A laboratory study of high-performance cold mix asphalt mixtures reinforced with natural and synthetic fibres

Hayder Kamil Shanbara [a,c,*], Felicite Ruddock [b] and William Atherton [b]

[a] Department of Civil Engineering, Faculty of Engineering and Technology, Liverpool John Moores University, Henry Cotton Building, Liverpool L3 2ET, UK
[b] Department of Civil Engineering, Faculty of Engineering and Technology, Liverpool John Moores University, Peter Jost Centre, Liverpool L3 3AF, UK
[c] Civil Engineering Department, College of Engineering, Al Muthanna University, Sammawa, Iraq
*Corresponding author
E-mail address: H.K.Shanbara@2014.ljmu.ac.uk, hayder.shanbara82@gmail.com

Abstract:

This research aims to examine the impact of using natural and synthetic fibres as reinforcing materials, on the mechanical properties and water susceptibility of cold mix asphalt (CMA) 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 CMA, with and without fibres, were fabricated and tested. Traditional hot mix asphalt (HMA) was also used for comparison. The results indicate a significant improvement in the indirect tensile stiffness modulus, for all fibre-reinforced CMA mixtures, 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 and 60°C). When using glass and hemp fibres as reinforcing materials, there was

a significant improvement in CMA in terms of water sensitivity. Resistance to surface cracking was also improved when fibres were incorporated. Based on the test results, 0.35% fibre content by mass of dry aggregate and 14mm fibre length are recommended to achieve the optimum performance output for indirect tensile stiffness.

Keywords: Cold mix asphalt, emulsion, mechanical properties, natural fibre, reinforcing, surface course, synthetic fibre.

1. Introduction

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 [1]. 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 in 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 [2]. Reinforcing bituminous mixtures is one of the methods used to improve their tensile strength and engineering properties, especially when conventional mixes do not meet traffic, environmental and pavement structure requirements, as mentioned in [3, 4].

Fibre reinforcement improves fatigue life and retards future rutting by increasing resistance to cracking and permanent deformation. Different types of fibres are used to enhance the engineering properties of bituminous mixes to achieve this [5]. These fibres have desirable properties and are used to reinforce other materials which also require such properties [6-10]. There is a better chance of improving the tensile strength and cohesion of asphalt mixtures by using fibres which have high tensile strength, as compared to asphalt mixtures alone [11]. 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 [5]. 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 [12, 13]. In addition, fibres improve the viscosity of asphalt mixtures [10], resistance to rutting [14-16], stiffness modulus [17], moisture susceptibility [10] and retard reflection cracking for pavements [18, 19].

Currently, synthetic and natural fibres are used as reinforcing materials in Hot Mix Asphalt (HMA). Synthetic fibres such as carbon, polymer and glass, have high tensile strength in comparison to bituminous mixtures, therefore, using such fibres to reinforce asphalt mixtures has the potential to help develop resistance to rutting and creep compliance [20], moisture susceptibility [21], stiffness modulus [22] and freeze-thaw resistance [23]. Natural fibres (plant based), which are annual renewable sources, are also used to reinforce the polymer matrix. The natural framework component of these fibres are cellulose, hemicelluloses, lignin, pectin and wax [24]. These components provide certain benefits such as high strength, acceptable thermal properties and enhanced energy recovery [20].

The overall objective of this study is the laboratory investigation of the performance of a range of natural, fibre-reinforced Cold Mix Asphalt (CMA) mixtures. These mixtures are also compared with traditional cold and hot mix asphalt mixtures, and with CMA mixtures containing synthetic fibres as a reinforcing material.

2. Cold mix asphalt (CMA) reinforcement

CMA is an emulsified asphalt mixture that can be produced at ambient temperatures and used in roadway construction. 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 contents. Therefore, it is necessary to find a method to improve the performance of such mixtures, extending service life and reducing mixture difficulties, so that it can be used in the place of HMA, in any situation and under a range of environmental conditions. The addition of fibres to bituminous mixtures as a reinforcing material, may constitute an interesting method to achieve this goal.

Reinforcement can be defined as incorporating materials which have specific properties, within other materials that lack said properties [25]. The primary purpose of fibres as a reinforcing material, is to provide additional tensile and shear strength in the resulting mixtures and then to develop an appropriate amount of strain resistance during the rutting and fatigue process of the mixture [5]. Fibres in bituminous mixtures also have the ability to decrease the drain-down of those mixtures [26], at the same time increasing ductility due to enhancement of their mechanical properties [27]. Fibre reinforcing bituminous mixtures work as a crack barrier by carrying tensile stresses to prevent the formation and propagation of cracks [28]. Ferrotti, et al. [29] conducted research on the experimental characterisation of a high-performance CMA mixture reinforced with three different synthetic fibres; cellulose, gals-cellulose and nylon-polyester-cellulose. Different curing times of 1, 7, 14 and 28 days were investigated under two conditions, wet and dry. The testing procedures included Marshall, indirect tensile, abrasion and compactability. Within 7 days curing time, mixtures containing 0.15% cellulose fibre, were found to have a better performance than the conventional mixture at 28 days curing.

3. Materials and experimental program

3.1 CMA mixtures

CMA mixtures consist of both coarse and fine crushed granite aggregates, traditional mineral filler (limestone) and cationic, slow-setting, bituminous emulsion (C50B3). An aggregate blend gradation of 14mm, close-graded surface coarse, was used in accordance with BS EN 933-1 [30], as shown in Figure 1. The cationic slow-setting emulsion was used as a binding agent for the aggregates. It is a cold asphalt binder (CAB 50) based on a 40/60 penetration grade bitumen, the bitumen residual content being 60%. A traditional binder consisting of 100/150 penetration grade bitumen, with a softening point of 43.5 °C, was used for the conventional hot mix asphalt mixture.

