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

3

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13

14 **Abstract:**

15 This research aims to examine the impact of using natural and synthetic fibres as reinforcing  
16 materials, on the mechanical properties and water susceptibility of cold mix asphalt (CMA)  
17 including indirect tensile stiffness and resistance to rutting, cracking and moisture damage. Four  
18 different types of fibres were used: glass as a synthetic fibre, and hemp, jute and coir as natural  
19 fibres. Various samples of CMA, with and without fibres, were fabricated and tested. Traditional  
20 hot mix asphalt (HMA) was also used for comparison. The results indicate a significant  
21 improvement in the indirect tensile stiffness modulus, for all fibre-reinforced CMA mixtures, over  
22 different curing times. The improved tensile behaviour represents a substantial contribution  
23 towards slowing crack propagation in bituminous mixtures, while scanning electron microscopy  
24 analysis confirmed the fibre shape and surface roughness characteristics. The improved  
25 performance of the reinforced mixtures with both natural and synthetic fibres, facilitated a  
26 substantially lower permanent deformation than traditional hot and cold mixtures at two different  
27 temperatures (45 and 60°C). When using glass and hemp fibres as reinforcing materials, there was

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

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

## 34 **1. Introduction**

35 Asphalt mixes are composite materials that mainly consist of asphalt as a binder, aggregate and  
36 voids. They have generally been used as a material for constructing flexible road pavements  
37 because of the good adhesion that exists between binder and aggregates [1]. However, due to  
38 increasing traffic volume in terms of traffic load repetitions, high and low temperatures and water  
39 sensitivity, various types of distresses can appear on the surface of flexible pavements, such as  
40 rutting (permanent deformation), segregation and cracking. The perfect flexible pavement design  
41 should be durable, strong and resistant to permanent deformation and cracking, thus resisting these  
42 types of failures, or at least delaying future pavement deterioration. Although bituminous mixtures  
43 with additives such as polymers, crumb rubber and natural rubber have previously been used in an  
44 attempt to overcome deterioration, permanent deformation and fatigue cracking problems still  
45 exist. These problems occur because the tensile and shear strength of bituminous layers are weak  
46 [2]. Reinforcing bituminous mixtures is one of the methods used to improve their tensile strength  
47 and engineering properties, especially when conventional mixes do not meet traffic, environmental  
48 and pavement structure requirements, as mentioned in [3, 4].

49 Fibre reinforcement improves fatigue life and retards future rutting by increasing resistance to  
50 cracking and permanent deformation. Different types of fibres are used to enhance the engineering  
51 properties of bituminous mixes to achieve this [5]. These fibres have desirable properties and are  
52 used to reinforce other materials which also require such properties [6-10]. There is a better chance  
53 of improving the tensile strength and cohesion of asphalt mixtures by using fibres which have high  
54 tensile strength, as compared to asphalt mixtures alone [11]. The essential roles of these fibres as  
55 reinforcing materials, are to increase the tensile strength of the resulting mixtures and provide more  
56 strain resistance to fatigue cracking and permanent deformation [5]. Draining-down of asphalt  
57 concrete mixtures is prevented by using fibres, rather than polymers, during the paving and  
58 transportation of materials, therefore, fibres are specifically recommended [12, 13]. In addition,  
59 fibres improve the viscosity of asphalt mixtures [10], resistance to rutting [14-16], stiffness  
60 modulus [17], moisture susceptibility [10] and retard reflection cracking for pavements [18, 19].  
61 Currently, synthetic and natural fibres are used as reinforcing materials in Hot Mix Asphalt  
62 (HMA). Synthetic fibres such as carbon, polymer and glass, have high tensile strength in  
63 comparison to bituminous mixtures, therefore, using such fibres to reinforce asphalt mixtures has  
64 the potential to help develop resistance to rutting and creep compliance [20], moisture  
65 susceptibility [21], stiffness modulus [22] and freeze-thaw resistance [23]. Natural fibres (plant  
66 based), which are annual renewable sources, are also used to reinforce the polymer matrix. The  
67 natural framework component of these fibres are cellulose, hemicelluloses, lignin, pectin and wax  
68 [24]. These components provide certain benefits such as high strength, acceptable thermal  
69 properties and enhanced energy recovery [20].  
70 The overall objective of this study is the laboratory investigation of the performance of a range of  
71 natural, fibre-reinforced Cold Mix Asphalt (CMA) mixtures. These mixtures are also compared

72 with traditional cold and hot mix asphalt mixtures, and with CMA mixtures containing synthetic  
73 fibres as a reinforcing material.

