and Atherton, 2018b).

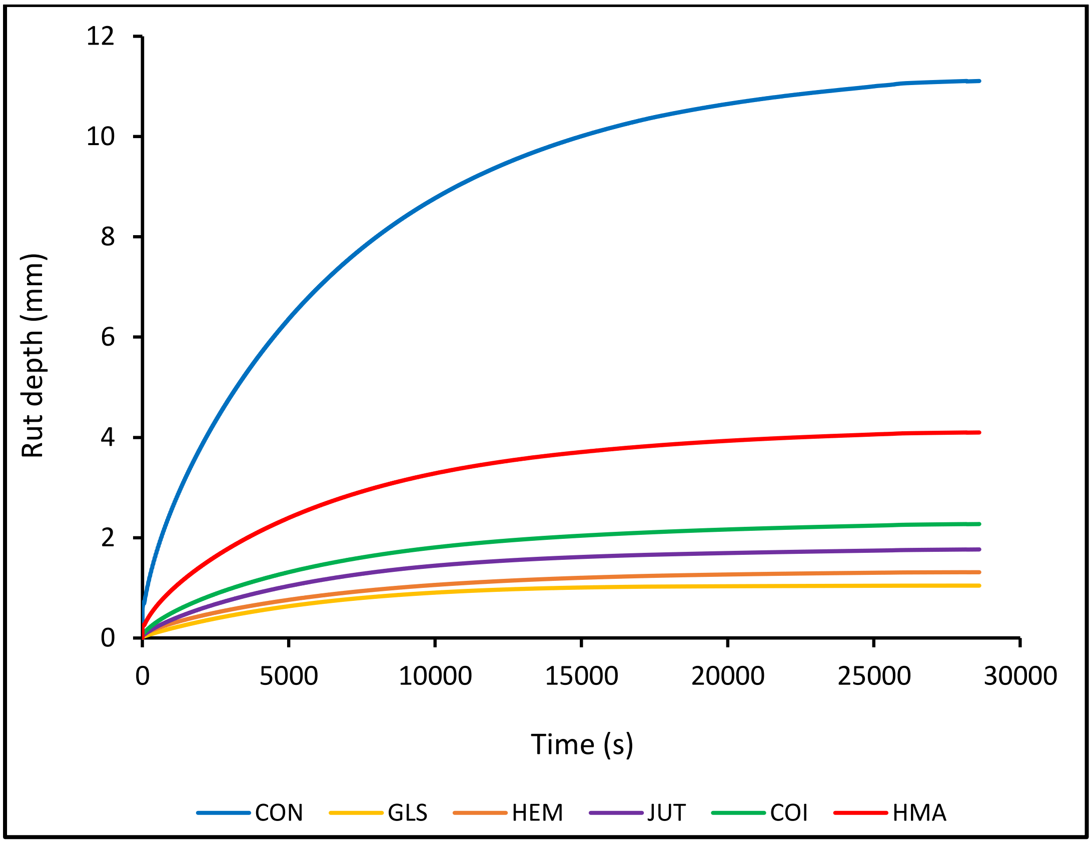


Figure 5.53: Predicted rutting for static loading at 45 °C

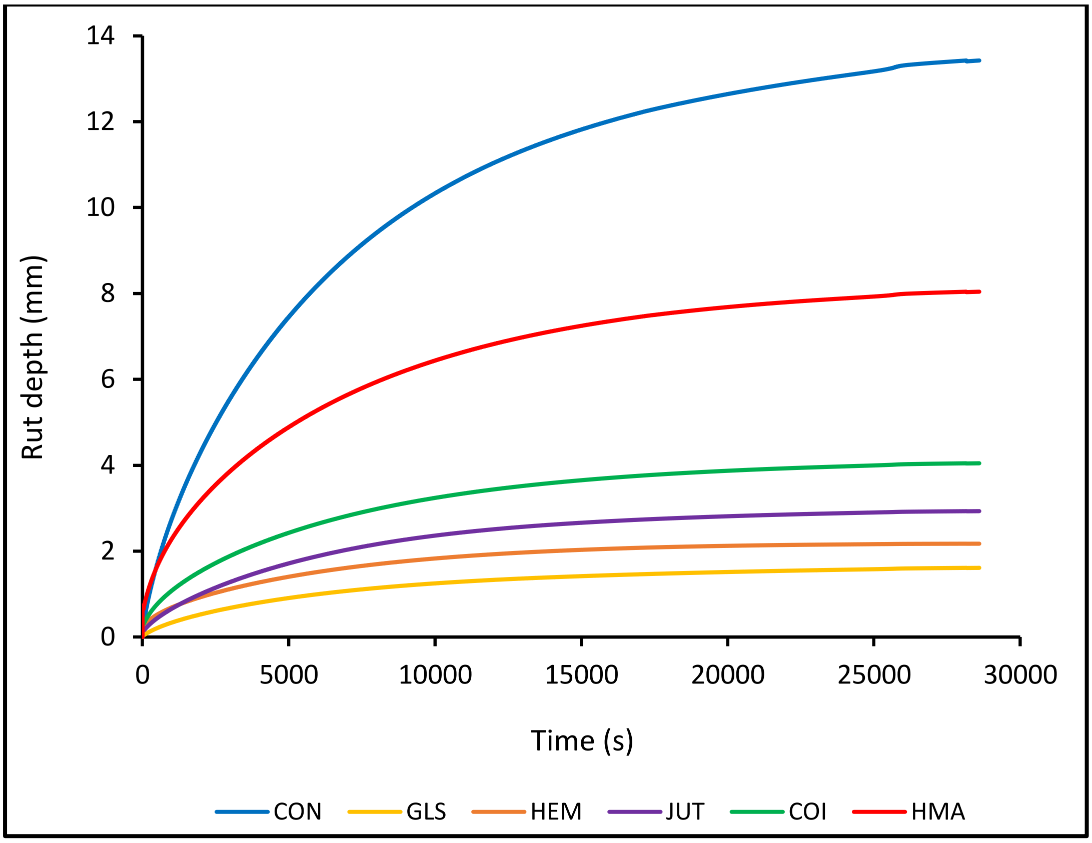


Figure 5.54: Predicted rutting for static loading at 60 °C

5.4.2 Temperature Attributes

The permanent deformation of flexible pavements is closely related to pavement temperature as variation in temperature affects stiffness modulus and shear stress (Shanbara, Ruddock and Atherton, 2018c). Repeated applied wheel loads were performed with a speed of 0.6 km/h for 3,472 cycles on the slabs' surface. Rutting resistance increases when the pavement temperature is low (around 0 °C) because of the high stiffness of asphalt pavements (Li et al, 2017). The variation in pavement rutting in terms of viscoelastic properties for different temperatures (5 °C and 20 °C) is shown in Figure 5.55 – 5.66. As expected from the model, the CBEMs at low temperatures show lower permanent deformation than those at high temperatures.