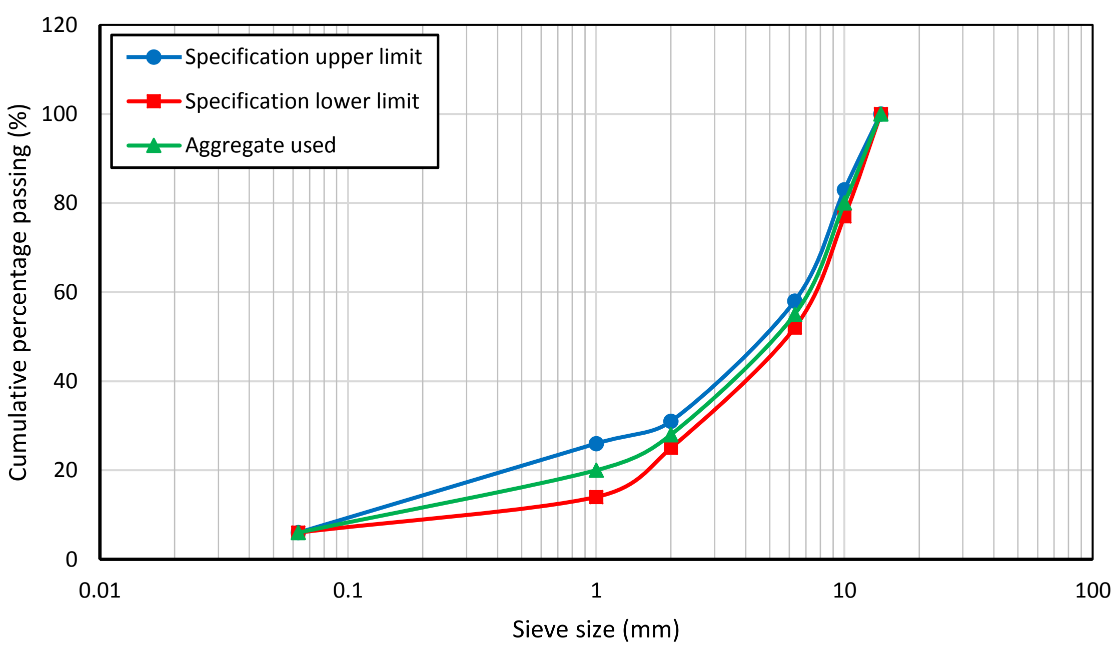

Figure 1. 14 mm close graded surface course

3.2 Fibres

Four different types of fibres were examined in this study; one synthetic glass fibre (supplied by Fibre Technologies International Limited-UK), and three natural fibres: hemp and jute (supplied by Wild Fibres-UK), and coir (supplied by The Upholstery Warehouse-UK). The physical properties of these fibres are presented in Table 1.

Table 1. 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
Moisture content (%)	0.5	10	11	14

3.3 Samples preparation

CMA samples were prepared according to the Marshall method for emulsified asphalt aggregate cold mixture designs (MS-14), as adopted by the Asphalt Institute [31]. According to this procedure, the pre-wetting water content, optimum emulsion content, optimum total liquid content at compaction and optimum residual bitumen contents were 3%, 12.4%, 15.4% and 6.2%, respectively. These results are comparable to those published by [32-34]. 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 fibres were mixed using an electric blender for 15-25 seconds [13], this followed by the addition of water then the emulsion. This process allows for the best fibre distribution in the mixtures [5].

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 mix well with other materials because some of the fibres may lump together creating a clumping or balling problem. On the other hand, fibres which are too short might not perform well as a reinforcing material, serving only as an expensive filler in the mixture. Therefore, it is necessary to optimize fibre length and content to avoid such problems and to ensure 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. 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 bituminous mixtures. Based on the results of the indirect tensile stiffness modulus (ITSM) test, an optimized fibre length and content were selected and used for the other experimental tests [7].

3.4 Testing program and procedures

The testing program 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 (CON) CMA and HMA mixtures, and the optimised fibre-reinforced CMA mixtures with four different fibres (glass (GLS), hemp (HEM), jute (JUT) and coir (COI)), were researched using different laboratory tests as detailed below.

3.4.1 Indirect tensile stiffness modulus (ITSM) test

The ITSM test is a non-rupture test where cylindrical samples are positioned vertically, a diametrical load then applied, as shown in Figure 2. This test is used in the current research to determine the stiffness modulus of the bituminous mixtures. Samples are subject to repeated load pulses, with a rest period, along the vertical diameter of the sample, using two loading strips

12.5mm in width. Loading is applied in a half sine waveform, the loading time 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 ± 4ms. 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 3.0 ± 0.1s.

In order to determine the stiffness modulus, all CMA specimens were kept in their mould for one day at room temperature (20°C), followed by different curing times (2, 7, 14, 28, 90, 180 and 360 days). The tests were conducted at 20°C following the standard BS EN 12697-26 [35], using a Cooper Research Technology HYD 25 testing apparatus. The stiffness modulus was set at the average value of five tested samples.

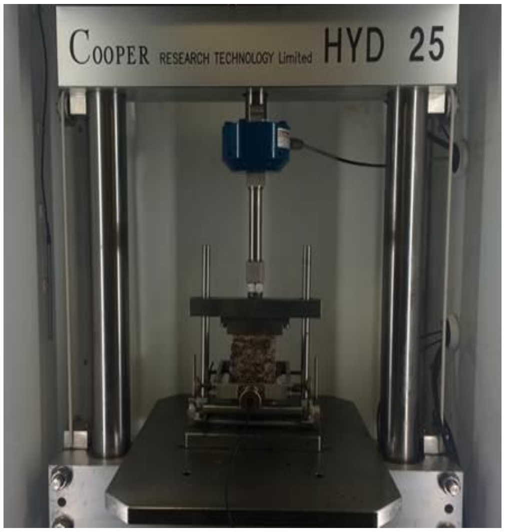

Figure 2. HYD 25 indirect tensile apparatus

3.4.2 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. These are agreed as the temperatures of bituminous material in hot weather, according to the European Committee for Standardization [36]. Prior to carrying out the tests, the loose bituminous mixtures were mixed and compacted in a steel mould under a steel roller compactor, resulting in a solid slab measuring 405mm (length) × 300mm (width) × 50mm (thickness). The specimens were kept in the mould for 24 hours at room temperature. Following this, the slabs were cured for 14 days, inside a ventilated oven at 40°C, to achieve full curing [37]. For the test, a single wheel with a standard vehicle tyre pressure of 0.7MPa, was applied to the surface of the bituminous slab as shown in Figure 3. The wheel was rolled on the surface of the bituminous slab covering a distance of 230mm at a speed of 42 (±1) times/min (16.1 cm/s) along the centre line of the slab, for 460 minutes under dry conditions.