## 74 **2. Cold mix asphalt (CMA) reinforcement**

75 CMA is an emulsified asphalt mixture that can be produced at ambient temperatures and used in  
76 roadway construction. To date, it has been considered as an inferior mixture, in comparison to  
77 HMA, because of low early stiffness, a long curing time needed to reach its final strength and high  
78 air void contents. Therefore, it is necessary to find a method to improve the performance of such  
79 mixtures, extending service life and reducing mixture difficulties, so that it can be used in the place  
80 of HMA, in any situation and under a range of environmental conditions. The addition of fibres to  
81 bituminous mixtures as a reinforcing material, may constitute an interesting method to achieve this  
82 goal.

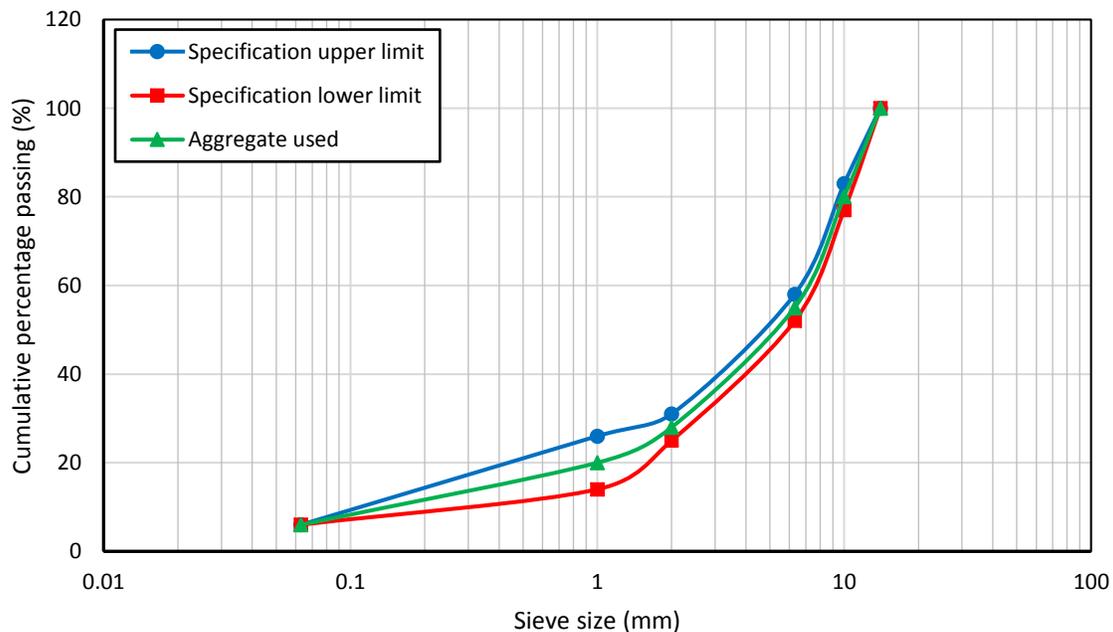
83 Reinforcement can be defined as incorporating materials which have specific properties, within  
84 other materials that lack said properties [25]. The primary purpose of fibres as a reinforcing  
85 material, is to provide additional tensile and shear strength in the resulting mixtures and then to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

94 testing procedures included Marshall, indirect tensile, abrasion and compactability. Within 7 days  
95 curing time, mixtures containing 0.15% cellulose fibre, were found to have a better performance  
96 than the conventional mixture at 28 days curing.

### 97 3. Materials and experimental program

#### 98 3.1 CMA mixtures

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



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Figure 1. 14 mm close graded surface course

108 *3.2 Fibres*

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

113  
114 Table 1. Natural and synthetic fibre properties

Items	Fibre type			
	Glass	Hemp	Jute	Coir
Density (kg/m <sup>3</sup> )	1380	1500	1450	1250
Tensile strength (MPa)	1600	900	450	175
Moisture content (%)	0.5	10	11	14

115

116 *3.3 Samples preparation*

117 CMA samples were prepared according to the Marshall method for emulsified asphalt aggregate  
118 cold mixture designs (MS-14), as adopted by the Asphalt Institute [31]. According to this  
119 procedure, the pre-wetting water content, optimum emulsion content, optimum total liquid content  
120 at compaction and optimum residual bitumen contents were 3%, 12.4%, 15.4% and 6.2%,  
121 respectively. These results are comparable to those published by [32-34]. The fibres were added  
122 and blended into the mixtures to improve the mechanical properties and prevent binder drain-  
123 down. To ensure a consistent distribution of the fibres, water and emulsion in the mixtures, the  
124 fibres were mixed using an electric blender for 15-25 seconds [13], this followed by the addition  
125 of water then the emulsion. This process allows for the best fibre distribution in the mixtures [5].