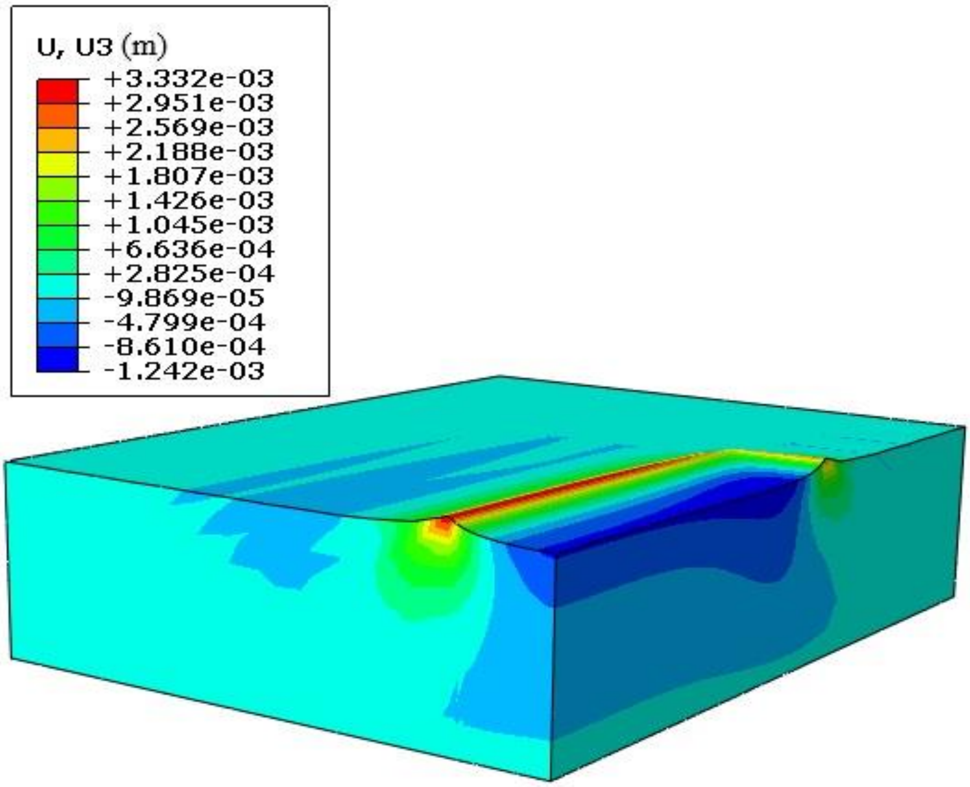


Figure 5.55: Permanent deformation shape of CON at 5 °C

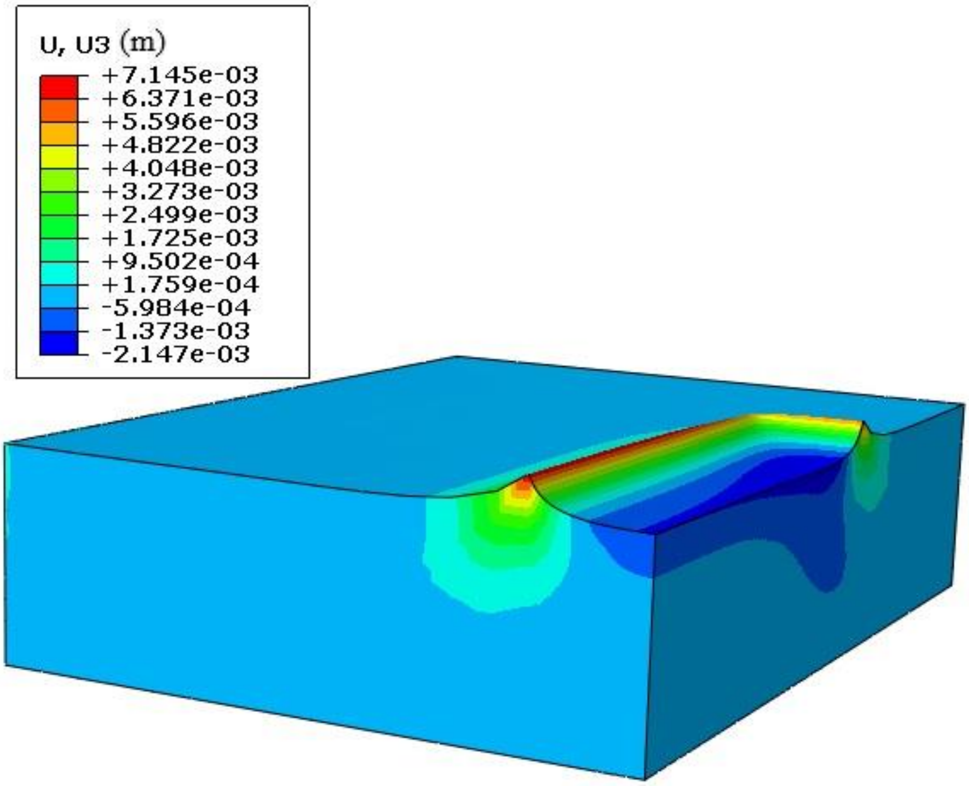


Figure 5.56: Permanent deformation shape of CON at 20 °C

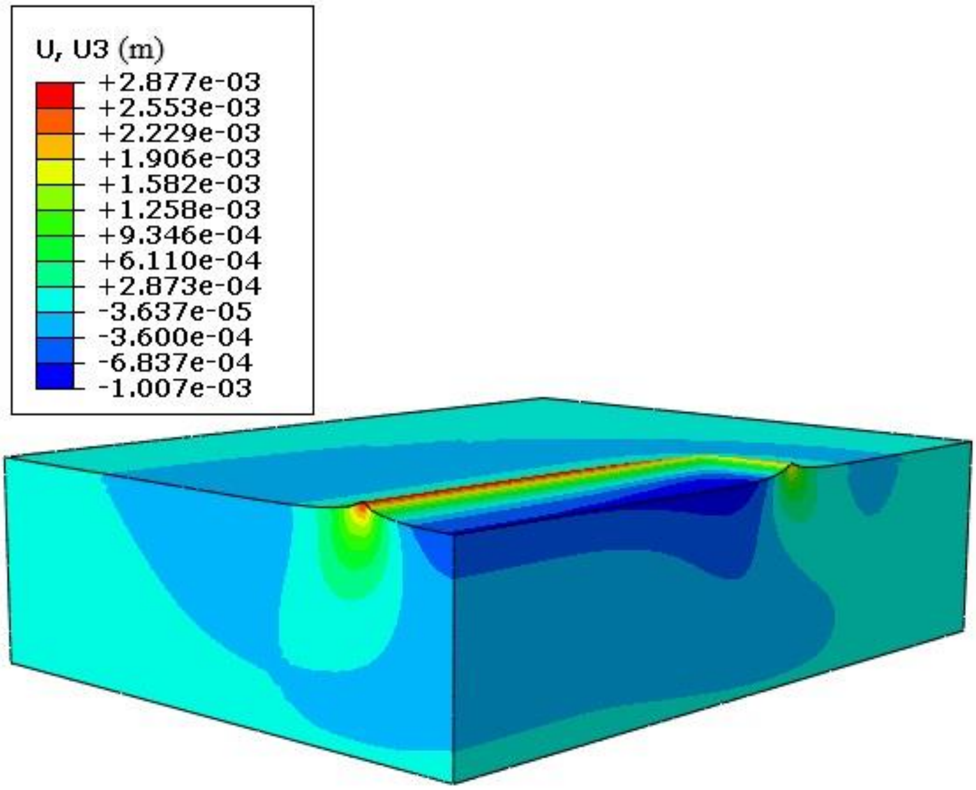


Figure 5.57: Permanent deformation shape of HMA at 5 °C

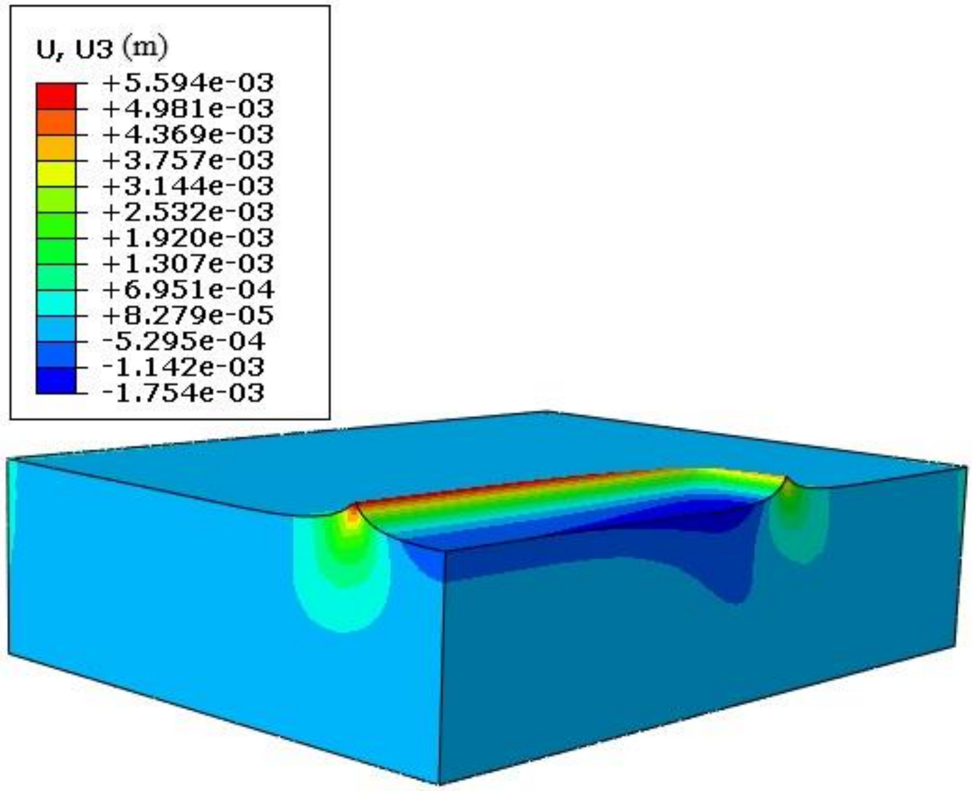


Figure 5.58: Permanent deformation shape of HMA at 20 °C

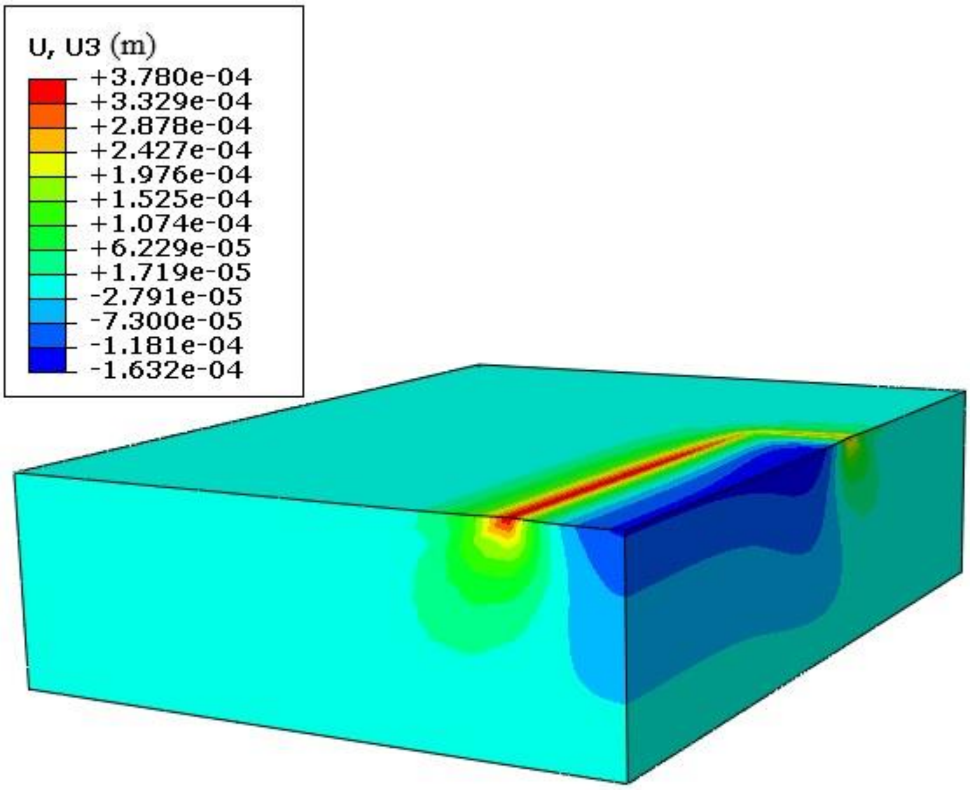


Figure 5.59: Permanent deformation shape of GLS at 5 °C

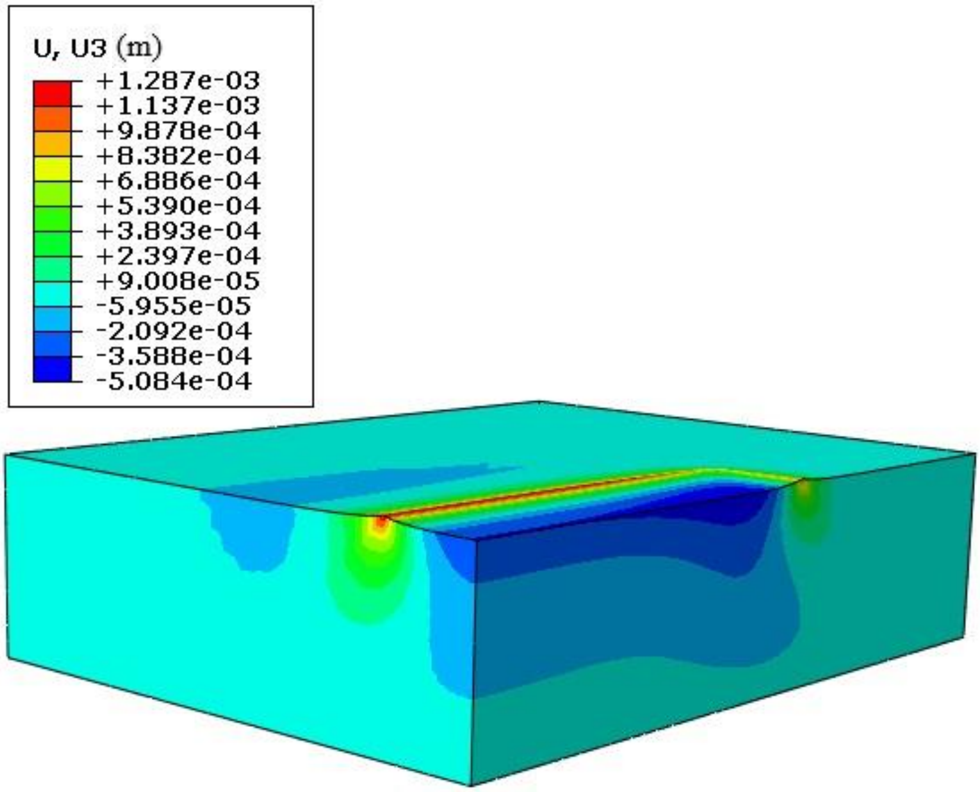


Figure 5.60: Permanent deformation shape of GLS at 20 °C

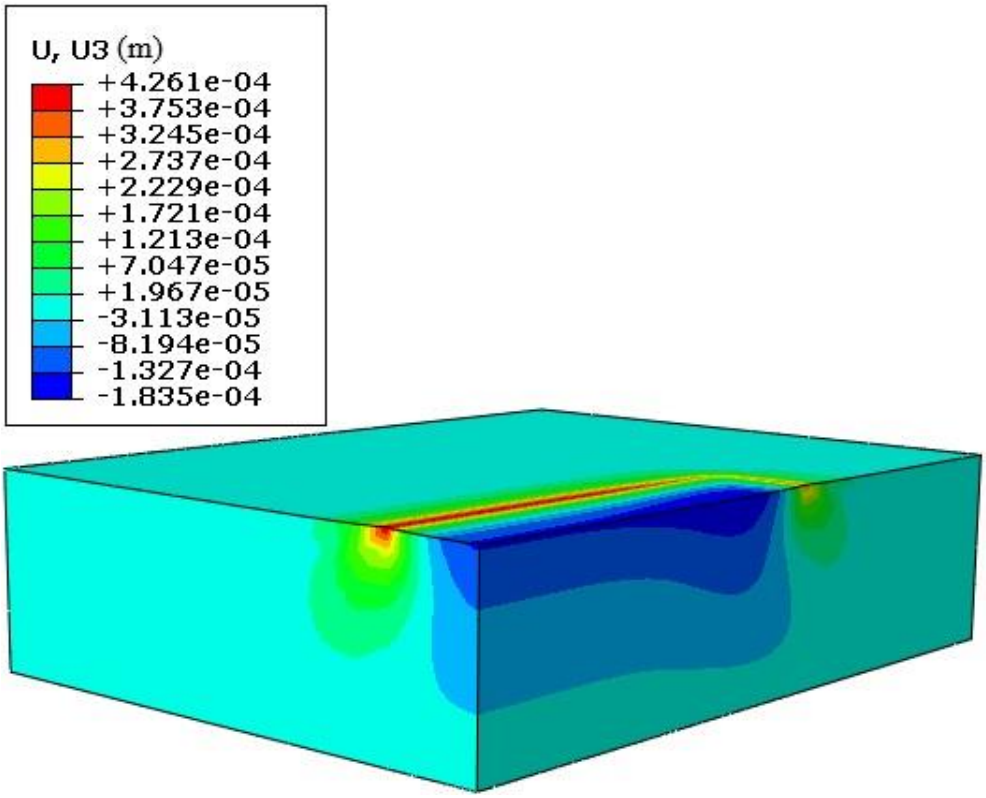


Figure 5.61: Permanent deformation shape of HEM at 5 °C

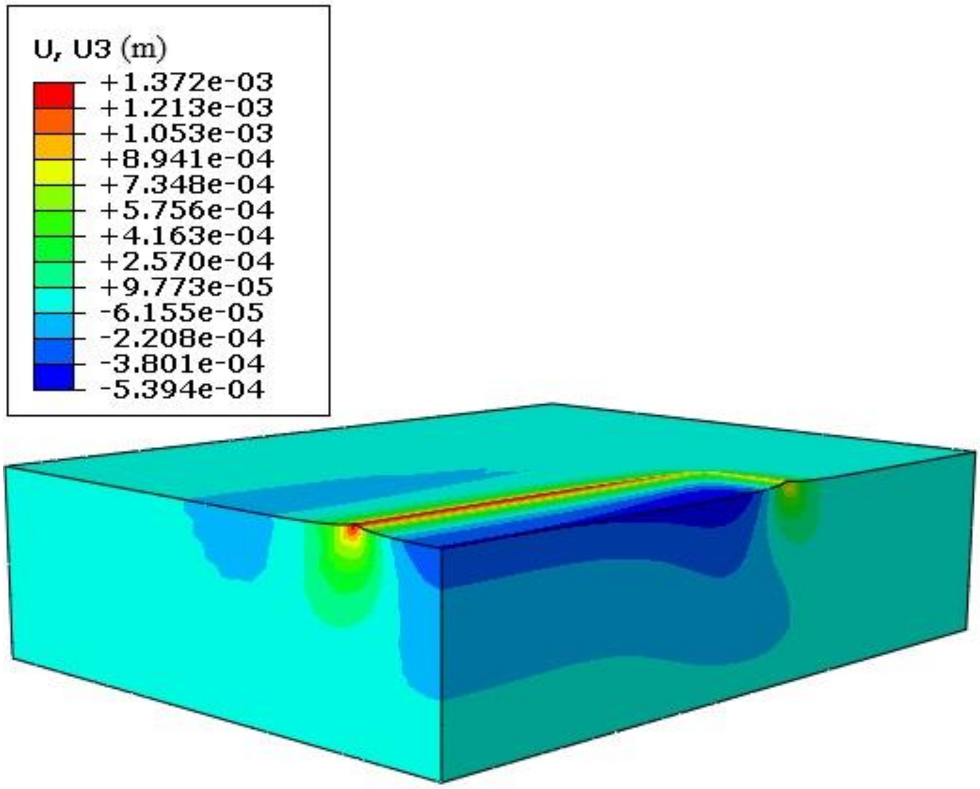


Figure 5.62: Permanent deformation shape of HEM at 20 °C

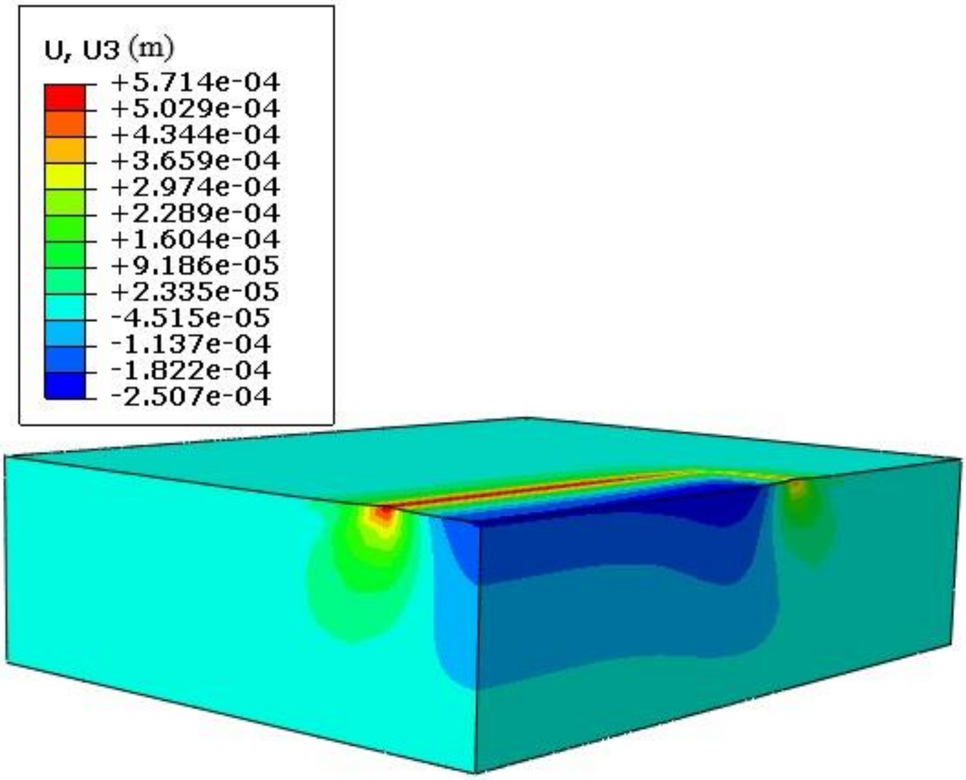


Figure 5.63: Permanent deformation shape of JUT at 5 °C

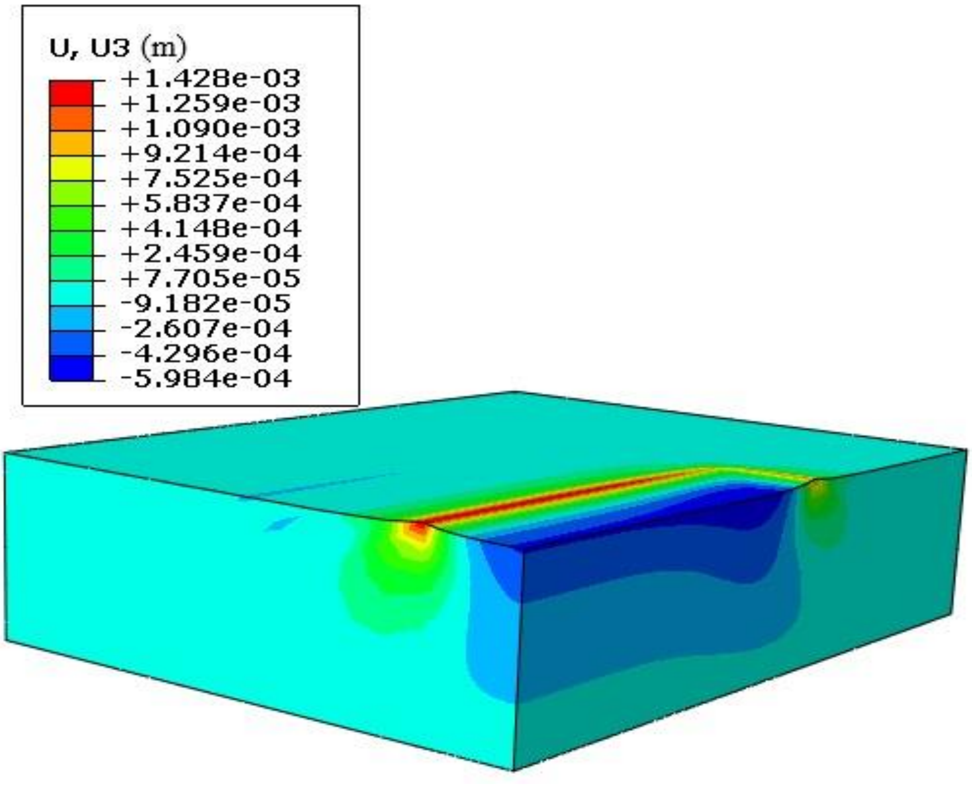


Figure 5.64: Permanent deformation shape of JUT at 20 °C

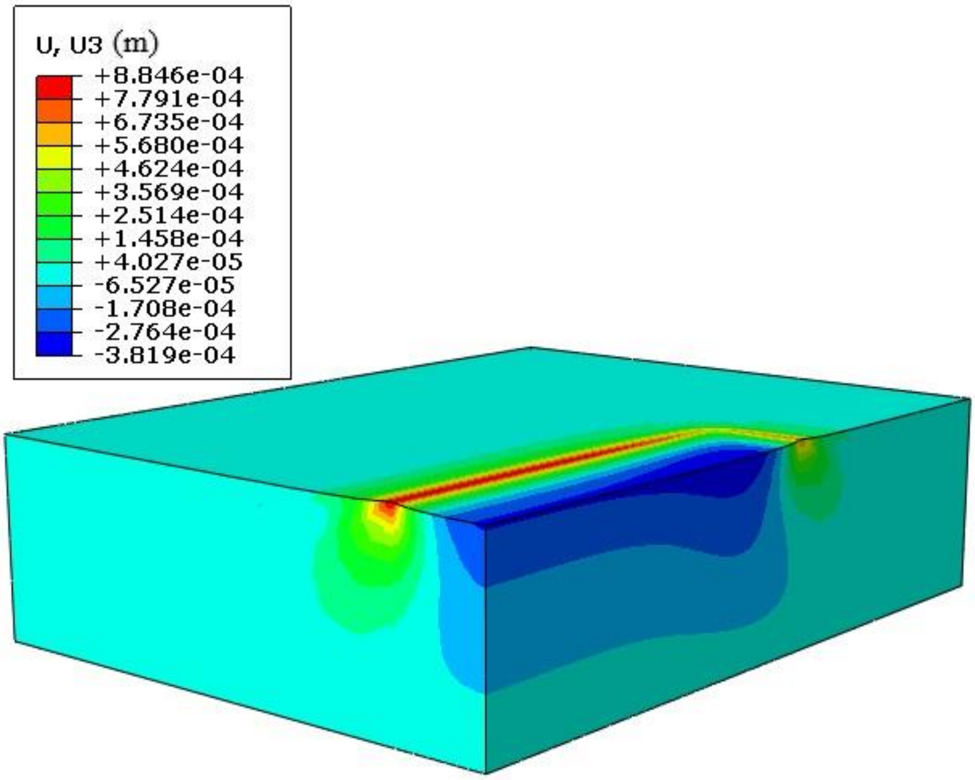


Figure 5.65: Permanent deformation shape of COI at 5 °C

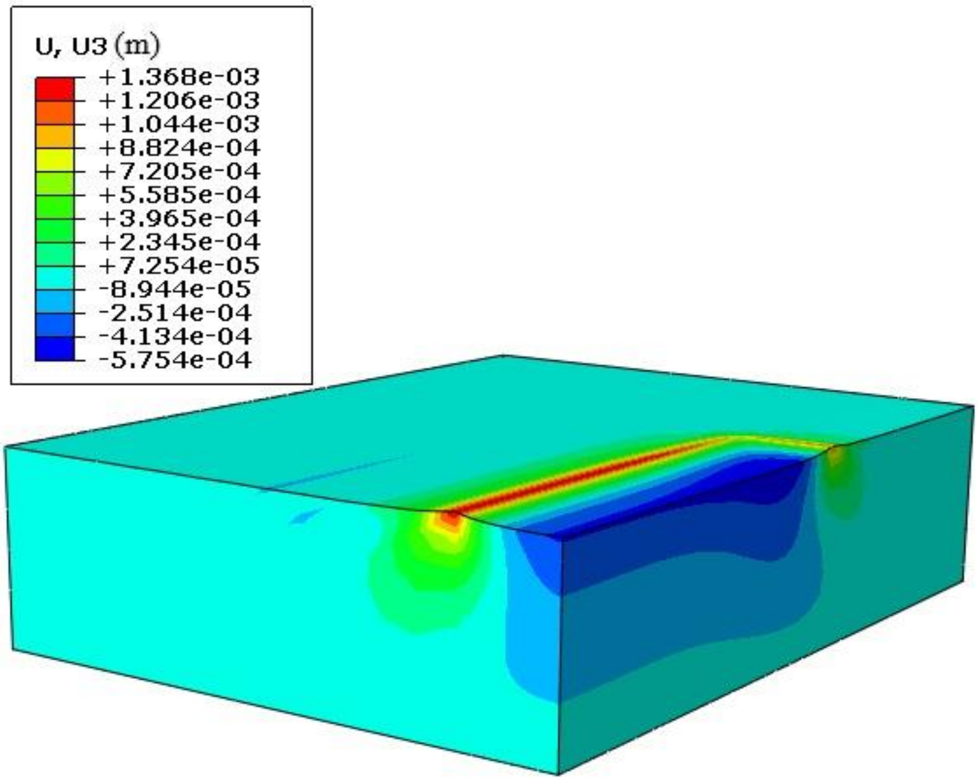


Figure 5.66: Permanent deformation shape of COI at 20 °C

For the viscoplastic models, to examine the effect of the temperature on the rutting response of the reinforced and unreinforced CBEMs using natural and synthetic fibres, two different temperatures were adopted as a moderate to low temperature, i.e. 20 °C and 5 °C. Figure 5.67 and 5.68 show the rutting variation of the reinforced CBEM and conventional CBEM and HMA mixtures at different temperatures (20 °C and 5 °C). Flexible pavement design procedures and analysis should consider the actual road pavement temperatures that have an important impact on permanent deformation.

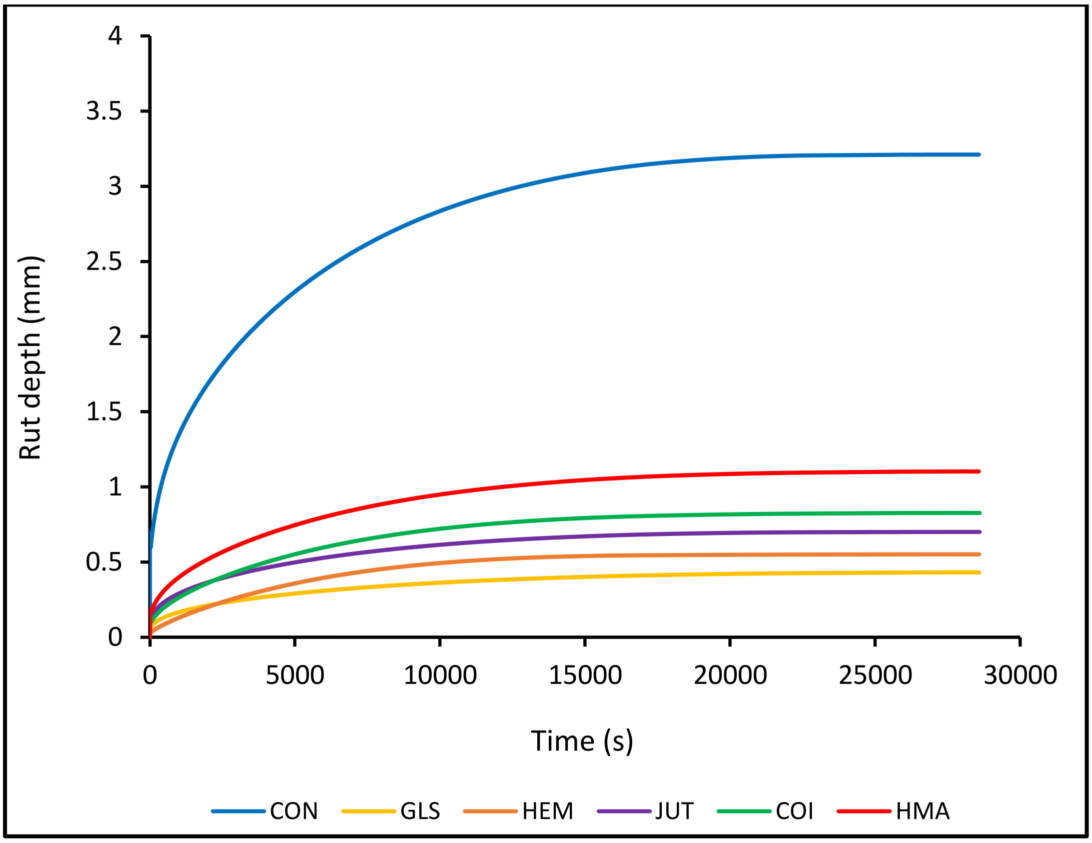


Figure 5.67: Predicted rutting of different mixtures at 5 °C

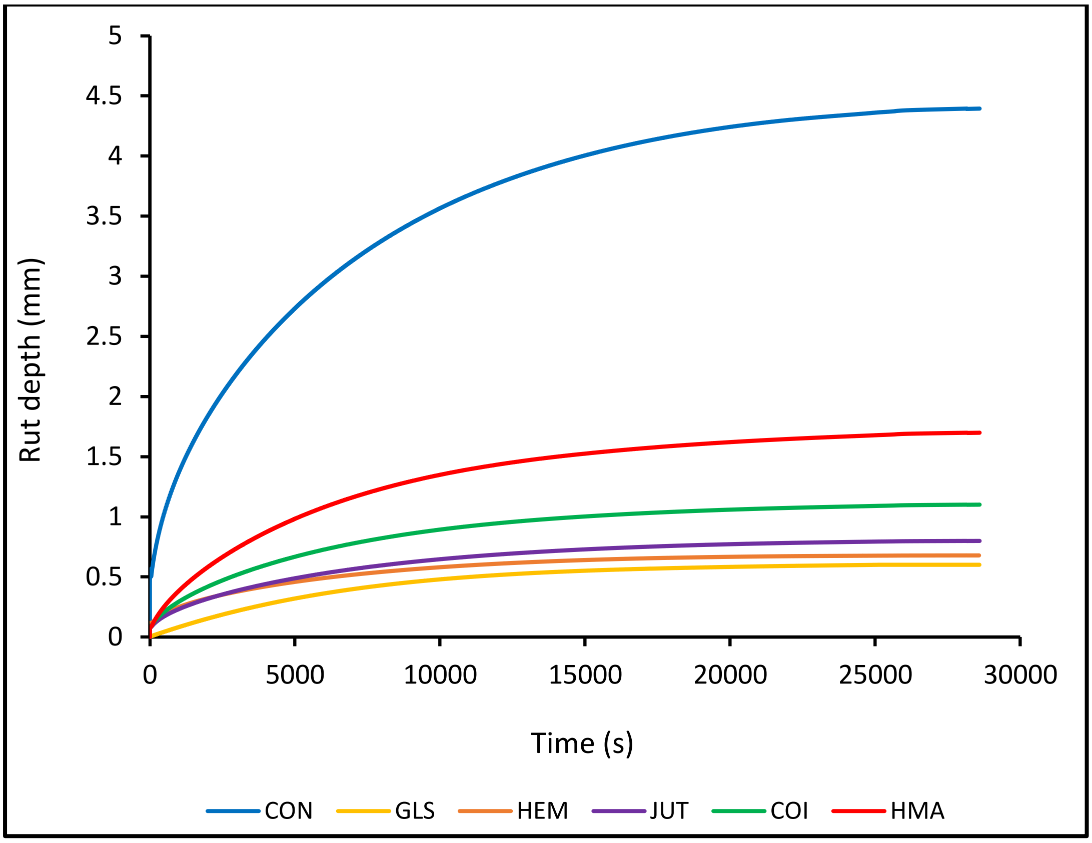


Figure 5.68: Predicted rutting of different mixtures at 20 °C

5.4.3 Repeated Applied Wheel Load Speed Attributes

Zhi et al (2012) stated that static loads are more damaging to asphalt pavements than moving loads. A comparison was carried out, using the viscoelastic model, on the effect of different traffic speeds (5 km/h, 30 km/h and 60 km/h) on reinforced and unreinforced CBEMs. Cumulative pavement rutting on the top of the asphalt layer at 30 km/h is significantly less than that at 5 km/h. The rutting variation between 30 km/h and 60 km/h is relatively small, as shown in Table 5.3. The loading time for each repeated wheel pass on each element on the pavement surface is dependent on vehicle speed. It was 0.0216 s at 5 km/h, 0.0036 s at 30 km/h and 0.0018 s at 60 km/h.