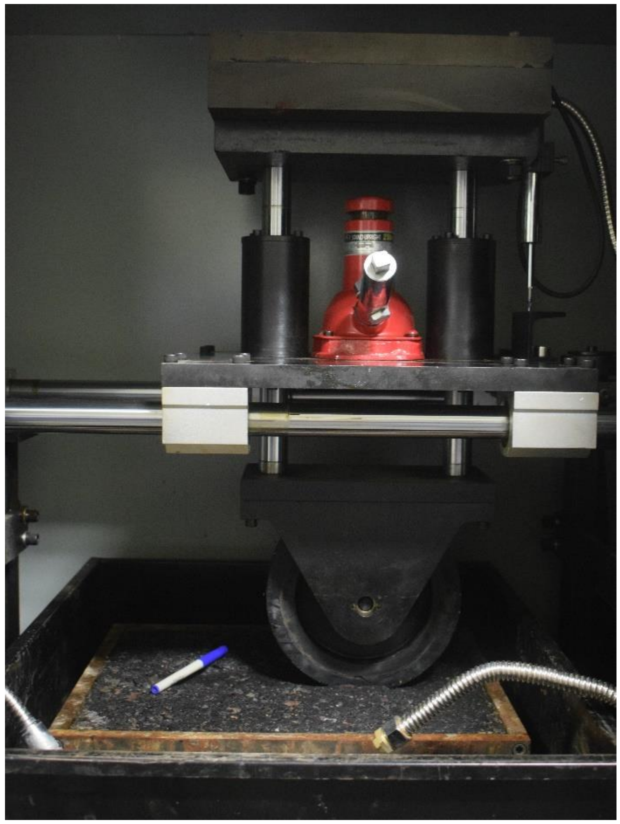

Figure 3. Wheel-tracking test equipment

3.4.3 Scanning electron microscopy (SEM) analysis

In order to characterise the microstructure and fracture surfaces of the raw fibres, 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 3-4nm, a high vacuum and a test voltage of 10kV.

3.4.4 Water sensitivity test

The ability of a bituminous mixture to resist moisture distress is critical to its long-term performance [38]. These mixtures are identified as being sensitive to moisture if the laboratory specimens fail in a water sensitivity test. In this research, the water sensitivity test was conducted in accordance with BS EN 12697-12 [39]. 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 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 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-condition 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 (6.7kPa for 30 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 at 40°C for three days, before being tested. Five sets of each sample were tested for each mixture type. Water sensitivity was calculated using the stiffness modulus ratio (*SMR*) as shown in equation (1):

$$SMR = (wet\ stiffness\ /\ dry\ stiffness) \times 100 \qquad (1)$$

3.4.5 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 dynamic loading. Slab samples of length 400mm, width 305mm and depth 50mm, were prepared and compacted using a streel roller compactor which simulated pavement compaction in the field. After full curing, three cylindrical specimens measuring 150mm in diameter and 50mm in height, were cored from each slab using an electrical extruder. Each specimen (core) was then cut into two equal halves (semi-circular specimens), through the middle, each half cut in the centre with a notch of 10mm depth and 0.35mm width to act as a pre-crack. 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 4). 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.

As per BS EN 12697-44 [40], the maximum stress at failure (σ_{max}), and the fracture toughness (K_{IC}), have been calculated in accordance with equations 2 and 3, respectively.

$$\sigma_{max} = \frac{4.263 \times F_{max}}{D \times t} \; N/mm^2 \quad (2)$$

where

D = the diameter of specimen (mm).

t = the thickness of specimen (mm).

F_{max} = the maximum force of specimen in Newtons.

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

where,

W = height of specimen (mm).

A = notch depth of specimen (mm).

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

$f\,(a/W)$ = geometric factor of specimen, for $9 < a < 11$ mm and $70 < W < 75$ mm, then, $f\,(a/W)$ = 5.956.