Table 5.3: Maximum rut depth for different repeated wheel load speeds after 5,000s

Temperature (°C)	Vehicle speed (km/h)	Max. rut depth (mm)					
		CON	HMA	GLS	HEM	JUT	COI
60	5	2.75	2.27	0.96	1.11	1.25	1.31
	30	1.22	1.03	0.51	0.55	0.68	0.79
	60	0.98	0.88	0.46	0.49	0.55	0.60
45	5	2.20	1.87	0.47	0.56	0.63	0.72
	30	0.87	0.62	0.30	0.31	0.38	0.44
	60	0.66	0.58	0.26	0.27	0.32	0.38
20	5	1.63	1.44	0.30	0.33	0.41	0.48
	30	0.57	0.79	0.14	0.18	0.21	0.31
	60	0.51	0.68	0.12	0.15	0.18	0.28
5	5	0.74	0.43	0.09	0.14	0.20	0.26
	30	0.29	0.11	0.01	0.02	0.09	0.12
	60	0.26	0.09	0.01	0.01	0.07	0.10

The influence of the traffic load speeds was also investigated using the validated numerical viscoplastic model on both cold and hot mixtures with different speeds (5 km/h, 30 km/h and 60 km/h) as shown in Table 5.4. At 5 km/h, it can be seen that the cumulative rutting on the bituminous surface layer is significantly more than that at 30 km/h, whereas a slight variation in rutting between the 30 km/h and 60 km/h is observed. The loading time for each repeated wheel pass on each element on the pavement surface depends on the moving loads speed. It was 0.0216 s at 5 km/h, 0.0036 s at 30 km/h and 0.0018 s at 60 km/h.

Table 5.4: Maximum rut depth for different wheel load speeds after 20,000 cycles

Temperature	Vehicle speed	Max. rut depth (mm)					
(°C)	(km/h)	CON	HMA	GLS	HEM	JUT	COI
60	5	6.29	4.31	1.01	1.28	1.52	1.78
	30	4.55	2.86	0.63	0.73	0.79	1.01
	60	3.76	2.02	0.54	0.65	0.71	0.89
45	5	5.22	2.15	0.62	0.74	0.81	1.00
	30	3.40	1.09	0.36	0.49	0.56	0.66
	60	2.96	0.88	0.29	0.41	0.47	0.60
20	5	3.75	1.57	0.41	0.45	0.49	0.63
	30	1.79	0.84	0.25	0.31	0.27	0.41
	60	1.39	0.74	0.21	0.26	0.32	0.39
5	5	2.76	0.84	0.33	0.39	0.44	0.52
	30	1.23	0.47	0.10	0.15	0.19	0.30
	60	0.79	0.39	0.07	0.11	0.16	0.26

5.4.4 Stress Distribution

In the previous sections, the validated model was used to study the rutting behaviour of the bituminous mixtures in terms of temperature, static loading condition and repeated applied wheel load speed that cannot be obtained from the experimental results. This model was also used to investigate the effect of different rutting depths during the repeated moving wheel load on different types of bituminous mixtures. The rutting depth of the reinforced CBEMs was lower than that in the conventional CBEM and HMA mixtures. This reduction is due to the decrease of the pavement stresses at the area underneath the repeated moving load. Figure 5.69 – 5.80 show the stress distribution of all mixtures selected under repeated wheel load, viscoelastic material properties and 3,472 load repetitions at two temperatures (5 °C and 20 °C).

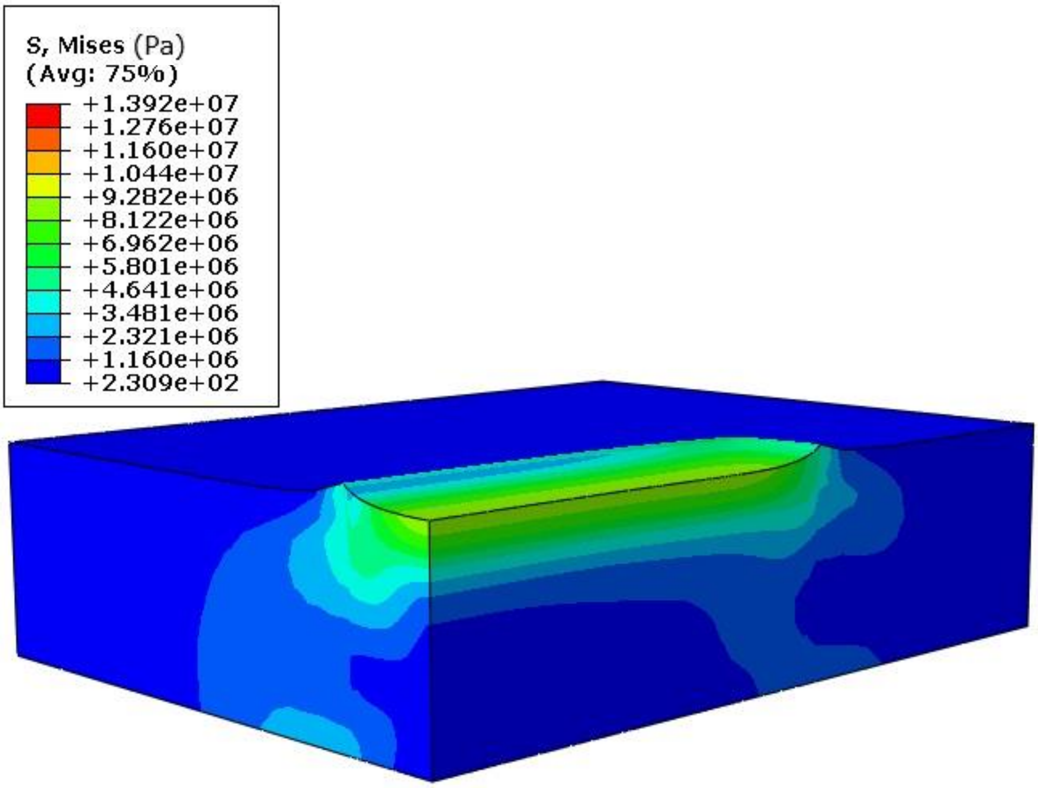


Figure 5.69: Stress distribution in CON at 5 °C

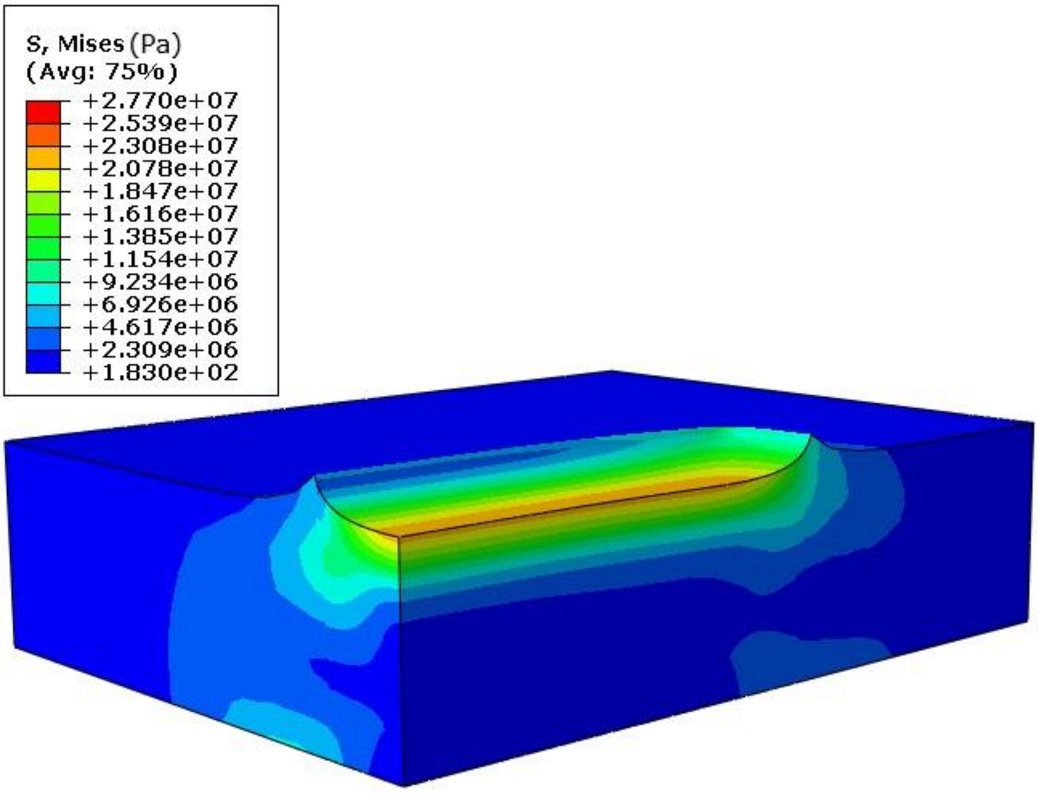


Figure 5.70: Stress distribution in CON at 20 °C

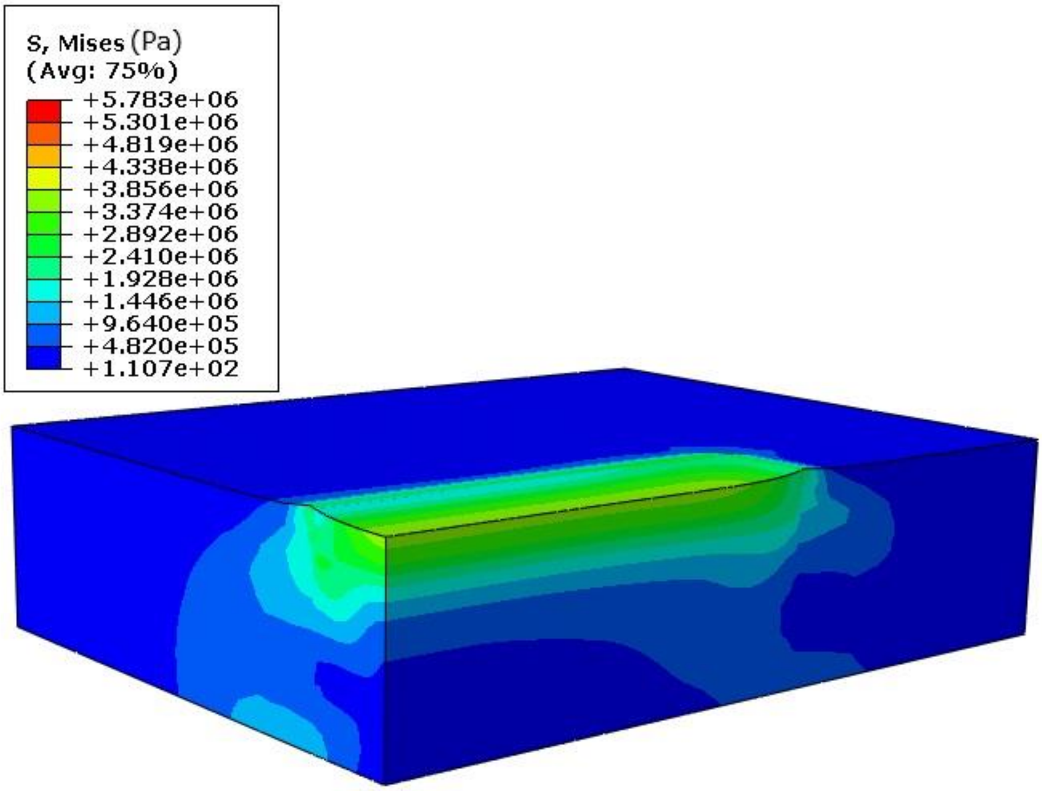


Figure 5.71: Stress distribution in HMA at 5 °C

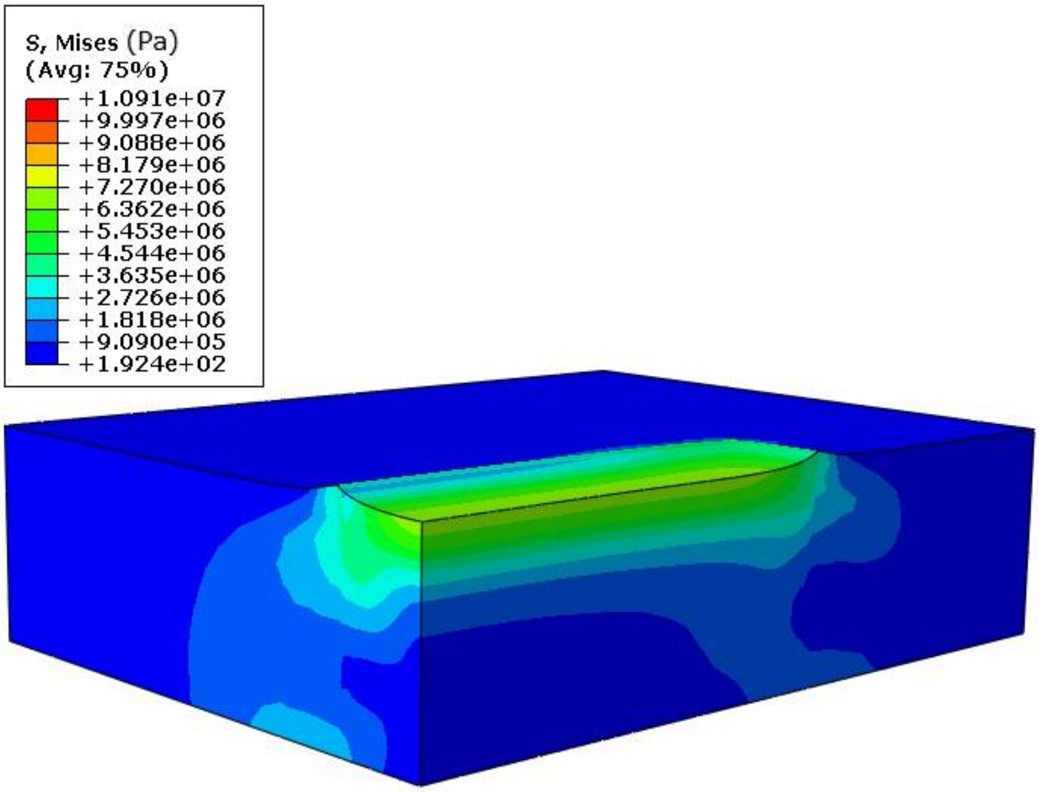


Figure 5.72: Stress distribution in HMA at 20 °C

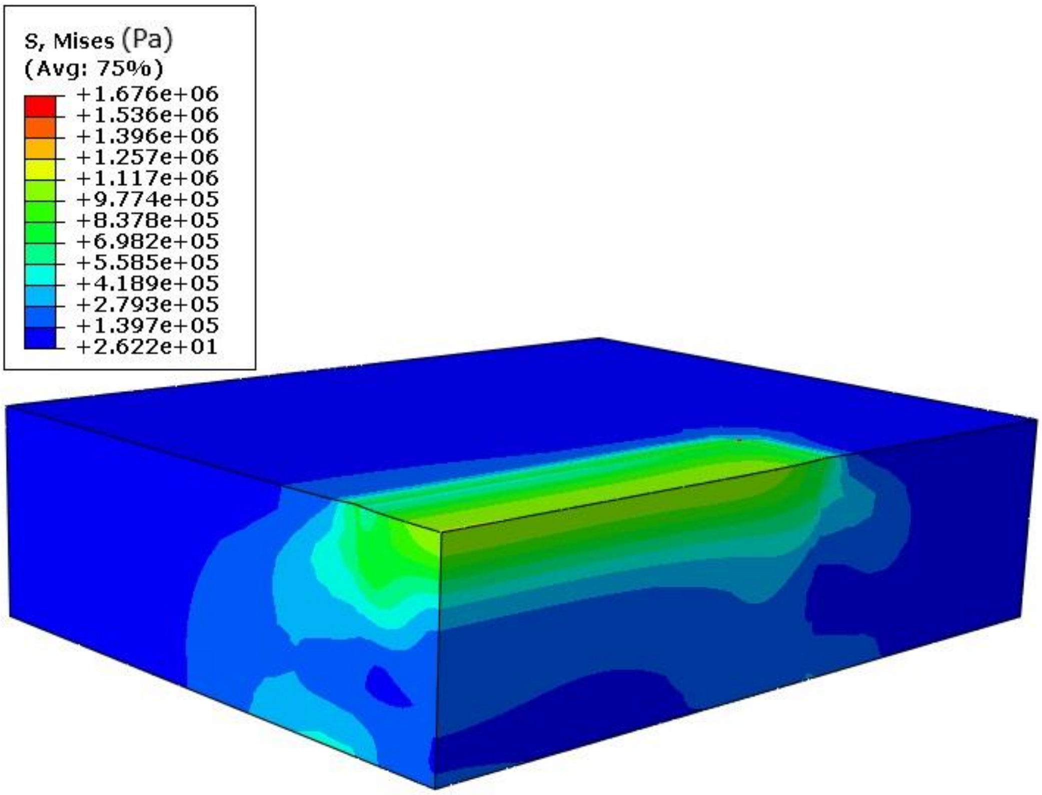


Figure 5.73: Stress distribution in GLS at 5 °C

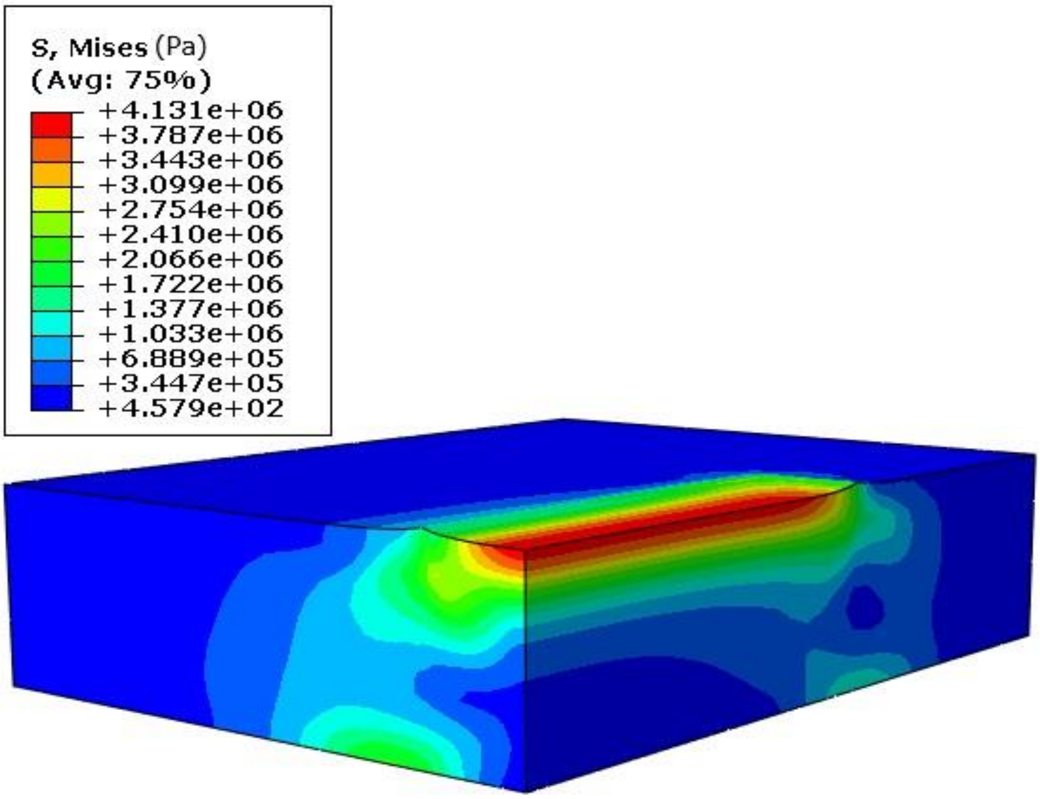


Figure 5.74: Stress distribution in GLS at 20 °C

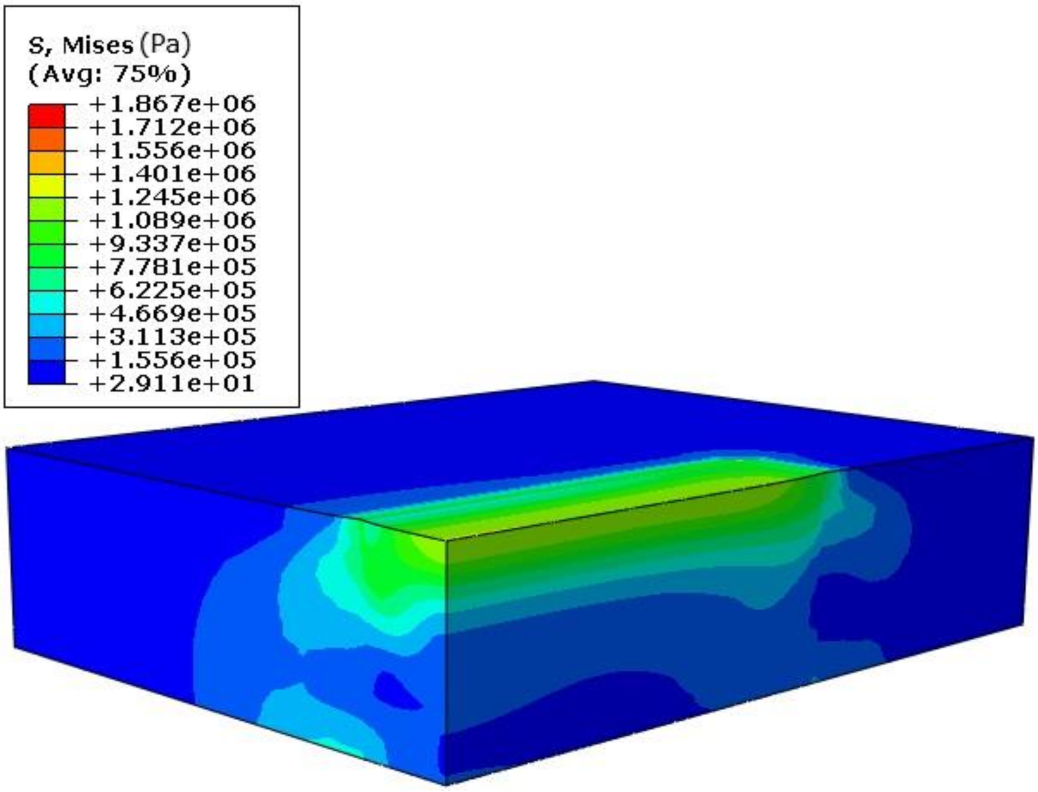


Figure 5.75: Stress distribution in HEM at 5 °C

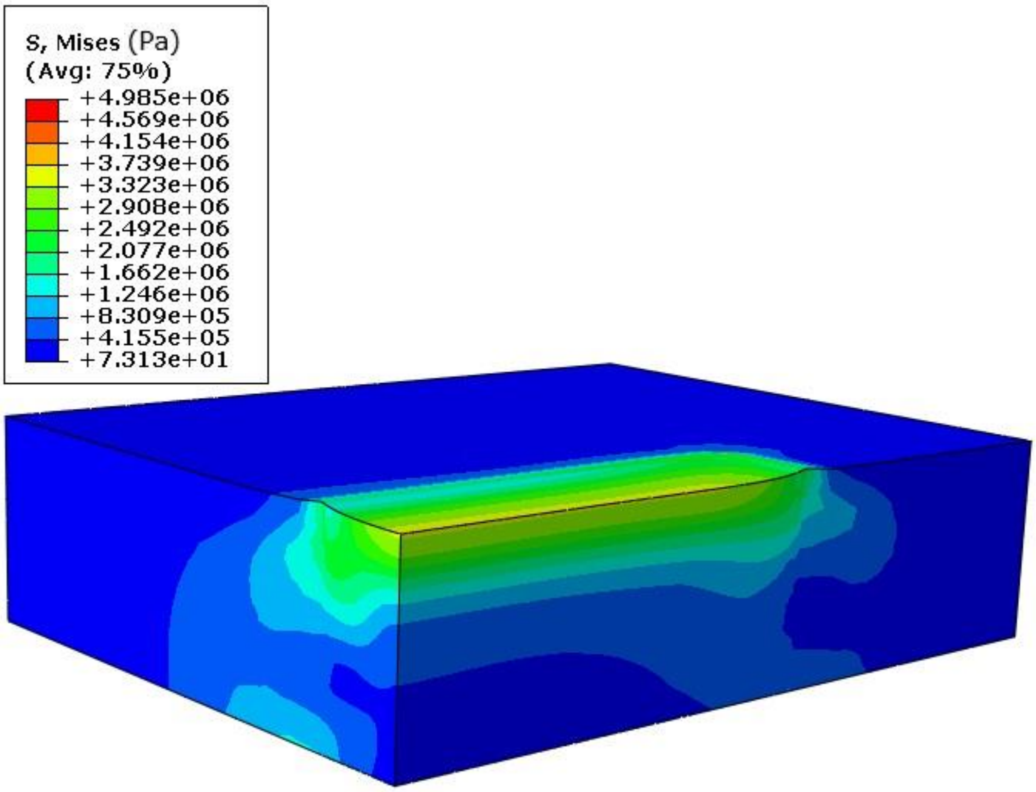


Figure 5.76: Stress distribution in HEM at 20 °C

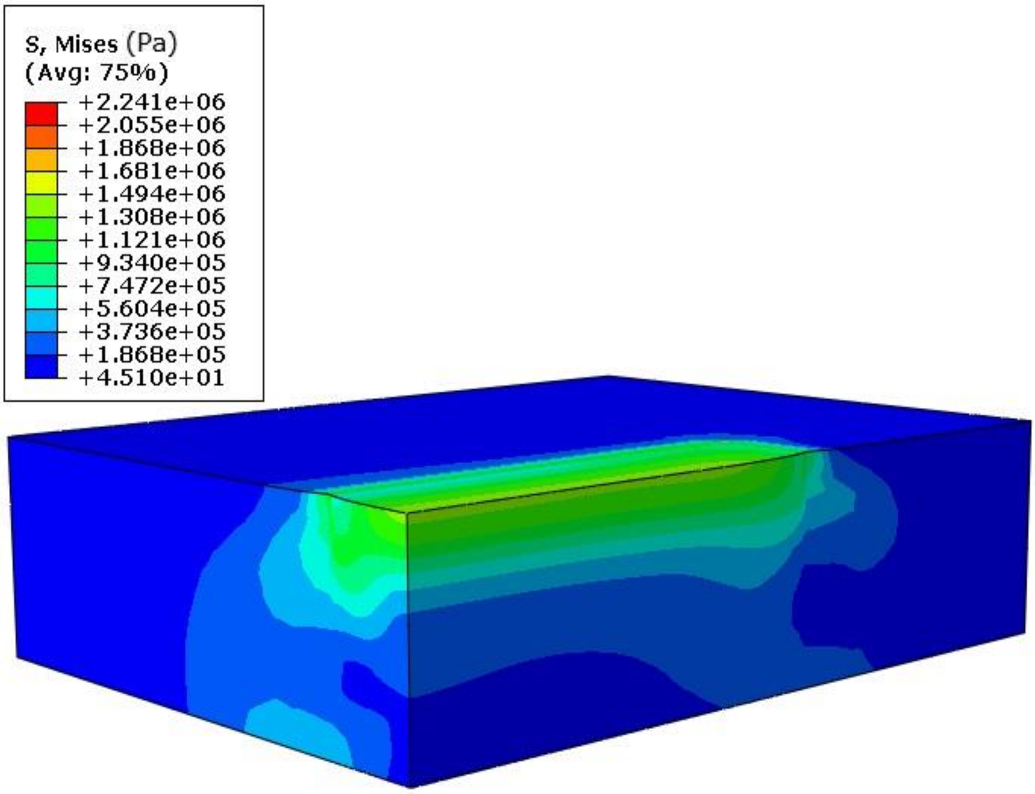


Figure 5.77: Stress distribution in JUT at 5 °C

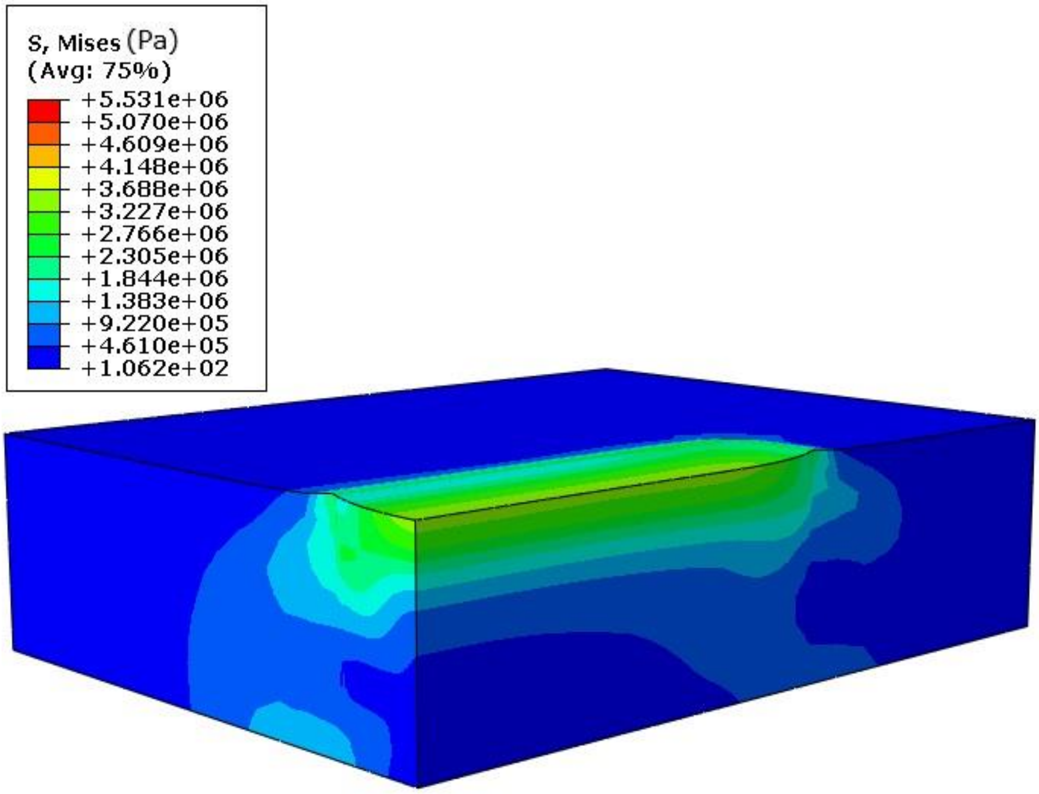


Figure 5.78: Stress distribution in JUT at 20 °C

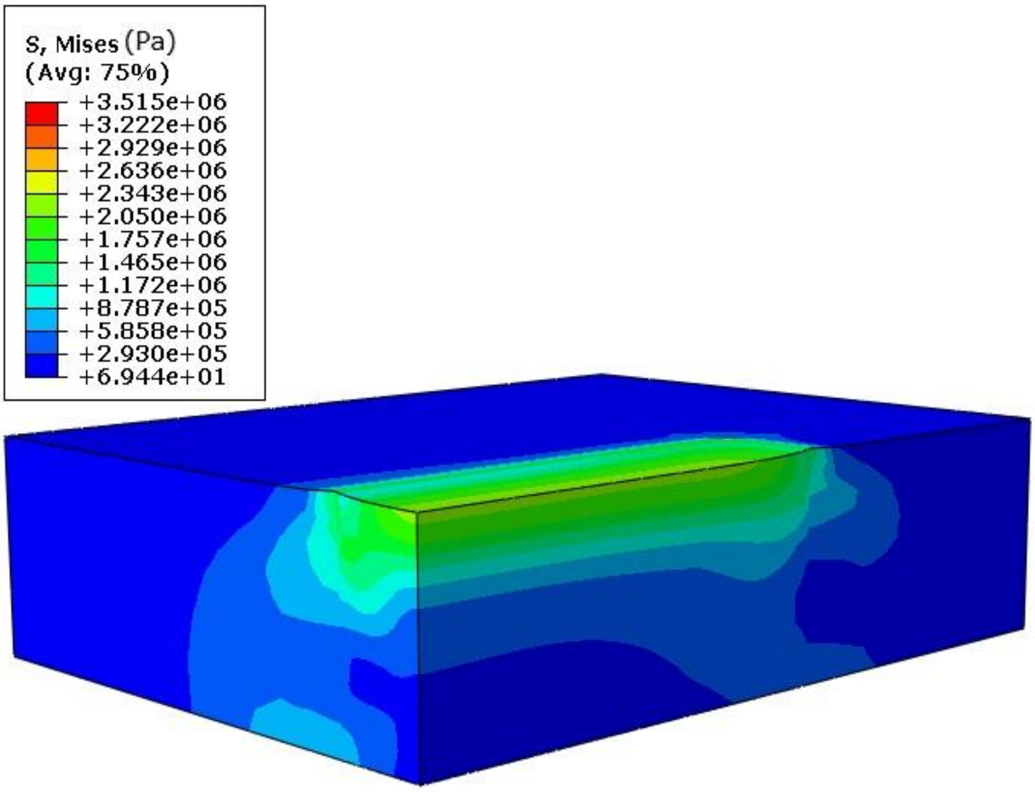


Figure 5.79: Stress distribution in COI at 5 °C

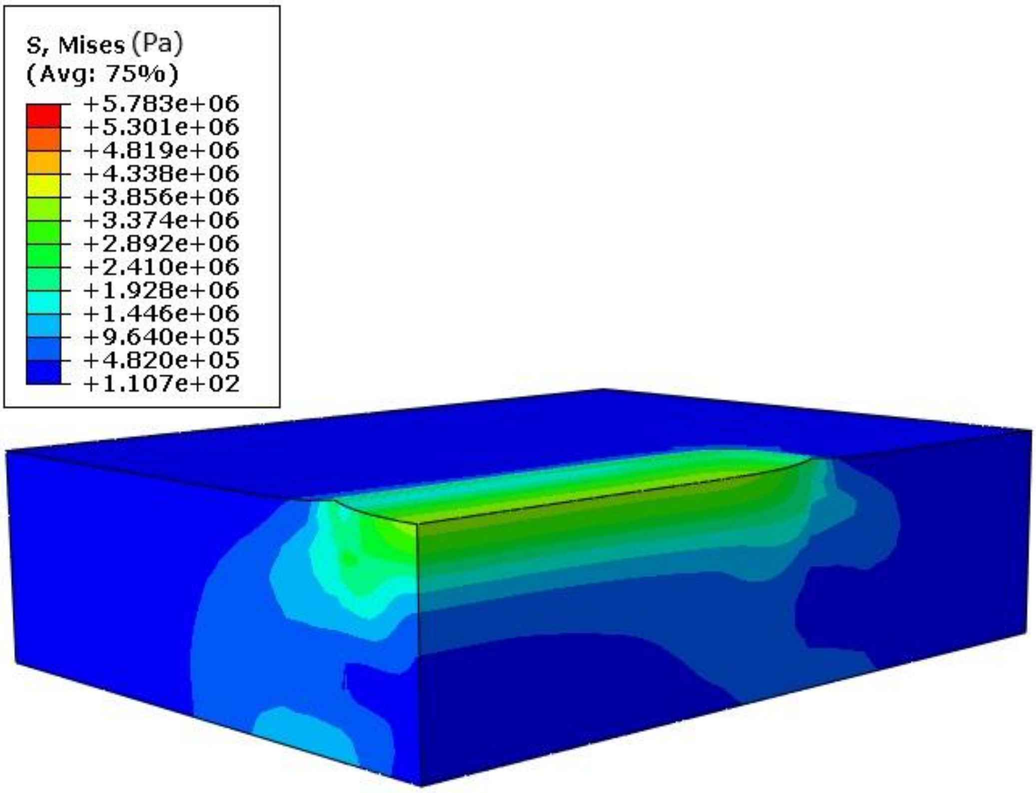


Figure 5.80: Stress distribution in COI at 20 °C

For the viscoplastic model, the maximum stress distribution is located close to and below the repeated moving wheel footprint. Such stress distribution is mostly characterised by vertical stresses with possible horizontal stresses. Figure 5.81 – 5.92 show the stress distribution of the all mixtures under repeated moving wheel load, viscoplastic material properties and 28,600 load repetitions at two different temperatures (5 °C and 20 °C). According to the result of the model, the stress distribution within pavement elements varies significantly with different mixtures.