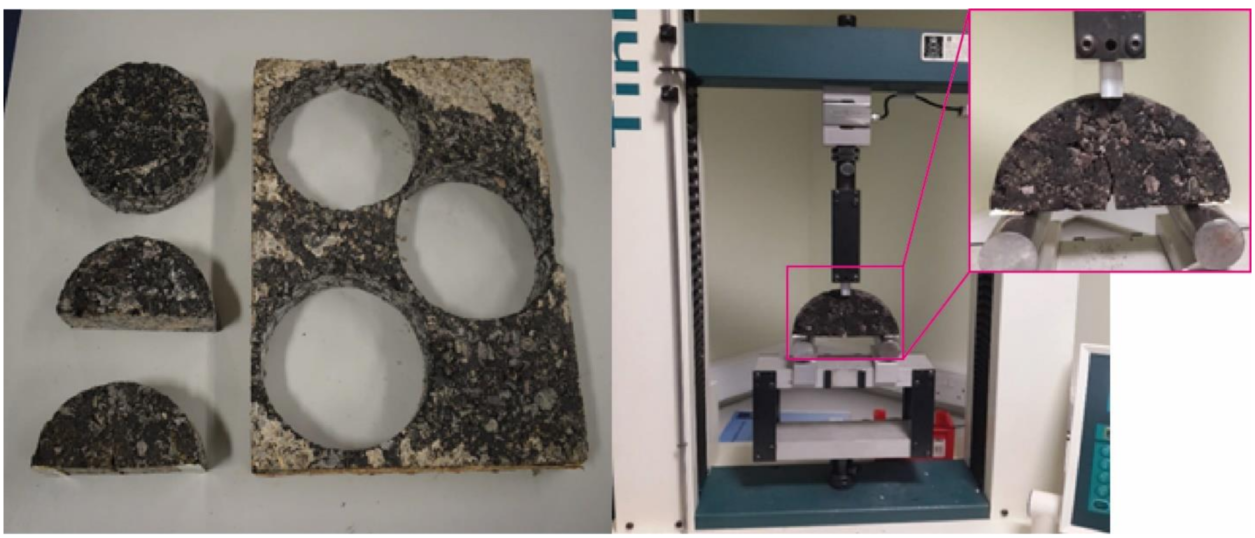

Figure 4. Schematic of SCB specimen preparation and fracture test

4. Results and analysis

4.1 ITSM

The Indirect Tensile Stiffness modulus is regarded as key when evaluating the effect of different fibre lengths and contents on CMA mixture performance, taking into account the effect of curing time and condition. Figure 5 shows that ITSM initially increases then decreases, with increasing fibre content, for all fibre lengths. The CMA mixture 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 Chen, et al. [13] and Xu, et al. [41] who recommend that the optimum fibre content should be between 0.3% and 0.4%, based on the results from similar tests. 14mm long fibres, cured for 2 days, developed the ITSM of the reinforced CMA mixtures to the maximum value. This indicates that the reinforced mixture with 14mm fibre length and 0.35% content, adheres well to the bitumen [20]. According to Liu, et al. [42], short fibres (10mm) cannot properly reinforce mixtures that have a larger size of aggregate (maximum 14mm) while long fibres (longer than the maximum size of the aggregate) can lead to loss 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 [43]. Because of the use of an appropriate length of fibre (14mm in this research), the placement and distribution of this fibre in the bituminous mixture, produced enhanced interlocking between the fibre and the paste, hence the lateral strain was delayed and the mixture strength improved [44]. This optimisation process was only performed for the glass fibre, the optimized fibre length and content then adopted for all other fibre types.

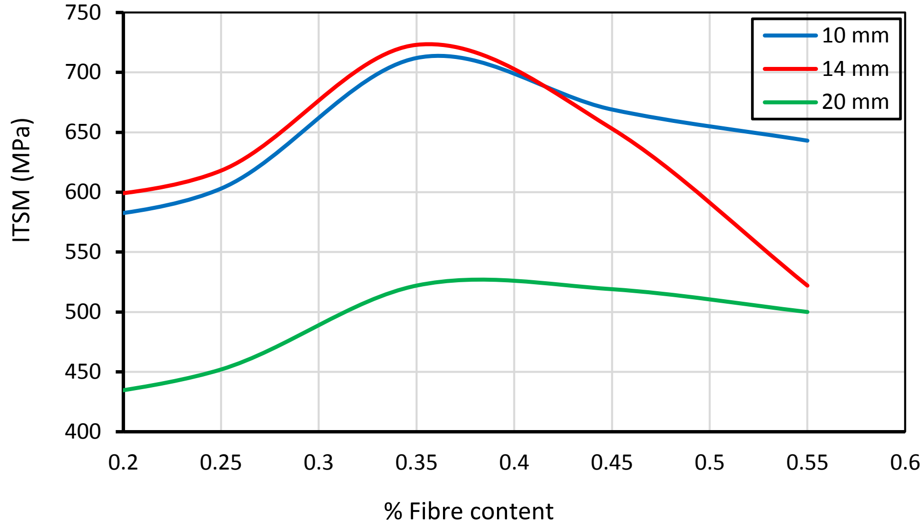

Figure 5. Glass fibre optimization at 20°C after 2 days

The results of the ITSM tests are shown in Figure 6 for both reinforced and unreinforced CMA mixtures. 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 curve of the slope due to reaching a definitive level, this achieved after about 28 days of curing. This behaviour is due to the bitumen emulsion emitting volatile components, allowing the CMA mixtures to be cured and reach their final strength [29]. The HMA presents no significant stiffness modulus change over time [45, 46]. It can also be seen from Figure 6 that the significant development in ITSM specifically depends on the fibres as these provide a three-dimensional reinforcement for the CMA mixtures [20, 26, 29, 41, 47]. Therefore, the stiffness modulus of CMA mixtures, reinforced with natural and synthetic fibres, reached or exceeded the stiffness of HMA between 40 to 80 days, depending on the fibre type. Conventional (unreinforced) CMA mixture still has low stiffness in comparison to HMA, after one year of curing. For all types of fibre, the reinforced CMA mixtures provide almost the same, or slightly higher, stiffness modulus compared to the HMA mixture, over medium curing times (28-90 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 CMA mixtures are used. When it is possible to have a longer curing time, the natural and synthetic fibre-reinforced CMA mixtures are able to ensure high performance, significantly exceeding the performance of the HMA mixture.