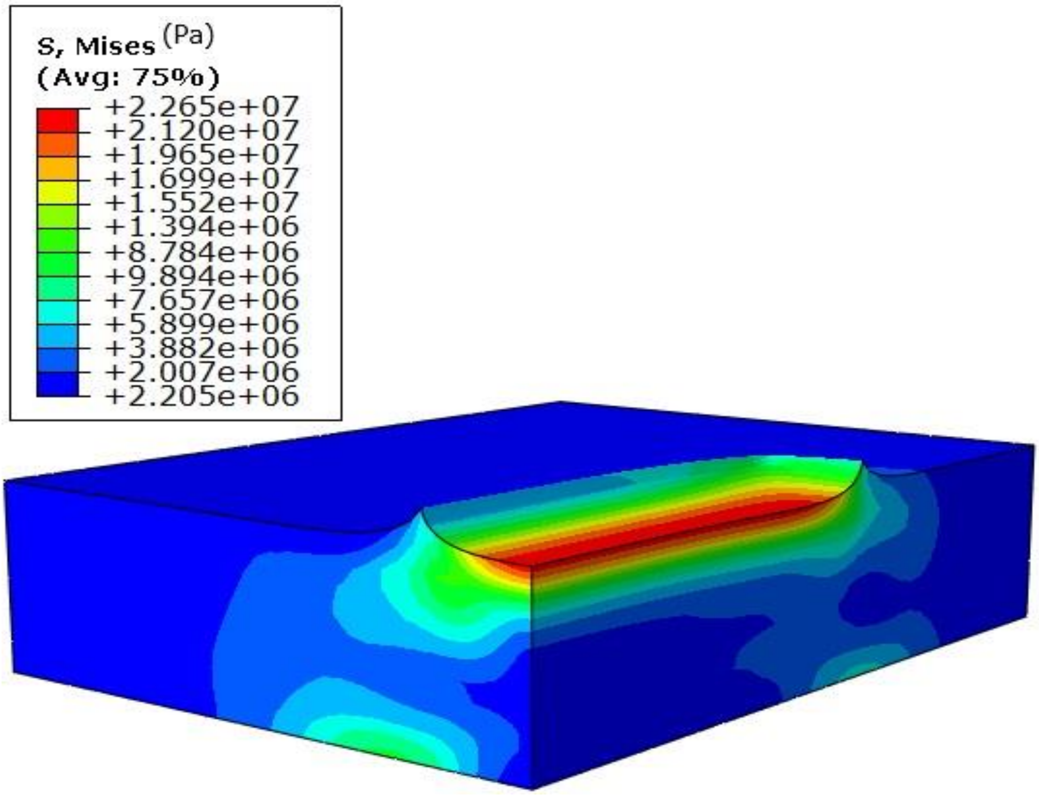


Figure 5.81: Stress distribution in CON at 5 °C

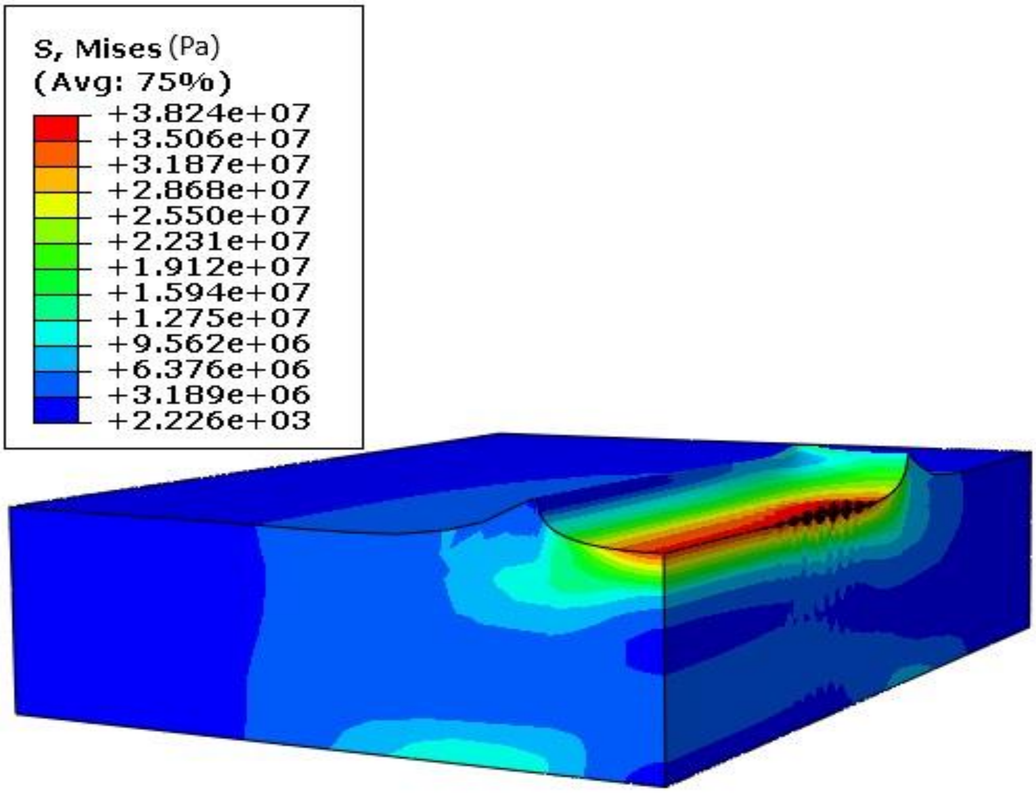


Figure 5.82: Stress distribution in CON at 20 °C

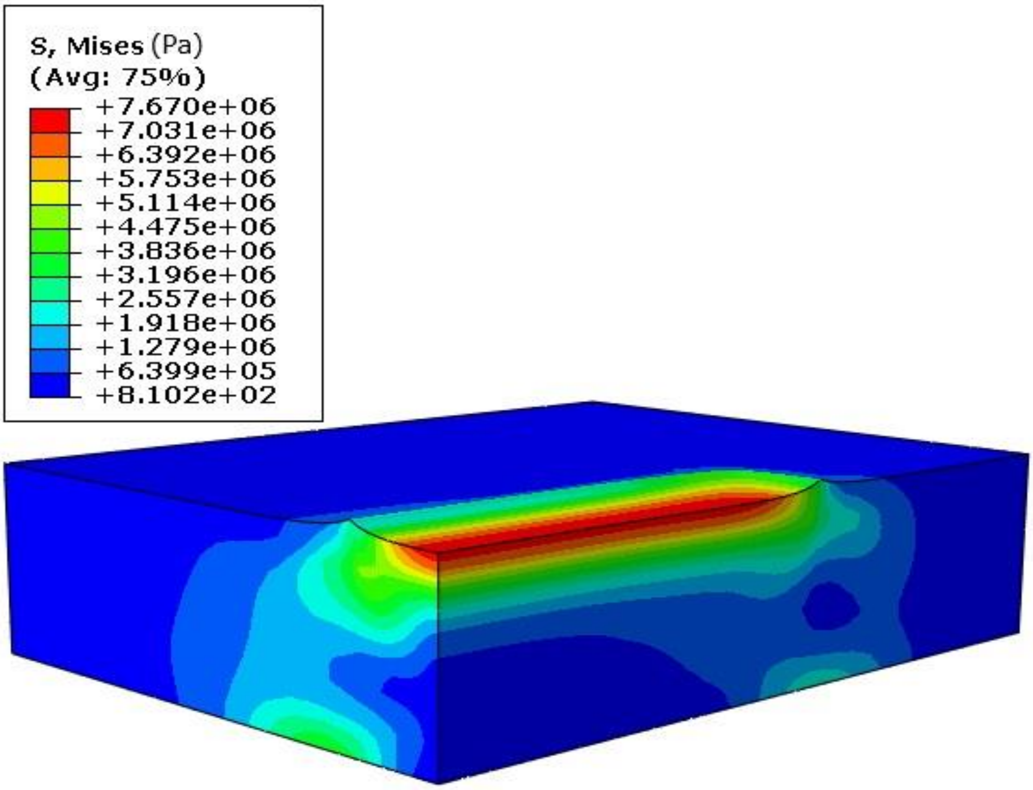


Figure 5.83: Stress distribution in HMA at 5 °C

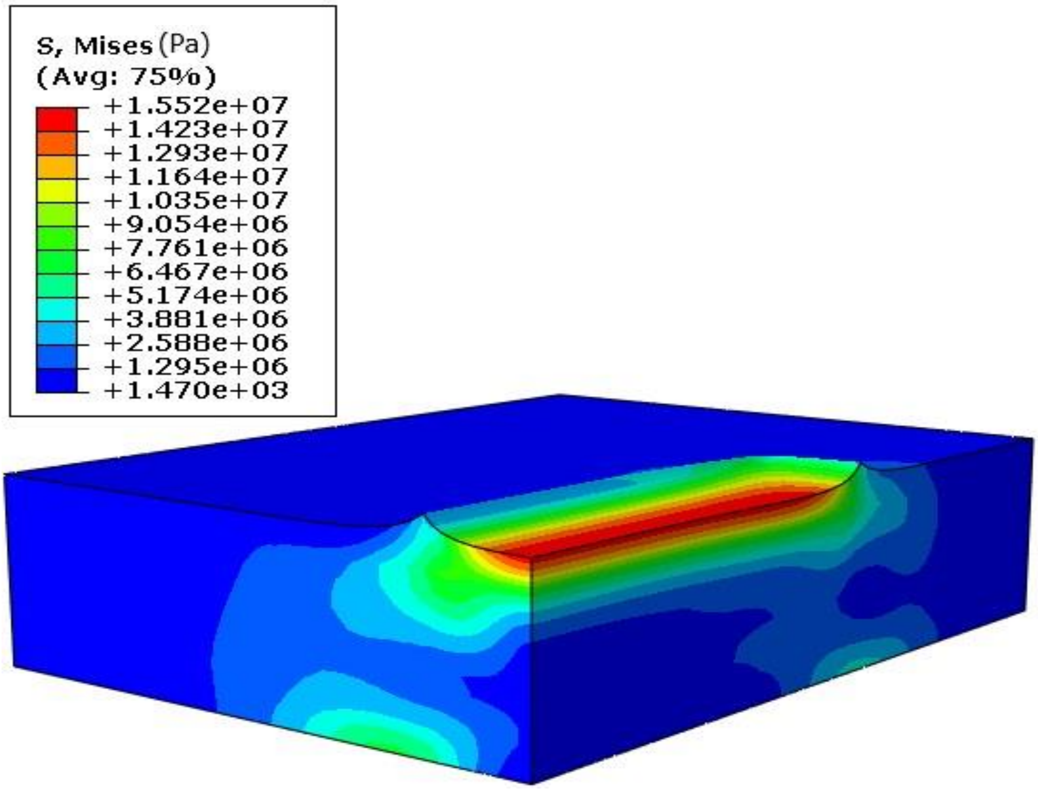


Figure 5.84: Stress distribution in HMA at 20 °C

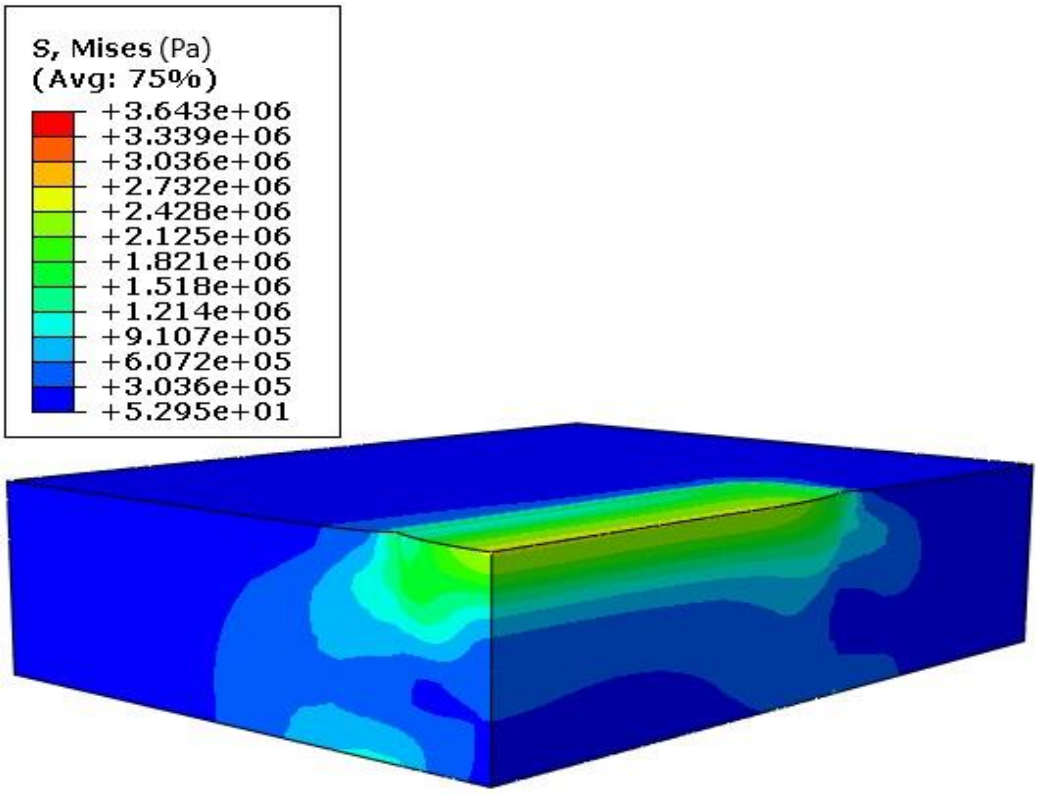


Figure 5.85: Stress distribution in GLS at 5 °C

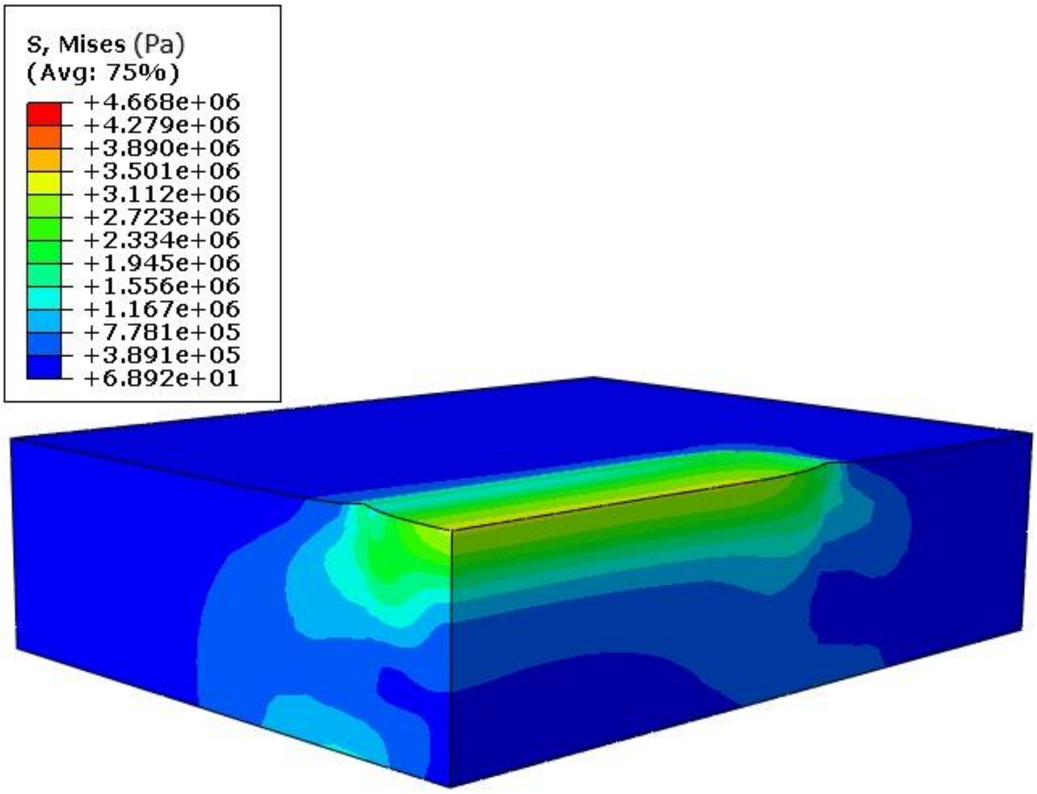


Figure 5.86: Stress distribution in GLS at 20 °C

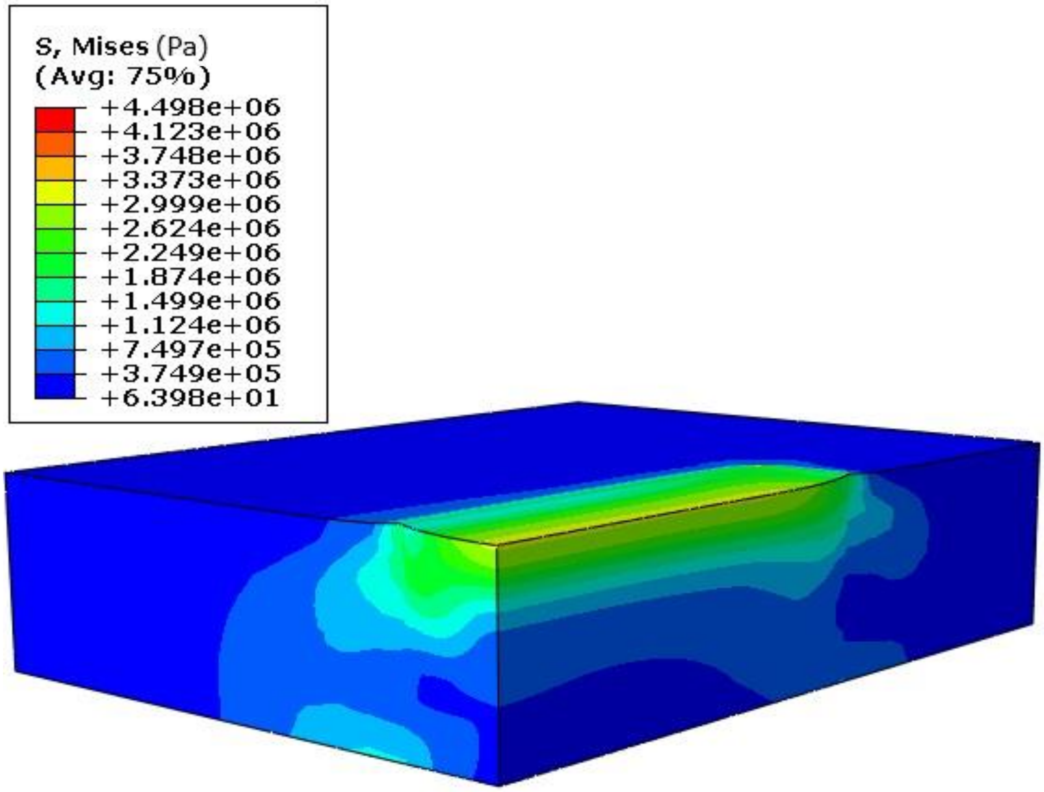


Figure 5.87: Stress distribution in HEM at 5 °C

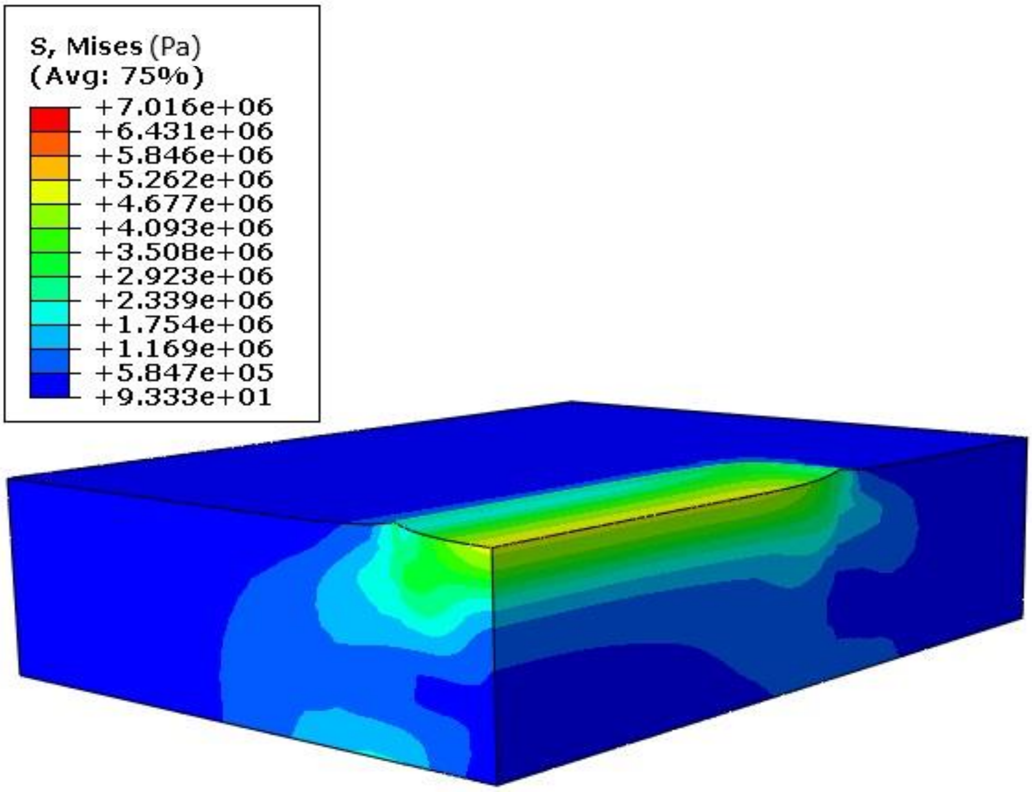


Figure 5.88: Stress distribution in HEM at 20 °C

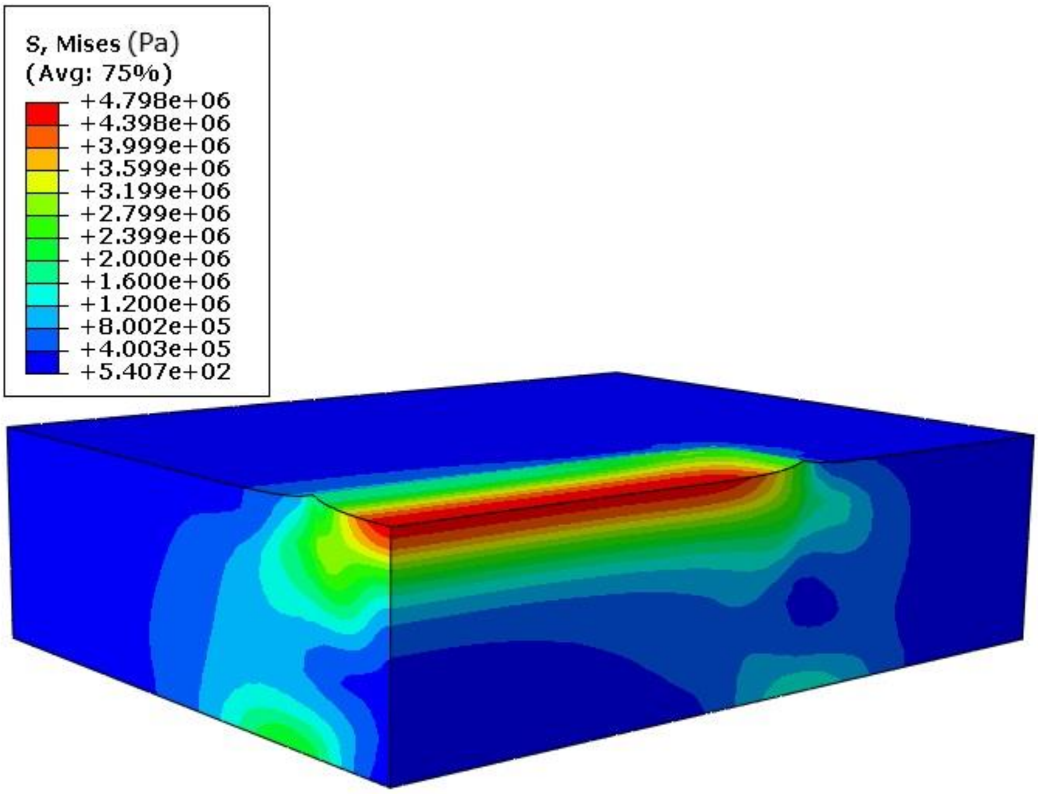


Figure 5.89: Stress distribution in JUT at 5 °C

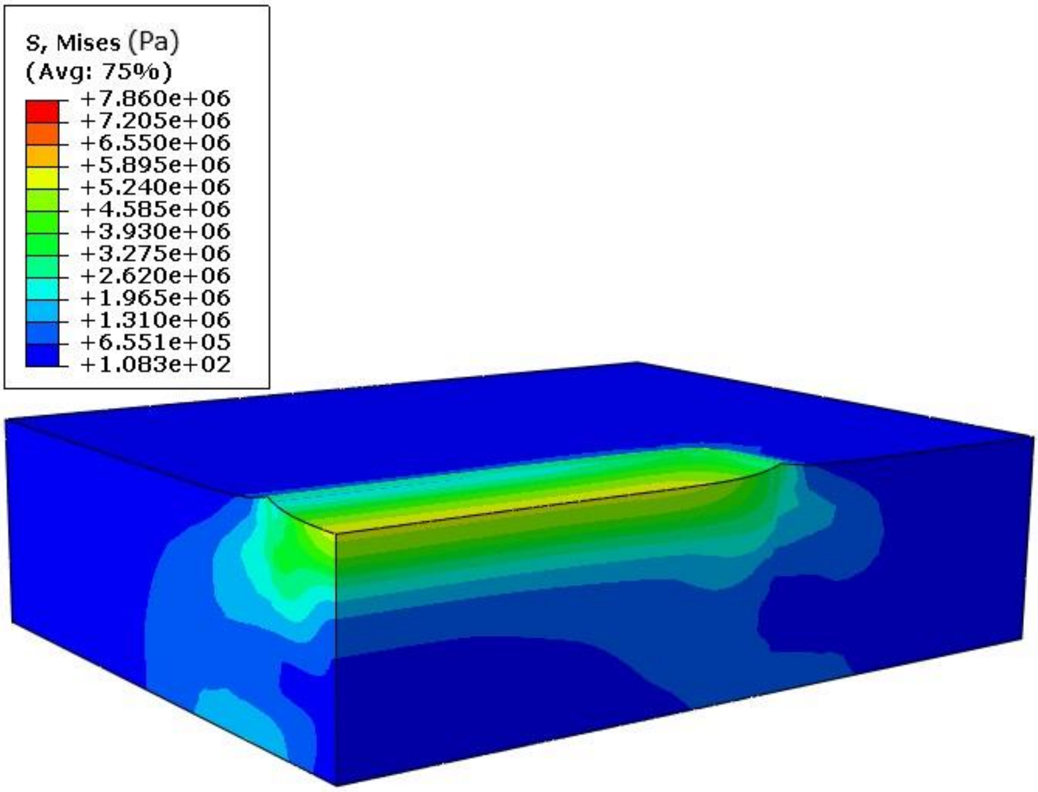


Figure 5.90: Stress distribution in JUT at 20 °C

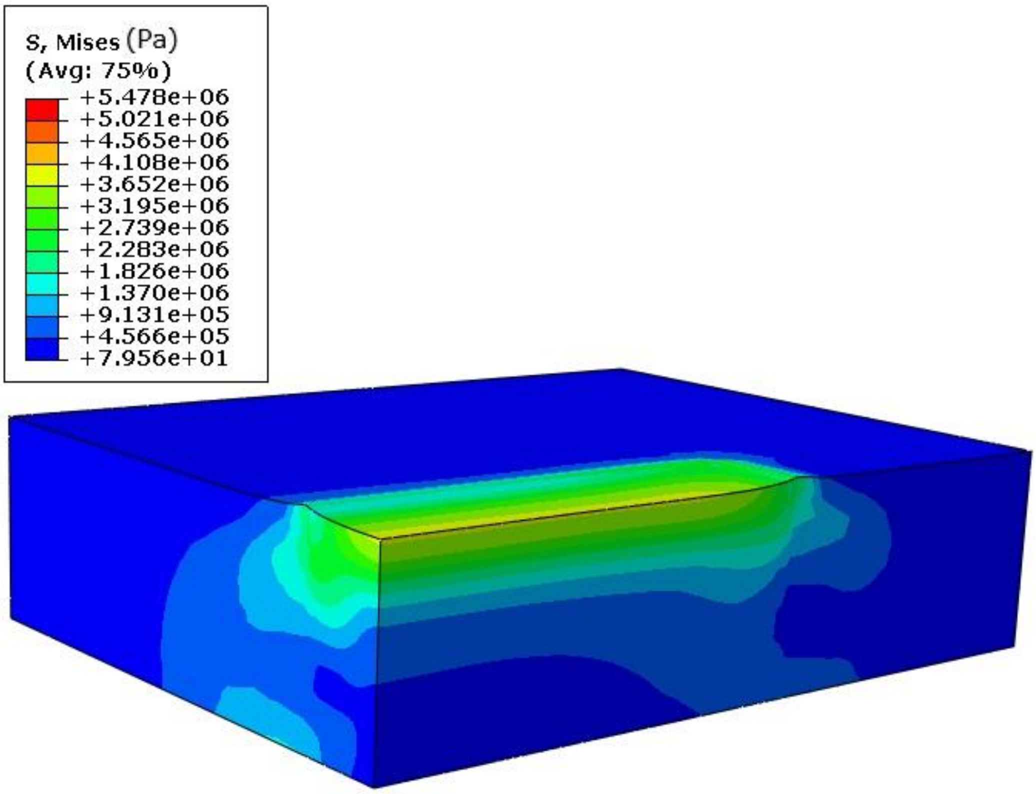


Figure 5.91: Stress distribution in COI at 5 °C

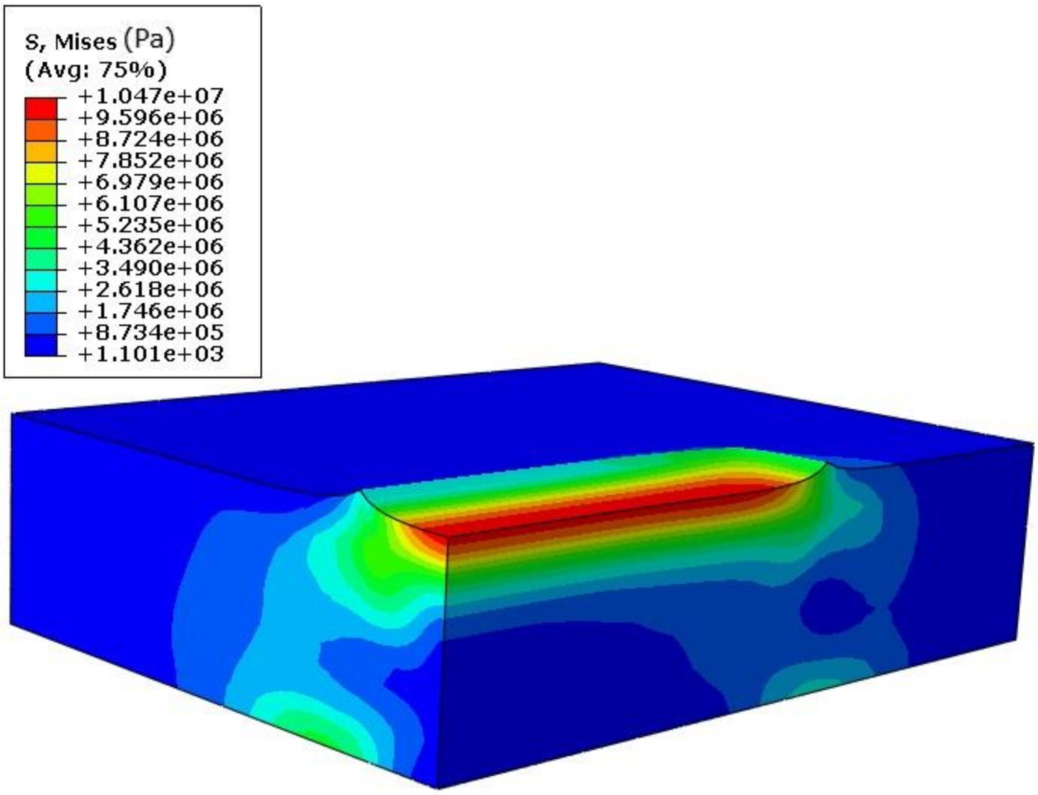


Figure 5.92: Stress distribution in COI at 20 °C

5.5 Summary

This chapter has presented the numerical simulation procedures and theories used to predict the permanent deformation response of the conventional CBEM and HMA, together with reinforced CBEM with natural and synthetic fibres. The commercial code ABAQUS was used for developing the FE models. The geometry, material properties, boundary and loading conditions for the different models were presented and discussed. Based on the mesh sensitivity studies, the suitable element size for the bituminous models was selected. The bituminous slabs were modelled as viscoelastic and viscoplastic materials considering the loading effects by using different wheel load repetitions. Prony series parameters and creep power law coefficients were determined experimentally using creep and relaxation testing to prepare the viscoelastic and viscoplastic models, respectively. Then, the numerical models were validated against the corresponding experimental results based on the rutting trace and permanent deformation shape. The comparisons between the numerical and experimental results were made for the rutting performance for all mixtures selected under different loading conditions. Reasonably good agreements between the experimental data and FE results were obtained. In addition, the validated FE models were also employed to perform parametric studies to examine the influences of natural and synthetic fibres on the rutting behaviour of the CBEMs. The effect of the static loading condition, temperatures, repeated applied moving load speed and stress distribution on the rutting of the bituminous mixtures were selected to be investigated in the parametric studies. The results showed that the static loading condition and low tyre speed have a considerable influence, while the higher speed has insignificant effect on the rutting behaviour. Also it was concluded that decreasing the temperatures from 60 °C to 5 °C led to a reduction in the rutting of all mixtures selected.

Chapter 6

Conclusions and Recommendations for Future Work

6.1 Introduction

This study was conducted with the aim to gain a better understanding of the behaviour of CBEM, and to improve this behaviour using natural and synthetic fibres as reinforcing materials under different environmental and loading conditions. The work included a series of experimental work, numerical modelling using ABAQUS/standard and parametric studies of the CBEM rutting behaviour.

The experimental work covered material and mechanical tests, including the use of scanning electron microscopy. The CBEMs were reinforced using different natural and synthetic fibres, such as hemp, jute, coir and glass fibres. The reinforced and unreinforced CBEMs, and HMA mixture for comparison purposes, were subjected to different loadings with different laboratory tests to study the effect of several parameters, such as stiffness modulus, rutting, crack propagation, moisture and temperature sensitivity. In addition, scanning electron microscopy of the fibre structure was used to investigate the shape of the fibres and their surface roughness characteristics.

Numerical models were developed and validated against the corresponding experimental results. Based on these models, parametric studies were further carried out to investigate the influence of the parameters with more variation. Furthermore, simplified models were proposed to predict the permanent deformation and the stress distribution for the bituminous mixtures.

This chapter summarises the main findings of the study and provides recommendations for future work.

6.2 Experimental Study

This study considered the influence of the novel natural and synthetic fibres as reinforcing materials on the mechanical performance of the cold asphalt mixtures, under different environmental and loading conditions. The study also found that significant improvements were achieved in the mechanical properties of CBEMs due to incorporation of fibres. These improvements might be attributed to the developed tensile and shear strength occurring inside reinforced mixtures, which could be related as these fibres provide a three-dimensional reinforcement for the CBEMs. The main conclusions of the novel reinforced CBEMs are summarised as follows:

- Based on the optimisation of fibres' length and content in terms of ITSM, it can be concluded that the optimum fibre length is 14 mm and optimum fibre content is 0.35% of the dry aggregate. These results were found for each type of fibre used.
- The early life strength of the novel reinforced CBEMs can be enhanced and curing times significantly shortened by incorporating natural and synthetic fibres.
- Natural and synthetic fibres increase the curing rate, in terms of stiffness modulus, and the ultimate stiffness modulus of CBEMs. The substantial improvement in the indirect tensile stiffness values (from 144% to 160%, dependant on fibre type) after two days of curing has resulted in the development of a new generation of high performance CBEMs.
- At moderate curing (28 to 90 days), the novel reinforced CBEMs have comparable stiffness properties to the conventional hot mixture.

- All novel reinforced CBEMs were also found to reduce temperature susceptibility relative to the HMA and unreinforced CBEMs. Accordingly, it can be concluded that the reinforced mixtures suffer less permanent deformation and fracture during hot and cold weather, respectively, in comparison with the conventional CBEM and HMA.
- The novel CBEMs, reinforced with both natural and synthetic fibres, have excellent resistance to rutting in wheel tracking tests at high temperatures. These results are better than those for CBEM and HMA, meaning that the reinforced mixtures can carry heavier traffic loads in hot climatic conditions. The findings show that the accumulated permanent strain in the reinforced mixtures was found to be for example 462% to 766% (depending on fibres type) less than the conventional CBEM at 45 °C.
- A microanalysis technique, namely SEM, has provided understanding of the role of the fibres as reinforcing materials in CBEM, ensuring that the fibres' shape and surface have a positive effect on the mechanical properties of the reinforced mixtures. A rough fibre surface was observed by SEM, this is responsible for improved mechanical interlocking between the fibres and binder mixture.
- In the durability evaluation, the novel reinforced CBEMs showed less susceptibility to severe environmental conditions such as moisture damage. Water action weakens CBEM strength. However, the fibre-reinforced CBEMs can be successfully used for road works during rainy periods as such mixtures provide adequate mechanical performance, similar to that of HMA. Taking into account that during the periods of very heavy rain, curing time needs to be longer.

- An improvement in the fracture toughness and an increased tendency for the fracture to become more ductile were also confirmed for the novel reinforced mixtures using natural and synthetic fibres. Resistance to crack propagation in the reinforced CBEMs was additionally improved by both natural and synthetic fibres. This effect is magnified by the random orientation of the fibres in the mixtures.
- Using natural and synthetic fibres in CBEM can also significantly improve the creep resistance at different temperatures (from 13% to 54%, dependant on fibre type and temperature) when compared with the conventional CBEM.
- Bituminous mixture deformation has recoverable (elastic and viscoelastic) and irrecoverable (plastic and viscoplastic) components. The creep and relaxation test conducted at various temperatures allows the measurement of all four components. The viscoplastic strain is concluded to be the major contributor to the bituminous mixture rutting. The conventional CBEM and HMA, and reinforced CBEMs', parameters (A, n and m) can be determined from the creep and relaxation test results analysis. Each bituminous mixture has a unique set of parameters: A, n and m.

6.3 Numerical Modelling

Finite element modelling has been used to produce novel models with viscoelastic and viscoplastic analysis of the CBEM. A series of finite element simulations were conducted to investigate the benefits of using natural and synthetic fibres as novel reinforcing materials in CBEM for different cases of loading and environment conditions. These simulations were based on the viscoelastic and viscoplastic material properties and were validated using the wheel tracking tests. The results of these simulations provide insights and important information about the effects of fibre reinforcement on permanent deformation in CBEM and HMA, and how these fibres can enhance the performance of CBEMs under traffic loading and severe environmental conditions, as summarised below:

- The results presented in this study provide strong evidence that the 3-D non-linear finite element models developed are capable of predicting the rutting behaviour and the total deformation shape for the bituminous mixtures subjected to repeated moving load. This proves that the associated material properties used are appropriate and performed effectively. The numerical results show that the viscoelastic and viscoplastic material properties could be used to simulate the bituminous mixtures.
- The comparison between the numerical and experimental rutting for the conventional CBEM and HMA, and the novel reinforced CBEMs subjected to multiple moving wheel loading with different temperatures, show that the predicted rutting and mixtures' deformed shape correlate reasonably well to the corresponding experimental results. In addition, the deformation modes predicted are similar to those captured experimentally.
- In terms of the rutting and the deformation shape, the agreement between the predicted results and the corresponding experimental data is reasonably good for all mixture types with different temperatures. The numerical models also indicate that with the increasing temperature, the rutting is increased. In addition, the novel reinforced CBEMs with natural and synthetic fibres show less rutting compared with the conventional CBEM and HMA mixtures. However, both of the reinforced and unreinforced mixtures exhibit similar deformation modes regardless of the rutting values. All these predictions agree reasonably well with the experimental findings.

- The numerical and experimental results correlate very well for both the viscoelastic and viscoplastic material properties that were subjected to different numbers of repeated moving wheel load with different temperatures. It is clear that the models are able to predict all features of the traces (the depression and the two sides of the rutting upheaval).
- Using the validated models, parametric studies have been carried out on parameters covering the static loading condition, temperature, repeated moving wheel speed and stress distribution. The numerical predictions show that the static loading condition increases the rutting of all mixture types and temperatures. At lower temperatures (5 °C and 20 °C), the bituminous mixtures suffer less rutting compared with the high temperatures due to the higher stiffness of the mixtures. Increasing the speed of the applied moving load from 0.6 km/h to 5 km/h and to 30 km/h has a considerable influence on reducing rutting of all reinforced and unreinforced mixtures at different temperatures, whereas, increasing speed from 30 km/h to 60 km/h shows a slightly lower rutting for all mixtures and temperatures. The novel reinforced mixtures exhibit higher stress to resist rutting than unreinforced mixtures.

6.4 Recommendations for Future Work

Based on the investigation and outputs above, a number of further research studies can be carried out to improve the knowledge and understanding, and the design, of the CBEMs in some areas which could not be covered in this study:

- Although an asphalt concrete mixture was used to validate the use of natural and synthetic fibres in understanding the performance of the CBEMs, it would be beneficial to investigate other mixtures such as stone mastic asphalt, porous asphalt and hot rolled asphalt (HRA).

- An economic study is highly recommended to estimate the actual cost effectiveness of incorporating natural and synthetic fibres as reinforcing materials in CBEM instead of conventional HMA.
- The current study has focused on the predicting rutting of the reinforced and unreinforced CBEMs that have been supported from the bottom by a fixed un-deformable steel plate (simulating only one bituminous layer), but in reality, there are different deformable layers (embankment or bituminous layers) laid down to support the bottom of the bituminous surface layer. Therefore, further studies could be undertaken experimentally and numerically to investigate the influence of the deformable under-layers on the rutting behaviour of CBEMs.
- Further studies could be carried out experimentally and numerically to investigate the effect of the repeated heavy loads with different wheel configurations on the rutting performance of the reinforced and unreinforced CBEMs.
- The present study focuses on the rutting behaviour of the reinforced and unreinforced CBEMs under different loading and environmental conditions. It is strongly recommended experimentally and numerically to investigate how natural and synthetic fibres affect the fatigue response of the CBEMs. In fatigue tests, there is a significant difference in the number of cycles taken to reach failure and the reasons behind this are often not clear. The numerical model might give improved understanding of this.
- More results of crack propagation response variables need to be obtained from other well developed finite element models to investigate the effects of natural and synthetic fibres as reinforcing materials in CBEM on the

mitigation of the crack initiation. Future research is also needed to utilise the accelerated full scale test results for a detailed analysis and better understanding of the complicated pavement behaviour due to various combinations of the effects of spee○d, load, tyre pressure, and tyre type.

References

ABAQUS (2015) *online documentation. Version 6.12., 2015*.

Abiola, O.S., Kupolati, W.K., Sadiku, E.R. and Ndambuki, J.M. (2014) Utilisation of natural fibre as modifier in bituminous mixes: A review. *Construction and Building Materials*, 54, 305-312.

Abtahi, S.M., Sheikhzadeh, M. and Hejazi, S.M. (2010) Fiber-reinforced asphalt-concrete – A review. *Construction and Building Materials*, 24 (6), 871-877.

Al-Busaltan, S., Al Nageim, H., Atherton, W. and Sharples, G. (2012a) Green Bituminous Asphalt relevant for highway and airfield pavement. *Construction and Building Materials*, 31, 243-250.

Al-Busaltan, S., Al Nageim, H., Atherton, W. and Sharples, G. (2012b) Mechanical properties of an upgrading cold-mix asphalt using waste materials. *Journal of materials in civil engineering*, 24 (12), 1484-1491.

Al-Busaltan, S.F. (2012) *Development of New Cold Bitunimous Mixtures For Road and Highway Pavements*. PhD Thesis thesis, Liverpool John Moores University.

Al-Hadidy, A.I. and Yi-qiu, T. (2009) Mechanistic approach for polypropylene-modified flexible pavements. *Materials & Design*, 30 (4), 1133-1140.

Al-Hdabi, A. (2014) *High Strength Cold Rolled Asphalt Surface course Mixtures*. PhD Thesis thesis, Liverpool John Moores University.

Al-Hdabi, A., Al Nageim, H., Ruddock, F. and Seton, L. (2014) Development of Sustainable Cold Rolled Surface Course Asphalt Mixtures Using Waste Fly Ash and Silica Fume. *Journal of materials in civil engineering*, 26 (3), 536-543.