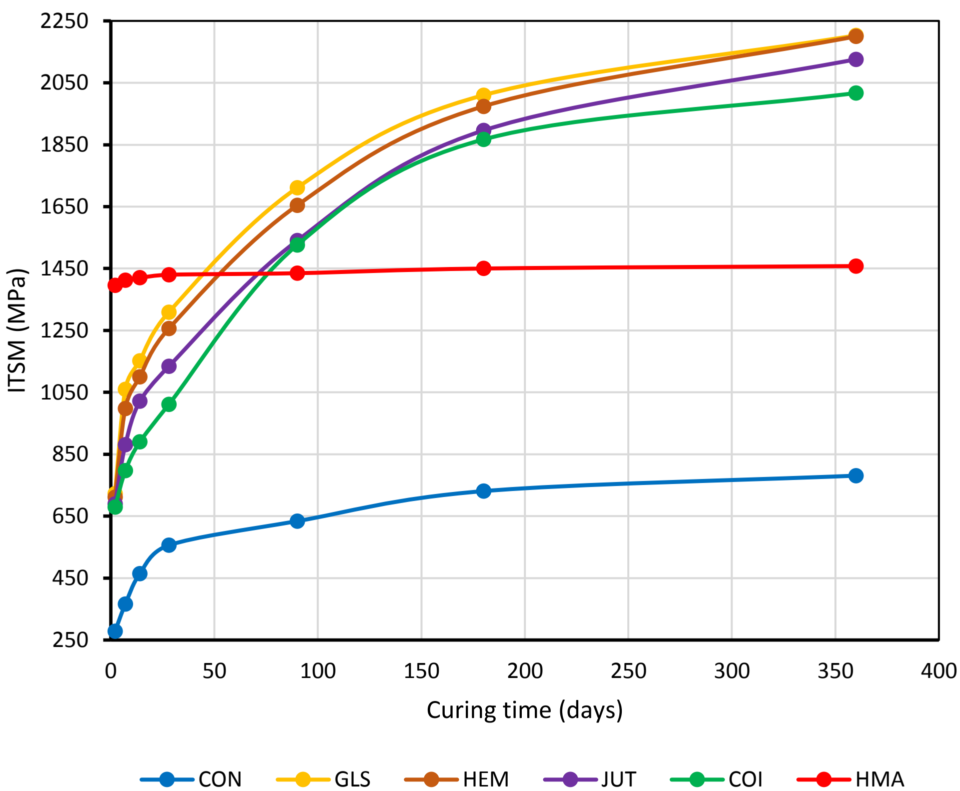

Figure 6. Effect of curing time on stiffness modulus

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):

$$ITSM = a\ln(t) + b \quad (4)$$

where, *a* and *b* are regression parameters. For each set of specimens, the regression parameter values are reported in Table 2, together with the corresponding R^2 (correlation coefficient squared).

Table 2. Logarithmic regression parameter values

Mixture type	*a*	*b*	R^2
CON	100.07	198.49	0.99
GLS	287.91	457.66	0.98
HEM	290.16	410.59	0.97
JUT	284.33	344.32	0.96
COI	281.88	281.23	0.93
HMA	11.51	1388.9	0.98

The comparison between the conventional and reinforced CMA mixtures, shows that glass fibre gives the highest ITSM. Figure 7 shows the ITSM results for samples at 28 and 90 days of curing. These times have been selected to illustrate the capacity of such mixtures to withstand traffic loads within medium curing times. All in all, the CMA mixture containing natural and synthetic fibres, could be an alternative for HMA, as the stiffness modulus reached a similar value within 28 days.

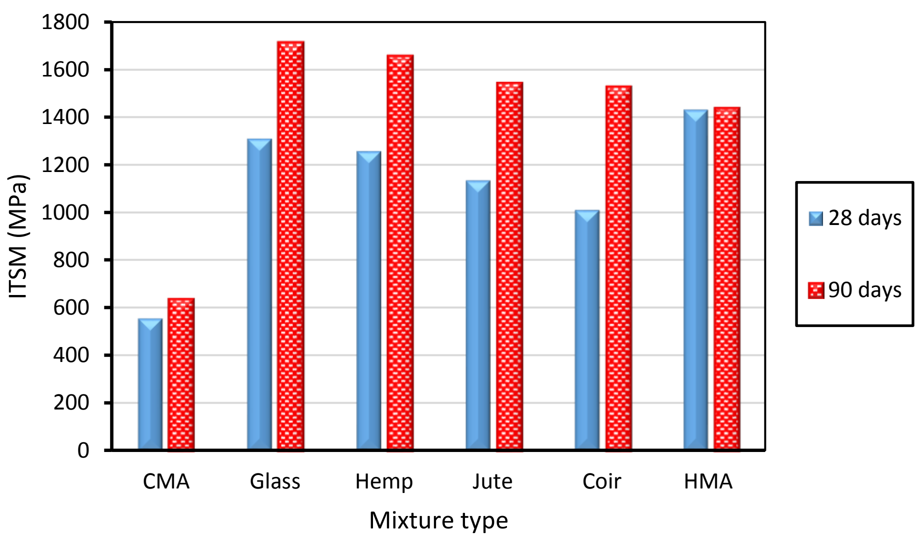

Figure 7. Stiffness modulus after 28 and 90 curing days

Using different natural and synthetic fibres as a reinforcing material in CMA mixtures, produces outstanding improvements in their mechanical properties and reduces the curing time needed to obtain a mixture of definitive strength. These improvements are because the fibre reinforcement improves the shear and tensile strength of mixtures and the ability to transfer stress from the mixture to the fibres [20]. This transfer of stress plays a major role in evaluating the mechanical properties of the bituminous mixtures.

4.2 Rutting

The test results in Figures 8 and 9 show the variation in accumulated rutting depth, under cumulative loading cycle times, at 45°C and 60°C, respectively. The reinforced CMA mixtures have significantly reduced accumulated rutting (permanent deformation). The accumulated rutting in CMA with synthetic fibres (glass) is slightly lower than for the CMA with natural fibres at both test temperatures. Glass, hemp, jute and coir fibres have a reduced rut depth by 766%, 636%, 610%, and 462%, at 45°C after 20000 cycles (27600 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 [41]. It was observed that after a certain number of load repetitions, this rate of rutting depth decreased and sometimes followed a horizontal line, this mainly due to the high shear strength of the reinforced CMA mixtures under shear stress [41, 47]. At this stage, the increase in rate of rutting depth with time, tends to be almost horizontal, indicative of the high stiffness modulus of the bituminous mixture. In contrast, the development of rutting for the conventional CMA mixture is faster initially followed by a gentle decrease. The faster the rutting development rate, the earlier the road pavement enters into its failure stage [48]. In this case, it is highly probable that the serviceable life of bituminous pavements will be shortened.