Al-Hdabi, A., Al Nageim, H. and Seton, L. (2014a) Performance of gap graded cold asphalt containing cement treated filler. *Construction and Building Materials*, 69, 362-369.

Al-Hdabi, A., Al Nageim, H. and Seton, L. (2014b) Superior cold rolled asphalt mixtures using supplementary cementations materials. *Construction and Building Materials*, 64, 95-102.

Al-Husainy, A.S.S. (2017) *Impact Response of Recycled Aggregate Concrete Filled Steel Tube Columns Strengthened with CFRP*. PhD Thesis thesis, The University of Liverpool.

Al-Thairy, H. (2012) *Behaviour and Design of Steel Column Subjected to Vehicle Impact*. PhD Thesis thesis, University of Manchester.

Al Nageim, H., Al-Busaltan, S.F., Atherton, W. and Sharples, G. (2012) A comparative study for improving the mechanical properties of cold bituminous emulsion mixtures with cement and waste materials. *Construction and Building Materials*, 36, 743-748.

Aliha, M.R.M., Razmi, A., Razavi, M. and Mansourian, A. (2017) The influence of natural and synthetic fibers on low temperature mixed mode I+II fracture behavior of warm mix asphalt (WMA) materials. *Engineering Fracture Mechanics*.

Allou, F., Takarli, M., Dubois, F., Petit, C. and Absi, J. (2015) Numerical finite element formulation of the 3D linear viscoelastic material model: Complex Poisson's ratio of bituminous mixtures. *Archives of Civil and Mechanical Engineering*, 15 (4), 1138-1148.

Ambassa, Z., Allou, F., Petit, C. and Eko, R.M. (2013) Fatigue life prediction of an asphalt pavement subjected to multiple axle loadings with viscoelastic FEM. *Construction and Building Materials*, 43, 443-452.

Ameri, M., Mansourian, A., Heidary Khavas, M., Aliha, M.R.M. and Ayatollahi, M.R. (2011) Cracked asphalt pavement under traffic loading – A 3D finite element analysis. *Engineering Fracture Mechanics*, 78 (8), 1817-1826.

Arabani, M., Jamshidi, R. and Sadeghnejad, M. (2014) Using of 2D finite element modeling to predict the glasphalt mixture rutting behavior. *Construction and Building Materials*, 68, 183-191.

Arabani, M. and Kamboozia, N. (2013) The linear visco-elastic behaviour of glasphalt mixture under dynamic loading conditions. *Construction and Building Materials,* 41, 594-601.

Arya, I. and Jain, P.K. (1993) *Development of design procedure for semi-dense emulsified asphalt aggregate mixtures fdr laying in different climatic conditions of India*. Paris, France: 1st World Congress on Emulsion**:** 531-535.

Asphalt Institute (1989) *Asphalt Cold Mix Manual, Manual Series No. 14 (MS-14), 3rd Edition, Lexington, Kentucky 4, USA.*

Asphalt Institute (2008) *Basic Asphalt Emulsion Manual, Manual Series No. 19 (MS-19), 4th Edition., Lexington, Kentucky, USA.*

Bai, F., Yang, X. and Zeng, G. (2016) A stochastic viscoelastic–viscoplastic constitutive model and its application to crumb rubber modified asphalt mixtures. *Materials & Design*, 89, 802-809.

Bocci, M., Grilli, A., Cardone, F. and Graziani, A. (2011) A study on the mechanical behaviour of cement–bitumen treated materials. *Construction and Building Materials*, 25 (2), 773-778.

Bocci, M., Virgili, A. and Colgrande, S. (2002) *A study of the Mechanical Characteristics of Cold Recycled Bituminous Concretes*. Proceeding of 4th European Symposium on Performance of Bituminous and Hydraulic Materials in Pavement: University of Nottingham**:** 227-235.

Bonaquist, B. (2011) Mix design practices for warm mix asphalt. *Transportation Research Board (TRB),*

Bouteiller, E. (2010) Asphalt emulsion for sustainable payments. *1st International Conference on Pavement Preservation,*

British Standard Institution (2011) *BS 434-1: Bitumen and road emulsions - Part 1: Specification for anionic bitumen road emulsions, UK.*

Brown, S.F. (1995) *Practical test procedures for mechanical properties of bituminous materials*. Proceedings of the Institution of Civil Engineers - Transport: ice. 111**:** 289-297.

Brown, S.F. and Needham, D. (2000) A Study of Cement Modified Bitumen Emulsion Mixtures. *Annual Meeting of the Association of Asphalt Paving Technologists,*

Bueno, B.d.S., Silva, W.R.d., Lima, D.C.d. and Minnete, E. (2003) Engineering Properties of Fiber Reinforced Cold Asphalt Mixes. *Journal of Environmental Engineering*, 129, 952-955.

Burmister, D.M., Palmer, L.A., Barber, E.S. and Middlebrooks, T.A. (1943) *The Theory of Stresses and Displacements in Layered Systems and Applications to Design of Airport Runways*. Chicago, USA: Highway Research Board. 23**:** 126-148.

Chávez-Valencia, L.E., Alonso, E., Manzano, A., Pérez, J., Contreras, M.E. and Signoret, C. (2007) Improving the compressive strengths of cold-mix asphalt using asphalt emulsion modified by polyvinyl acetate. *Construction and Building Materials*, 21 (3), 583-589.

Chazallon, C., Koval, G., Hornych, P., Allou, F. and Mouhoubi, S. (2009) Modelling of rutting of two flexible pavements with the shakedown theory and the finite element method. *Computers and Geotechnics*, 36 (5), 798-809.

Chen, F., Balieu, R. and Kringos, N. (2017) Thermodynamics-based finite strain viscoelastic-viscoplastic model coupled with damage for asphalt material. *International Journal of Solids and Structures*, 129, 61-73.

Chen, H. and Xu, Q. (2010) Experimental study of fibers in stabilizing and reinforcing asphalt binder. *Fuel*, 89 (7), 1616-1622.

Chen, H., Xu, Q., Chen, S. and Zhang, Z. (2009) Evaluation and design of fiber-reinforced asphalt mixtures. *Materials & Design*, 30 (7), 2595-2603.

Chen, J., Wang, H., Li, M. and Li, L. (2016) Evaluation of pavement responses and performance with thermal modified asphalt mixture. *Materials & Design*, 111, 88-97.

Chen, X., Zhang, J. and Wang, X. (2015) Full-scale field testing on a highway composite pavement dynamic responses. *Transportation Geotechnics*, 4, 13-27.

Cheung, C.Y. (1995) *Mechanical Behaviour of Bitumens and Biuminous Mixes*. PhD Thesis thesis, University of Cambridge.

Chun, S., Kim, K., Greene, J. and Choubane, B. (2015) Evaluation of interlayer bonding condition on structural response characteristics of asphalt pavement using finite element analysis and full-scale field tests. *Construction and Building Materials*, 96, 307-318.

Dardak, H. (1993) Performance of different mixes of sand emulsion in Indonesia. *1st World Congress on Emulsion*, 4-12

Dave, E., V.,, Buttlar, W., G.,, Paulino, G., H., and Hilton, H., H. (2006) Graded Viscoelastic Approach for Modeling Asphalt Concrete Pavements, in: Proceedings of the Multiscale and Functionally Graded Materials Conference, O'Ahu, Hawaiiof Conference.

Dinis-Almeida, M., Castro-Gomes, J., Sangiorgi, C., Zoorob, S.E. and Afonso, M.L. (2016) Performance of Warm Mix Recycled Asphalt containing up to 100% RAP. *Construction and Building Materials*, 112, 1-6.

Doh, Y.S., Baek, S.H. and Kim, K.W. (2009) Estimation of relative performance of reinforced overlaid asphalt concretes against reflection cracking due to bending more fracture. *Construction and Building Materials*, 23 (5), 1803-1807.

Doyle, T.A., McNally, C., Gibney, A. and Tabaković, A. (2013) Developing maturity methods for the assessment of cold-mix bituminous materials. *Construction and Building Materials*, 38, 524-529.

Dulaimi, A., Al Nageim, H., Ruddock, F. and Seton, L. (2016) New developments with cold asphalt concrete binder course mixtures containing binary blended cementitious filler (BBCF). *Construction and Building Materials*, 124, 414-423.

Dulaimi, A., Al Nageim, H., Ruddock, F. and Seton, L. (2017a) High performance cold asphalt concrete mixture for binder course using alkali-activated binary blended cementitious filler. *Construction and Building Materials*, 141, 160-170.

Dulaimi, A., Al Nageim, H., Ruddock, F. and Seton, L. (2017b) Laboratory Studies to Examine the Properties of a Novel Cold-Asphalt Concrete Binder Course Mixture Containing Binary Blended Cementitious Filler. *Journal of materials in civil engineering*, 29 (9).

Dulaimi, A., Nageim, H.A., Ruddock, F. and Seton, L. (2017c) Performance Analysis of a Cold Asphalt Concrete Binder Course Containing High-Calcium Fly Ash Utilizing Waste Material. *Journal of materials in civil engineering*, 29 (7), 04017048.

Dulaimi, A.F.D. (2017) *Development of a New Cold Binder Course Emulsion Asphalt*. PhD Thesis thesis, Liverpool John Moores University.

Eisenmann, J., Lempe, U. and Leykauf, G. (1977) Method for the Structural Design of Asphalt Pavements. *The 4th International Conference on the Structural Design of Asphalt Pavements*, 342-352

European Asphalt Pavement Association (2010) *The use of Warm Mix Asphalt*. Brussels, Belgium: European Asphalt Pavement Association.

European Asphalt Pavement Association. (2015) *The Use Of Bitumen Emulsion In Europe* [online] Available at: http://www.eapa.org/publications.php?c=73 [Accessed: 12/04/2018]

European Committee for Standardization - Part 1 (2006) *BS EN 13108-1: Bituminous mixtures — Material specifications, Asphalt Concrete, British Standards Institution, London, UK.*

European Committee for Standardization - Part 1 (2012) *BS EN 933-1: Tests for geometrical properties of aggregates: Determination of particle size distribution — Sieving method, British Standards Institution, London, UK.*

European Committee for Standardization - Part 4 (2006) *BS EN 13108-4: Bituminous mixtures — Material specifications, Hot Rolled Asphalt, British Standards Institution, London, UK.*

European Committee for Standardization - Part 5 (2006) *BS EN 13108-5: Bituminous mixtures — Material specifications, Stone Mastic Asphalt, British Standards Institution, London, UK.*

European Committee for Standardization - Part 12 (2008) *BS EN 12697: Bituminous mixtures - Test methods for hot mix asphalt-determination of the water sensitivity of bituminous specimens, British Standards Institution, London, UK.*

European Committee for Standardization - Part 13 (2000) *BS EN 12697: Bituminous mixtures — Test methods for hot mix asphalt, Temperature measurement, British Standards Institution, London, UK.*

European Committee for Standardization - Part 22 (2003) *BS EN 12697-22: Bituminous mixtures — Test methods for hot mix asphalt — Wheel tracking, British Standards Institution, London, UK.*

European Committee for Standardization - Part 25 (2005) BS EN 12697-25: Bituminous mixtures — Test methods for hot mix asphalt — Cyclic compression test, British Standards Institution, London, UK.

European Committee for Standardization - Part 26 (2012) *BS EN 12697: Bituminous mixtures - Test methods for hot mix asphalt- stiffness, British Standards Institution, London, UK.*

European Committee for Standardization - Part 44 (2010) *BS EN 12697: Bituminous mixtures — Test methods for hot mix asphalt, Crack propagation by semi-circular bending test, British Standards Institution, London, UK.*

European Committee for Standardization - PD 6691 (2010) *PD 6691. Guidance on the use of BS EN 13108 Bituminous mixtures – Material specifications, London, UK: British Standards Institution.*

European Committee for Standardization (2013) *BS EN 13808: Bitumen and bituminous binders - Framework forspecifying cationic bituminous emulsions, British Standards Institution, London, UK.*

European Environment Agency (2013) *EMEP/EEA air pollutant emission inventory guidebook 2013*. Luxembourg: Publications Office of the European Union, EEA Technical report. No 12/2013.

Fakhri, M. and Hosseini, S.A. (2017) Laboratory evaluation of rutting and moisture damage resistance of glass fiber modified warm mix asphalt incorporating high RAP proportion. *Construction and Building Materials*, 134, 626-640.

Fallah, S. and Khodaii, A. (2015) Reinforcing overlay to reduce reflection cracking; an experimental investigation. *Geotextiles and Geomembranes*, 43 (3), 216-227.

Fang, H., Haddock, J.E., White, T.D. and Hand, A.J. (2004) On the characterization of flexible pavement rutting using creep model-based finite element analysis. *Finite Elements in Analysis and Design*, 41 (1), 49-73.

Fang, X., Garcia, A., Winnefeld, F., Partl, M.N. and Lura, P. (2016) Impact of rapid-hardening cements on mechanical properties of cement bitumen emulsion asphalt. *Materials and Structures*, 49 (1-2), 487-498.

Fazaeli, H., Samin, Y., Pirnoun, A. and Dabiri, A.S. (2016) Laboratory and field evaluation of the warm fiber reinforced high performance asphalt mixtures (case study Karaj – Chaloos Road). *Construction and Building Materials*, 122, 273-283.

Ferrotti, G., Pasquini, E. and Canestrari, F. (2014) Experimental characterization of high-performance fiber-reinforced cold mix asphalt mixtures. *Construction and Building Materials*, 57, 117-125.

Forth, J., Zoorob, S. and Thanaya, I. (2006) Development of bitumen-bound waste aggregate building blocks. *Proceedings of the Institution of Civil Engineers - Construction Materials*, 23-32

Fu, Z., Shen, W., Huang, Y., Hang, G. and Li, X. (2017) Laboratory evaluation of pavement performance using modified asphalt mixture with a new composite reinforcing material. *International Journal of Pavement Research and Technology*.

Gadallab, A.A., Wood, L.E. and Yoder, E. (1977) Suggested Method for the Preparation and Testing of Asphalt Emulsion Treated Mixtures using Marshall Equipment. *Association of Asphalt Paving Technologists Proc*, 46196-227

García, A., Lura, P., Partl, M.N. and Jerjen, I. (2013) Influence of cement content and environmental humidity on asphalt emulsion and cement composites performance. *Materials and Structures*, 46 (8), 1275-1289.

Ghauch, Z.G. and Abou-Jaoude, G.G. (2013) Strain response of hot-mix asphalt overlays in jointed plain concrete pavements due to reflective cracking. *Computers & Structures*, 124, 38-46.

Gómez-Meijide, B. and Pérez, I. (2014) A proposed methodology for the global study of the mechanical properties of cold asphalt mixtures. *Materials & Design*, 57, 520-527.

Gu, F., Luo, X., Luo, R., Hajj, E.Y. and Lytton, R.L. (2017) A mechanistic-empirical approach to quantify the influence of geogrid on the performance of flexible pavement structures. *Transportation Geotechnics*, 13, 69-80.

Gu, F., Luo, X., Luo, R., Lytton, R.L., Hajj, E.Y. and Siddharthan, R.V. (2016) Numerical modeling of geogrid-reinforced flexible pavement and corresponding validation using large-scale tank test. *Construction and Building Materials*, 122, 214-230.

Guoming, L., Weimin, C. and Lianjun, C. (2017) Investigating and optimizing the mix proportion of pumping wet-mix shotcrete with polypropylene fiber. *Construction and Building Materials*, 150, 14-23.

Head, R.W. (1974) An informal report of cold mix research using emulsified asphalt as a binder. *Association of Asphalt Paving Technologists (AAPT) Conference*, 43110-131

Hesami, S., Ahmadi, S. and Nematzadeh, M. (2014) Effects of rice husk ash and fiber on mechanical properties of pervious concrete pavement. *Construction and Building Materials*, 53, 680-691.

Hu, X. and Walubita, L., F. (2011) Effects of Layer Interfacial Bonding Conditions on the Mechanistic Responses in Asphalt Pavements. *JOURNAL OF TRANSPORTATION ENGINEERING*, 137 (1), 28-36.

Huang, B., Mohammad, L.N. and Rasoulian, M. (2001) *Three-Dimensional Numerical Simulation of Asphalt Pavement at Louisiana Accelerated Loading Facility*. Washington, USA: Transportation Research Record.

Huang, C.W., Al-Rub, R.K.A., Masad, E.A. and Little, D.N. (2011) Three-Dimensional Simulations of Asphalt Pavement Permanent Deformation Using a Nonlinear Viscoelastic and Viscoplastic Model. *Journal of materials in civil engineering*.

Huang, Y.H. (1967) *Deformation and Volume Change Characteristics of a Sand Asphalt Mixture Under Constant Direct Triaxial Compressive Stresses*. USA: Highway Research Record. 178**:** 60.

Huang, Y.H. (2004) *Pavement Analysis and Design*. United States of America: Pearson Education, Inc.

Ibrahim, H. and Thom, N. (1997) The Effect of Emulsion Aggregate Mixture Stiffness on Both Moisture and Pavement Design. *Proceeding of the 2nd European symposium on Performance and Durability of Bituminous Materials*,

Ibrahim, H.E.-S.M. (1998) *Assessment and Design of Emulsion-Aggregate Mixtures for Use in Pavements*. PhD Thesis thesis, University of Nottingham.

Imaninasab, R., Bakhshi, B. and Shirini, B. (2016) Rutting performance of rubberized porous asphalt using Finite Element Method (FEM). *Construction and Building Materials*, 106, 382-391.

Jamshidi, A., Hamzah, M.O., Kurumisawa, K., Nawa, T. and Samali, B. (2016) Evaluation of sustainable technologies that upgrade the binder performance grade in asphalt pavement construction. *Materials & Design*, 95, 9-20.

Jaskuła, P., Stienss, M. and Szydłowski, C. (2017) Effect of Polymer Fibres Reinforcement on Selected Properties of Asphalt Mixtures. *Procedia Engineering*, 172, 441-448.

Jenkins, K.J. (2000) *Mix Design Considerations For Cold And Half-Warm Bituminous Mixes With Emphasis On Foamed Bitumen*. PhD Thesis thesis, University of Stellenbosch.

Jeon, J., Kim, W., Kim, G. and Jeon, C. (2016) Polyamide Fiber Reinforced Shotcrete for Tunnel Application. *Materials*, 9 (3), 163.

Kai, L. and Fang, W. (2011) Computer Modeling Mechanical Analysis for Asphalt Overlay under Coupling Action of Temperature and Loads. *Procedia Engineering*, 15, 5338-5342.

Khalid, H.A. (2003) Assessing the Potential in Fatigue of a Dense Wearing Course Emulsified Bitumen Macadam. *Proceedings of the 6th International RILEM Symposium on Performance testing and Evaluation of Bituminous Materials, Zurich, (ed. by Partl, M.N.), RILEM Publications, Bagneux, pp 349-356.*,

Khalid, H.A. and Eta, K.E. (1997) Structural Support Values for Emulsified Bitumen Macadams in Highway Reinstatement. *The 2nd European Symposium on Performance and Durability of Bituminous Materials*, 307- 326

Khalid, H.A. and Monney, O.K. (2009) Moisture damage potential of cold asphalt. *International Journal of Pavement Engineering*, 10 (5), 311-318.

Khanzada, S. (2000) *Permanent Deformation in Bituminous Mixtures*. PhD Thesis thesis, The University of Nottingham.

Kim, H. and Buttlar, W.G. (2009) Finite element cohesive fracture modeling of airport pavements at low temperatures. *Cold Regions Science and Technology*, 57, 123-130.

Kim, J., Lee, H.S. and Kim, N. (2010) Determination of Shear and Bulk Moduli of Viscoelastic Solids from the Indirect Tension Creep Test. *journal of engineering Mechanics*, 136 (9), 1067-1075.

Kim, Y., Im, S. and Lee, H.D. (2011) Impacts of Curing Time and Moisture Content on Engineering Properties of Cold In-Place Recycling Mixtures Using Foamed or Emulsified Asphalt. *Journal of materials in civil engineering*, 23 (5), 542-553.

Kim, Y., Lee, H.D. and Heitzman, M. (2007) Validation of New Mix Design Procedure for Cold In-Place Recycling with Foamed Asphalt. *Journal of materials in civil engineering*, 19 (11), 1000-1010.

Lanre, O.O. (2010) *A Study on The Development of Guidelines for The Production of Bitumen Emulsion Stabilised Raps for Roads in The Tropics*. PhD Thesis thesis, University of Nottingham.

Lee, K.W., Brayton, T.E., Gress, D. and Harrington, J. (2001) Performance-Based Mix-Design Method for Cold In-Place Recycling of Bituminous Pavements for Maintenance Management. *9th Maintenance Management Conference*, 2311-19

Leech, D. (1994) *Cold bituminous materials for use in the structural layers of roads*. Wokingham, United Kingdom: Transport Research Laboratory.

Li, C. and Li, L. (2012) Criteria for controlling rutting of asphalt concrete materials in sloped pavement. *Construction and Building Materials*, 35, 330-339.