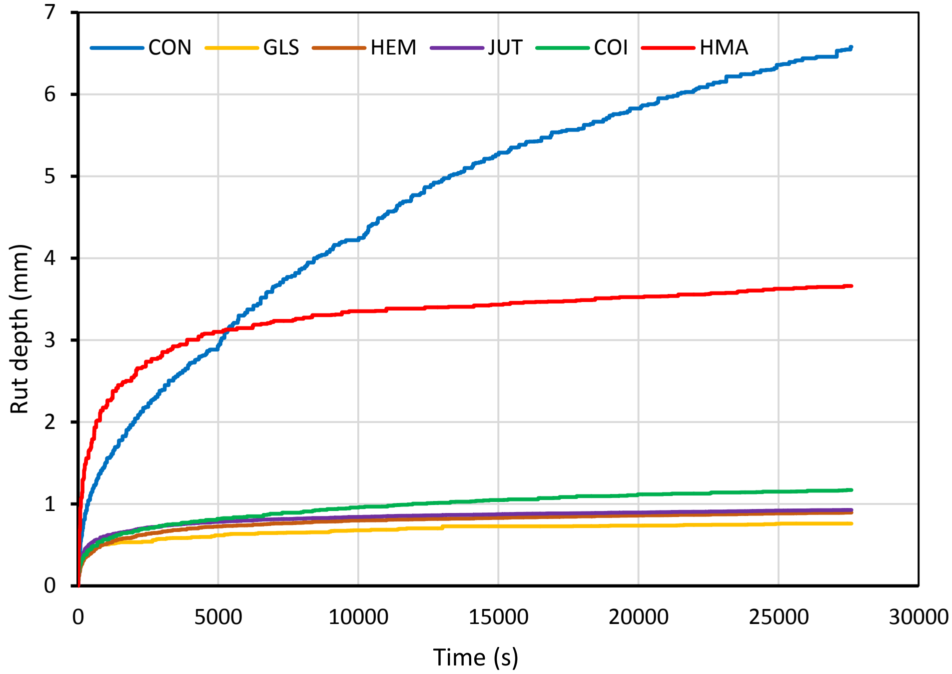

Figure 8. Rut depth at 45°C

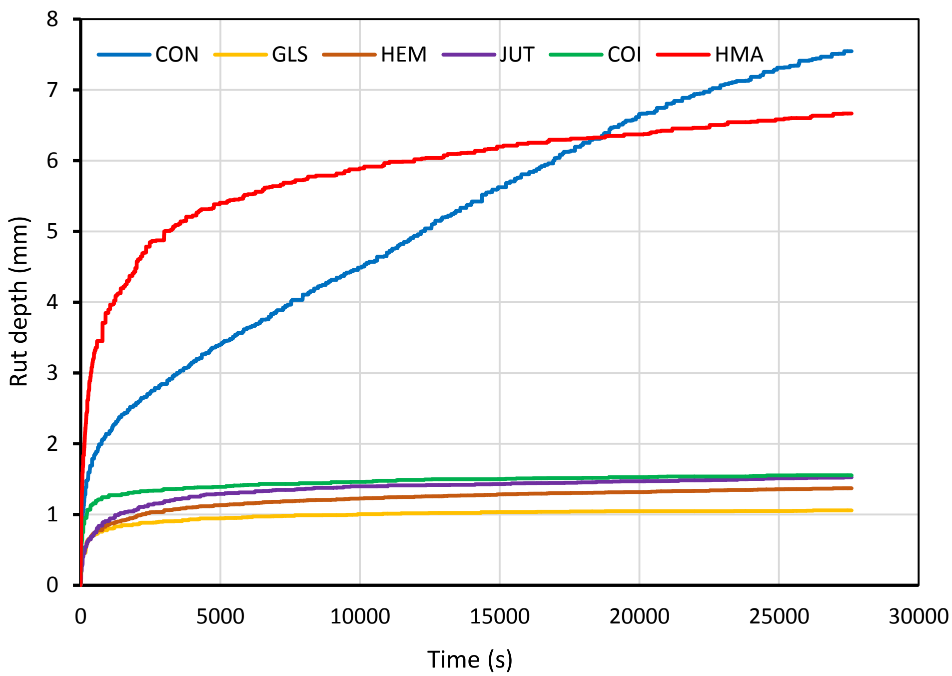

Figure 9. Rut depth at 60°C

The significant reduction in rutting depth of the reinforced CMA mixtures could be partially due to the ability of the fibres to stabilize and hold the bitumen on their surface, thus resisting the flow of bitumen at high temperatures [47]. The fibres form a three-dimensional network in the bituminous mixture, this reinforcing the skeleton structure, resisting shear and tensile stresses and reducing fluidity [41, 47]. 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.

4.3 Fibres microstructure characteristics

The SEM microstructure of fibres, shown in Figures 10a to d, reveals both the shape of the fibres and their surface roughness characteristics. Figure 10a shows a SEM image 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 [49].