Li, G., Zhao, Y., Pang, S.S. and Huang, W. (1998) Experimental study of cement-asphalt emulsion composite. *Cement and Concrete Research*, 28 (5), 635-641.

Li, Y., Liu, L., Xiao, F. and Sun, L. (2017) Effective temperature for predicting permanent deformation of asphalt pavement. *Construction and Building Materials*, 156, 871-879.

Liebenberg, J. and Visser, A. (2004) Towards a mechanistic structural design procedure for emulsion-treated base layers. *Journal of the South African Institution of Civil Engineering*, 46, 2-9.

Littel, D., N.,, Bhasin, A. and Allen, D., H. (2017) *Modeling and Design of Flexible Pavements and Materials*. Switzerland: Springer.

Liu, G., Cheng, W. and Chen, L. (2017) Investigating and optimizing the mix proportion of pumping wet-mix shotcrete with polypropylene fiber. *Construction and Building Materials*, 150, 14-23.

Maache, M., Bezazi, A., Amroune, S., Scarpa, F. and Dufresne, A. (2017) Characterization of a novel natural cellulosic fiber from Juncus effusus L. *Carbohydr Polym*, 171, 163-172.

Mahrez, A. and Rehan, K.M. (2010) Fatigue characteristics of stone mastic asphalt mix reinforced with fiber glass. *International Journal of the Physical Sciences*, 5 (12), 1840-1847.

Mallick, R.B. and El-Korchi, T. (2013) *Pavement engineering: principles and practice*. 3rd Edition, CRC Press, Taylor & Francis Group.

Marchal, J.L., Boussad, N. and Julien, P. (1993) *A New Approach to Cold-Mix Design and Performance*. Eurobitume, Sweden**:** 531-535.

Miljković, M. (2014) *Influence of Bitumen Emulsion and Reclaimed Asphalt on Mechanical and Pavement Design-related Performance of Asphalt Mixtures*. PhD Thesis thesis, Ruhr University Bochum.

Mirabdolazimi, S.M. and Shafabakhsh, G. (2017) Rutting depth prediction of hot mix asphalts modified with forta fiber using artificial neural networks and genetic programming technique. *Construction and Building Materials,* 148, 666-674.

Moghaddam, T., B.,, Karim, M., R., and Abdelaziz, M. (2011) A review on fatigue and rutting performance of asphalt mixes. *Academic Journals,* 6 (4), 670-682.

Monich, P.R., Berti, F.V., Porto, L.M., Henriques, B., Novaes de Oliveira, A.P., Fredel, M.C. and Souza, J.C.M. (2017) Physicochemical and biological assessment of PEEK composites embedding natural amorphous silica fibers for biomedical applications. *Mater Sci Eng C Mater Biol Appl*, 79, 354-362.

Nassar, A.I., Mohammed, M.K., Thom, N. and Parry, T. (2016) Mechanical, durability and microstructure properties of Cold Asphalt Emulsion Mixtures with different types of filler. *Construction and Building Materials*, 114, 352-363.

Nassar, A.I.M. (2016) *Enhancing the Performance of Cold Bitumen Emulsion Mixture using Supplementary Cementitious*. PhD Thesis thesis, The University of Nottingham.

National Cooperative Highway Research Program (2002) *Contributions of Pavement Structural Layers to Rutting of Hot Mix Asphalt Pavements*. Washington, USA: Transportation Research Board.

Needham, D. (1996) *Developments in bitumen emulsion mixtures for roads*. PhD Thesis thesis, University of Nottingham.

Niazi, Y. and Jalili, M. (2009) Effect of Portland cement and lime additives on properties of cold in-place recycled mixtures with asphalt emulsion. *Construction and Building Materials*, 23 (3), 1338-1343.

Nicholls, J.C. (2004) *Asphalt Surfacings*. USA and Canada: Taylor & Francis.

Nik, A.A., Nejad, F.M. and Zakeri, H. (2016) Hybrid PSO and GA approach for optimizing surveyed asphalt pavement inspection units in massive network. *Automation in Construction,* 71, 325-345.

Nikolaides, A.F. (1983) *Design of dense graded cold bituminous emulsion mixtures and evaluation of their engineering properties*. PhD Thesis thesis, University of Leeds.

Nikolaides, A.F. (1993) *Proposed Design Method for Cold Dense Graded Bituminous Mixtures (CDGM)*. Eurobitume, Sweden**:** 615-619.

Nikolaides, A.F. (1994) *A new design method for dense cold mixtures*. Proceedings of the first European symposium on performance and durability of bituminous materials. University of Leeds.

O'Flaherty, C.A. (2007) *Highways the Location, Design, Construction and Maintanance of Road Pavements*. Butterworth Heinemann, USA.

O'Rourke, B., McNally, C. and Richardson, M.G. (2009) Development of calcium sulfate–ggbs–Portland cement binders. *Construction and Building Materials*, 23 (1), 340-346.

Ojum, C., Kuna, K., Thom, N. and Airey, G. (2014) An investigation into the effects of accelerated curing on Cold Recycled Bituminous Mixes. *International Conference on Asphalt Pavements, ISAP*of Conference.

Ojum, C.K. (2015) *The Design and Optimisation of Cold Asphalt Emulsion Mixtures*. PhD Thesis thesis, University of Nottingham.

Oruc, S., Celik, F. and Akpinar, M.V. (2007) Effect of Cement on Emulsified Asphalt Mixtures. *Journal of Materials Engineering and Performance*, 16 (5), 578-583.

Oruc, S., Celik, F. and Aksoy, A. (2006) Performance of cement modified dense graded cold-mix asphalt and establishing mathematical model. *Indian Journal of Engineering & Materials Sciences*, 13.

Ossa, E.A., Deshpande, V.S. and Cebon, D. (2005) Phenomenological Model for Monotonic and Cyclic Behavior of Pure Bitumen. *Journal of materials in civil engineering*, 17, 188-197.

Park, P., El-Tawil, S., Park, S.-Y. and Naaman, A.E. (2015) Cracking resistance of fiber reinforced asphalt concrete at −20°C. *Construction and Building Materials*, 81, 47-57.

Pavement Interactive. (2012) *Rutting* [online] Available at: http://www.pavementinteractive.org/rutting/ [Accessed: 20 April 2018]

Pérez, I., Medina, L. and del Val, M.A. (2016) Nonlinear elasto–plastic performance prediction of materials stabilized with bitumen emulsion in rural road pavements. *Advances in Engineering Software*, 91, 69-79.

Perl, M., Uzan, J. and Sides, A. (1983) *Visco-elasto-plastic constitutive law for a bituminous mixture under repeated loading*. Washington, USA: Transportation Research Board**:** 20-27.

Picoux, B., El Ayadi, A. and Petit, C. (2009) Dynamic response of a flexible pavement submitted by impulsive loading. *Soil Dynamics and Earthquake Engineering*, 29 (5), 845-854.

Preston, J.N. (1991) *The Design of Bituminous Concrete Mixes*. PhD Thesis thesis, The University of Nottingham.

Prowell, B.D., Hurley, G.C. and Frank, B. (2011) *Warm-Mix Asphalt: Best Practices*. Lanham, MD, USA: 2nd Edition, National Asphalt Pavement Associatoin (NAPA), Quality Improvement Publication 125.

Ravikumar, D., Peethamparan, S. and Neithalath, N. (2010) Structure and strength of NaOH activated concretes containing fly ash or GGBFS as the sole binder. *Cement and Concrete Composites*, 32 (6), 399-410.

Read, J. (1996) *Fatigue Cracking of Bituminous Paving Mixtures*. PhD Thesis thesis, University of Nottingham.

Read, J. and Whiteoak, D. (2003) *The Shell Bitumen Handbook*. 5th Edition, London, UK: Thomas Telford Publishing.

Roadex Network. (2018) *What is permanent deformation and why we do not like it* [online] Available [Accessed: 10 April 2018]

Roberts, F.L., Engelbrecht, J.C. and Kennedy, T.W. (1984) Evaluation of Recycled Mixtures Using Foamed Asphalt. *Transportation Research Record No. 968*.

Roberts, F.L., Kandhal, P.S., Brown, E.R., Lee, D.Y. and Kennedy, T.W. (1991) *Hot mix asphalt materials, mixture design and construction*. Lanham, Maryland, USA: NAPA Education Foundation.

Robinson, H.L. (1997) *Thin Asphalt Surfacings Using Cold Mix Technology*. Aedificatio Publishers: The Second European Symposium on Performance and Durability of Bituminous Materials, Zurich**:** 369-384.

Robinson, R. and Thagesen, B. (2004) *Road Engineering for Development*. London and New York: 2nd Edition, Spon Press, Taylor & Francis Group.

Rubio, M.C., Martínez, G., Baena, L. and Moreno, F. (2012) Warm mix asphalt: an overview. *Journal of Cleaner Production*, 24, 76-84.

Saeid, H., Saeed, A. and Mahdi, N. (2014) Effects of rice husk ash and fiber on mechanical properties of pervious concrete pavement. *Construction and Building Materials*, 53, 680-691.

Saeidi, H. and Aghayan, I. (2016) Investigating the effects of aging and loading rate on low-temperature cracking resistance of core-based asphalt samples using semi-circular bending test. *Construction and Building Materials*, 126, 682-690.

Safaei, F. and Castorena, C. (2017) Material nonlinearity in asphalt binder fatigue testing and analysis. *Materials & Design*, 133, 376-389.

Salomon, D.R. (2006) *Asphalt Emulsion Technology* Washington, USA: Transportation Research Board.

Santucci, L.E. (1977) Thickness Design Procedure for Asphalt and Emulsified Asphalt Mixes. *The 4th International Conference on Structural Design of Asphalt Pavements*, 424-456

Schmidt, R.J., Santucci, L.E. and Coyne, L.D. (1973) Performance characteristics of cement-modified asphalt emulsion mixes. *Association of Asphalt Paving Technologists (AAPT) Conference*, 300–319

Schneider, M., Romer, M., Tschudin, M. and Bolio, H. (2011) Sustainable cement production—present and future. *Cement and Concrete Research*, 41 (7), 642-650.

Serfass, J.P., Poirier, J.E., Henrat, J.P. and Carbonneau, X. (2004) Influence of Curing on Cold Mix Mechanical Performance. *Proceedings of the 6th International RILEM Symposium on Performance testing and Evaluation of Bituminous Materials, Zurich, (ed. by Partl, M.N.), RILEM Publications, Bagneux, pp 349-356.*,

Shan, L., Xu, Y., He, H. and Ren, N. (2016) Optimization criterion of viscoelastic response model for asphalt binders. *Construction and Building Materials*, 113, 553-560.

Shanbara, H.K., Dulaimi, A., Ruddock, F. and Atherton, W. (2016) The Linear Elastic Analysis of Cold Mix Asphalt by Using Finite Element Modeling. *The Second BUiD Doctoral Research Conference*, Dubai, United Arab Emiratesof Conference.

Shanbara, H.K., Ruddock, F. and Atherton, W. (2018a) A laboratory study of high-performance cold mix asphalt mixtures reinforced with natural and synthetic fibres. *Construction and Building Materials*, 172, 166-175.

Shanbara, H.K., Ruddock, F. and Atherton, W. (2018b) Predicting the rutting behaviour of natural fibre-reinforced cold mix asphalt using the finite element method. *Construction and Building Materials*, 167, 907-917.

Shanbara, H.K., Ruddock, F. and Atherton, W. (2018c) A viscoplastic model for permanent deformation prediction of reinforced cold mix asphalt. *Construction and Building Materials*, 186, 287-302.

Sheng, Y., Zhang, B., Yan, Y., Chen, H., Xiong, R. and Geng, J. (2017) Effects of phosphorus slag powder and polyester fiber on performance characteristics of asphalt binders and resultant mixtures. *Construction and Building Materials*, 141, 289-295.

Silva, F.d.A., Mobasher, B., Soranakom, C. and Filho, R.D.T. (2011) Effect of fiber shape and morphology on interfacial bond and cracking behaviors of sisal fiber cement based composites. *Cement and Concrete Composites*, 33 (8), 814-823.

Somé, S.C., Fredj, M.A., Nguyen, M.-L., Feeser, A. and Pavoine, A. (2017) Multi-parametric characterization of mode I fracture toughness of asphalt concrete: Influence of void and RA contents, binder and aggregate types. *International Journal of Pavement Research and Technology*.

Souza, F.V. and Castro, L.S. (2012) Effect of temperature on the mechanical response of thermo-viscoelastic asphalt pavements. *Construction and Building Materials*, 30, 574-582.

Staple, P.R. (1997) Cold Emulsion Macadam Performance Trials for Footway Surfacing in Leicestershire. *Proceedings of the Institution of Civil Engineers - Transport*, 123 (3), 174-177.

Sun, L. (2016a) The mechanism of initial damage for asphalt pavement. 297-388.

Sun, L. (2016b) Predictions of rutting on asphalt pavements. In: (ed.) *Structural Behavior of Asphalt Pavements.* pp. 601-648.

Sunarjono, S. (2008) *The Influence of Foamed Bitumen Characteristics on Cold-Mix Asphalt Properties*. PhD Thesis thesis, The University of Nottingham.

Tabaković, A., Braak, D., van Gerwen, M., Copuroglu, O., Post, W., Garcia, S.J. and Schlangen, E. (2017) The compartmented alginate fibres optimisation for bitumen rejuvenator encapsulation. *Journal of Traffic and Transportation Engineering (English Edition)*.

Taherkhani, H. (2006) *Experimental Characterisation of the Compressive Permanent Deformation Behaviour in Asphaltic Mixtures*. PhD Thesis thesis, The University of Nottingham.

Tanzadeh, J. and Shahrezagamasaei, R. (2017) Laboratory Assessment of Hybrid Fiber and Nano-silica on Reinforced Porous Asphalt Mixtures. *Construction and Building Materials*, 144, 260-270.

Taylor, M.B. (1997) Assessment of Cold Mix Emulsions. *Proceedings of the 2nd European Symposium on Performance and Durability of Bituminous Materials, University of Leeds, Zurich. Aedificatio Publishers, 399-408,*

Terrel, R.L. and Wang, C.K. (1971) Early curing behavior of cement modified asphalt emulsion mixtures. *Association of Asphalt Paving Technologists (AAPT) Conference,* 40108-125

Thanaya, I.N.A. (2003) *Improving The Performance of Cold Bituminous Emulsion Mixtures (CBEMs) Incorporating Waste Materials*. PhD Thesis thesis, The University of Leeds.

Thanaya, I.N.A. (2007) Review and Recommendation of Cold Asphalt Emulsion Mixtures (CAEMs) Design. *Civil Engineering Dimension*, 9 (No. 1), 49-56.

Thanaya, I.N.A., Forth, J.P. and Zoorob, S.E. (2009) A laboratory study on cold-mix, cold-lay emulsion mixtures. *Proceedings of the Institution of Civil Engineers* (1), 47-55.

Thanaya, I.N.A., Zoorob, S.E. and Forth, J.P. (2006) Utilisation of Coal Ashes in Hot and Cold Bituminous Mixtures. *International Coal Ash Technology Conference,*

Thom, N. (2008) *Principles of Pavement Engineering*. London: 2nd Edition, ICE Publishing.

U.S. Environmental Protection Agency (EPA) (2011) *Inventory of U.S. GreenhouseGas Emissions and Sinks: 1990–2011*. Washington, USA: U.S. Environmental Protection Agency.

Ullidtz, P., Battiato, G., Larsen, B.K. and Stubstad, R.N. (1987) Verification of the Analytical-Empirical Method of Pavement Evaluation Based on FWD Testing. *The 6th international conference on the structural design of asphalt pavements,* 1521-532

United States Environmental Protection Agency (2000) *Hot Mix Asphalt Plants Emissions Assessment Report*. North Carolina, USA: U.S. ENVIRONMENTAL PROTECTION AGENCY.

Uzarowski, L. (2006) *The Development of Asphalt Mix Creep Parameters and Finite Element Modeling of Asphalt Rutting*. PhD Thesis thesis, Waterloo, Ontario, Canada.

Vaitkus, A., Čygas, D., Laurinavičius, A. and Perveneckas, Z. (2009) Analysis and evaluation of possibilities for the use of warm mix asphalt in Lithuania. *The Baltic Journal of Road and Bridge Engineering*, 4 (2), 80-86.

Vaitkus, A., Čygas, D., Laurinavičius, A., Vorobjovas, V. and Perveneckas, Z. (2016) Influence of warm mix asphalt technology on asphalt physical and mechanical properties. *Construction and Building Materials,* 112, 800-806.

Vale, A.C.d., Casagrande, M.D.T. and Soares, J.B. (2014) Behavior of Natural Fiber in Stone Matrix Asphalt Mixtures Using Two Design Methods. *Journal of materials in civil engineering*, 26 (3), 457-465.

Waller, H.F. (1980) Emulsion Mix Design Methods: An Overview. *Transportation Research Record*, 754, 1-9.

Wang, Z. and Sha, A. (2010) Micro hardness of interface between cement asphalt emulsion mastics and aggregates. *Materials and Structures*, 43 (4), 453-461.

Wirtgen (2004) *Cold Recycling Rehabilitation of a Heavily Trafficked Road*. Windhagen, Germany: Wirtgen Group.

Wu, J. (2009) *The Influence of Mineral Aggregates and Binder Volumetrics on Bitumen Ageing*. PhD Thesis thesis, The University of Nottingham.

Wu, J., Liang, J. and Adhikari, S. (2014) Dynamic response of concrete pavement structure with asphalt isolating layer under moving loads. *Journal of Traffic and Transportation Engineering (English Edition)*, 1 (6), 439-447.

Wu, S.-P., Liu, G., Mo, L.-t., Chen, Z. and Ye, Q. (2006) Effect of fiber types on relevant properties of porous asphalt *Transactions of Nonferrous Metals of China*, 16, 791-795.

Wu, S., Ye, Q. and Li, N. (2008) Investigation of rheological and fatigue properties of asphalt mixtures containing polyester fibers. *Construction and Building Materials*, 22 (10), 2111-2115.

Xiao, Y., Zhang, Z., Chen, L. and Zheng, K. (2018) Modeling stress path dependency of cyclic plastic strain accumulation of unbound granular materials under moving wheel loads. *Materials & Design*, 137, 9-21.

Xiong, R., Fang, J., Xu, A., Guan, B. and Liu, Z. (2015) Laboratory investigation on the brucite fiber reinforced asphalt binder and asphalt concrete. *Construction and Building Materials*, 83, 44-52.

Xu, Q., Chen, H. and Prozzi, J.A. (2010) Performance of fiber reinforced asphalt concrete under environmental temperature and water effects. *Construction and Building Materials*, 24 (10), 2003-2010.

Xu, S.F.X., Zhao, Z.C., Xu, Y. and Wang, X.X. (2015) Mixture Design and Performance Evaluation of Cold Asphalt Mixture Using Polymer Modified Emulsion. *Advanced Materials Research*, 1065-1069, 760-765.

Xue, Q., Liu, L., Zhao, Y., Chen, Y.-J. and Li, J.-S. (2013) Dynamic behavior of asphalt pavement structure under temperature-stress coupled loading. *Applied Thermal Engineering*, 53 (1), 1-7.

Xue, Y. and Qian, Z. (2016) Development and performance evaluation of epoxy asphalt concrete modified with mineral fiber. *Construction and Building Materials*, 102, 378-383.

Yang, J.M., Kim, J.K. and Yoo, D.Y. (2016) Effects of amorphous metallic fibers on the properties of asphalt concrete. *Construction and Building Materials*, 128, 176-184.

Ye, Q., Wu, S. and Li, N. (2009) Investigation of the dynamic and fatigue properties of fiber-modified asphalt mixtures. *International Journal of Fatigue*, 31 (10), 1598-1602.

Yuliestyan, A., García-Morales, M., Moreno, E., Carrera, V. and Partal, P. (2017) Assessment of modified lignin cationic emulsifier for bitumen emulsions used in road paving. *Materials & Design*, 131, 242-251.

Zaumanis, M., Poulikakos, L.D. and Partl, M.N. (2018) Performance-based design of asphalt mixtures and review of key parameters. *Materials & Design*, 141, 185-201.

Zeinoddini, M., Harding, J.E. and Parke, G.A.R. (2008) Axially pre-loaded steel tubes subjected to lateral impacts (a numerical simulation). *International Journal of Impact Engineering*, 35 (11), 1267-1279.

Zhang, J., Zhu, C., Li, X., Pei, J. and Chen, J. (2017) Characterizing the three-stage rutting behavior of asphalt pavement with semi-rigid base by using UMAT in ABAQUS. *Construction and Building Materials*, 140, 496-507.

Zhang, Y. and Leng, Z. (2017) Quantification of bituminous mortar ageing and its application in ravelling evaluation of porous asphalt wearing courses. *Materials & Design*, 119, 1-11.

Zhi, S., Gun, W.W., Hui, L.X. and Bo, T. (2012) Evaluation of fatigue crack behavior in asphalt concrete pavements with different polymer modifiers. *Construction and Building Materials*, 27 (1), 117-125.