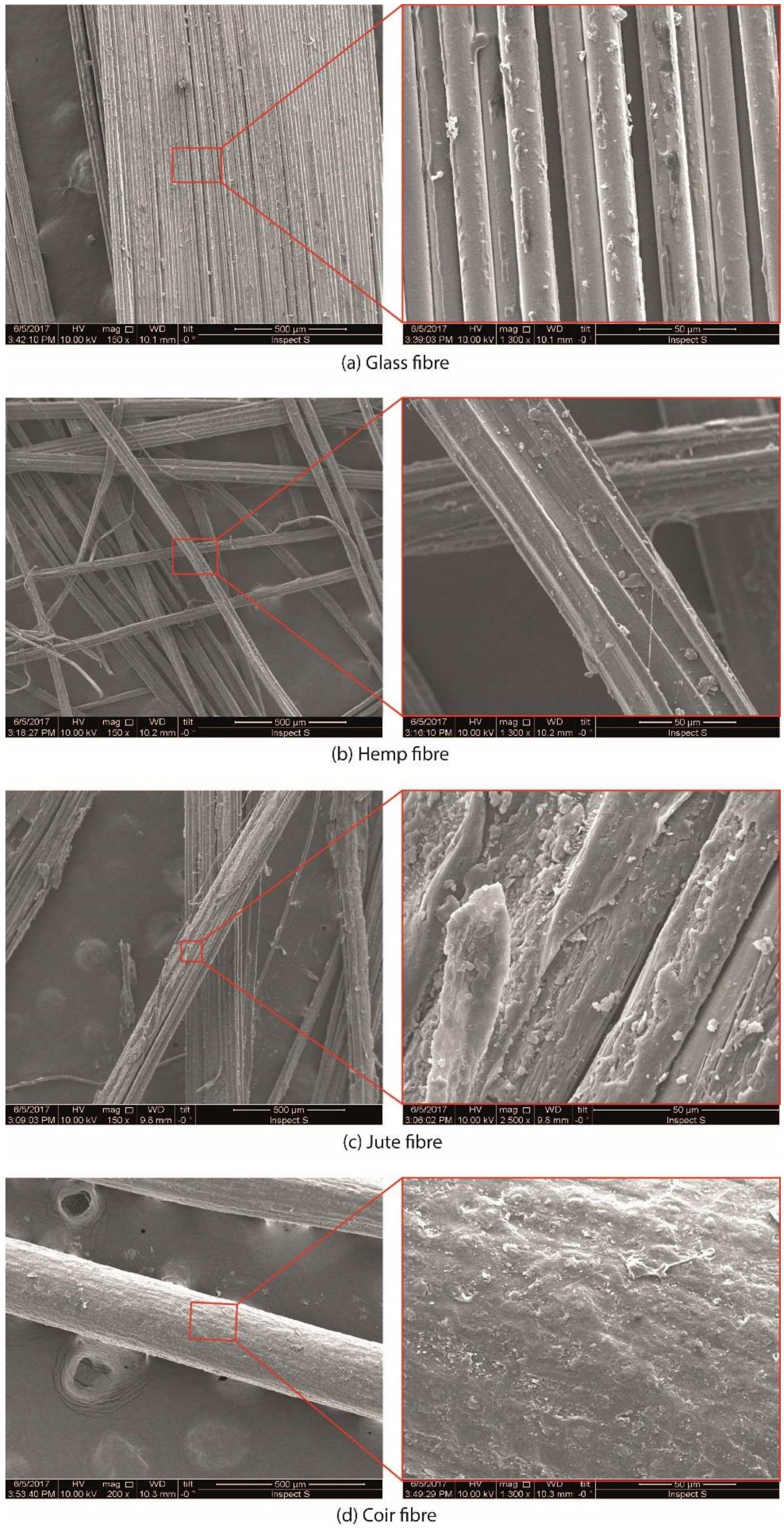

Figure 10. Fibres and their microstructure

Figure 10b 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 [50]. The surface of the hemp fibre (Figure 10c) is observed as a rough surface with strip protrusions, which provide good structural stability. The SEM images of coir fibres, presented in Figure 10d, 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.

In summary, it is worth noting that the shape of the fibre and surface area play a key role in promoting the absorption and holding of the bitumen binder and in providing enhanced bonding which resists fracturing [41, 51, 52]. Further tensile and shear resistance of the bituminous mixtures are generated due to the three-dimensional network effect of the fibres. This network resists aggregate sliding at the interface and reduces concentrations of stress [47].

4.4 Water sensitivity test

The evaluation of water damage is an important factor because of the direct effect on the performance and service life of flexible pavements [26, 53].The water sensitivity results revealed that all the natural and synthetic fibres significantly improved the moisture resistance of the CMA mixtures. Figure 11 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 CMA mixtures with natural and synthetic fibres, have better SMR values in comparison to the conventional CMA mixture. It is worth noting that the improved cohesion of the reinforced mixtures is the main reason for the improvement in performance against water action [5, 20, 29, 41].

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.

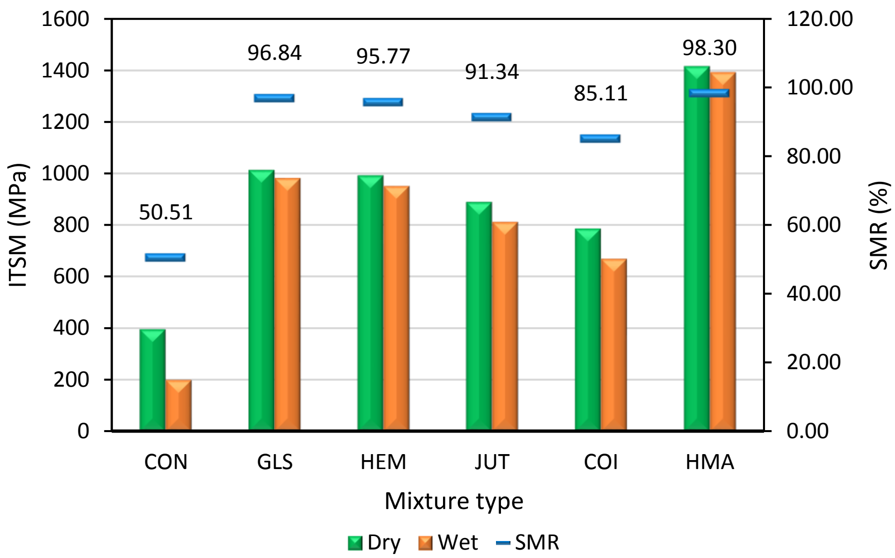

Figure 11. Water sensitivity results

4.5 Semi-circular bending test

The monotonic SCB test was performed to determine the fracture toughness of the conventional CMA, reinforced CMA and HMA mixtures. It is shown in Figure 12 that fibres have improved the fracture toughness of the CMA mixtures. The fracture toughness of the mixtures reinforced with glass and hemp fibres, have a superior performance in comparison to the others. Such improvements in fracture toughness, in comparison to the conventional CMA mixture, is due to the fact that the conventional CMA mixture is more brittle and susceptible to material failure at low temperatures [41]. Both the natural and synthetic fibres were found to be positively associated with the tensile strength of CMA mixtures in terms of their resistance to fracturing after crack initiation [54].

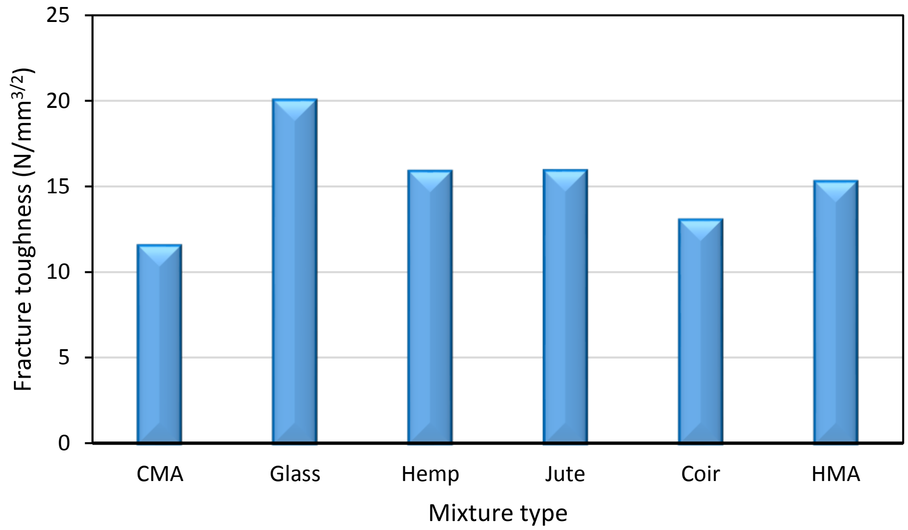

Figure 12. Effect of fibre-reinforced CMA on fracture toughness

Figure 13 shows the load-displacement curve for the 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 these conditions, due to the elastic behaviour of bituminous mixtures at low temperatures [28].

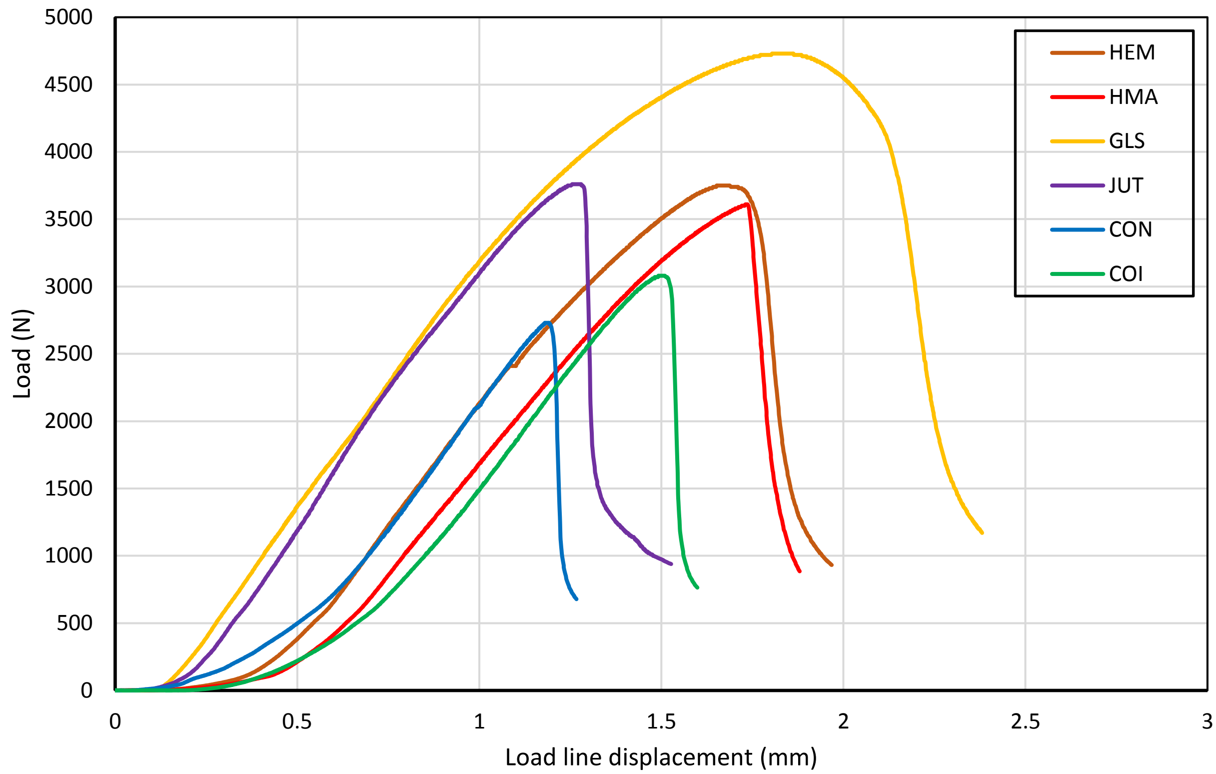

Figure 13. Typical load-displacement curves

5. Conclusions

This research has comprehensively studied the reinforcing effects of natural and synthetic fibres in CMA mixtures, under different environmental conditions, as well as the effect of water. The main conclusions are summarized as follows:

- The substantial improvement in the indirect tensile stiffness values (from 144% to 160%, dependant on fibre type) and after two days of curing, has resulted in the development of a new generation of high performance, CMA mixtures.
- The CMA mixtures, reinforced with both natural and synthetic fibres, have significant resistance to rutting in wheel track tests at high temperatures. These results are better than

those for HMA meaning that the reinforced mixtures can carry heavier traffic loads in hot climatic conditions.

- Water action weakens CMA strength. However, the fibre-reinforced CMA mixtures can be successfully used for road works during rainy periods as such mixtures provide adequate mechanical performance, similar to that of HMA.
- A rough fibre surface was observed by SEM, this responsible for improved mechanical interlocking between the fibres and binder mixture.
- Resistance to crack propagation in the reinforced CMA mixtures was improved by both natural and synthetic fibres. This effect is magnified by the random orientation of the fibres in the mixtures.

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