126 Fibre reinforcement of bituminous mixtures is deemed a random, direct inclusion of fibres into the  
127 mixture. If the fibres are too long, they might not mix well with other materials because some of  
128 the fibres may lump together creating a clumping or balling problem. On the other hand, fibres  
129 which are too short might not perform well as a reinforcing material, serving only as an expensive  
130 filler in the mixture. Therefore, it is necessary to optimize fibre length and content to avoid such  
131 problems and to ensure uniformity of fibre distribution in the mixtures. In this study, in order to  
132 find the optimum fibre length and content, fibres of varying lengths (10, 14 and 20 mm) were used.  
133 Fibre contents of 0.15, 0.25, 0.35, 0.45 and 0.55% of total aggregate weight for all fibre lengths,  
134 were included in the bituminous mixtures. Based on the results of the indirect tensile stiffness  
135 modulus (ITSM) test, an optimized fibre length and content were selected and used for the other  
136 experimental tests [7].

### 137 138 *3.4 Testing program and procedures*

139 The testing program was conducted in two phases. In the first phase, fibres were investigated to  
140 establish the optimum fibre length and content. In the second phase, the conventional (CON) CMA  
141 and HMA mixtures, and the optimised fibre-reinforced CMA mixtures with four different fibres  
142 (glass (GLS), hemp (HEM), jute (JUT) and coir (COI)), were researched using different laboratory  
143 tests as detailed below.

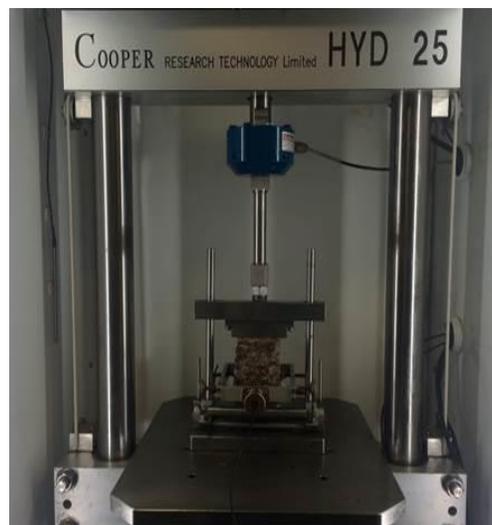
#### 144 145 *3.4.1 Indirect tensile stiffness modulus (ITSM) test*

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

150 12.5mm in width. Loading is applied in a half sine waveform, the loading time controlled during  
151 the test. The rise-time, measured from when the load pulse commences and the time taken for the  
152 applied load to increase from initial contact load to the maximum value, is  $124 \pm 4\text{ms}$ . The peak  
153 load value is adjusted to achieve a target peak, a transient horizontal deformation of 0.005% of the  
154 sample diameter. The applied load is measured using a load cell with an accuracy of 2%, the pulse  
155 repetition period  $3.0 \pm 0.1\text{s}$ .

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

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Figure 2. HYD 25 indirect tensile apparatus

172 3.4.2 *Wheel tracking test*

173 Wheel tracking tests were used to measure the rut depth (permanent deformation) of the  
174 bituminous mixtures at two different temperatures, 45°C and 60°C. These are agreed as the  
175 temperatures of bituminous material in hot weather, according to the European Committee for  
176 Standardization [36]. Prior to carrying out the tests, the loose bituminous mixtures were mixed and  
177 compacted in a steel mould under a steel roller compactor, resulting in a solid slab measuring  
178 405mm (length) × 300mm (width) × 50mm (thickness). The specimens were kept in the mould for  
179 24 hours at room temperature. Following this, the slabs were cured for 14 days, inside a ventilated  
180 oven at 40°C, to achieve full curing [37]. For the test, a single wheel with a standard vehicle tyre  
181 pressure of 0.7MPa, was applied to the surface of the bituminous slab as shown in Figure 3. The  
182 wheel was rolled on the surface of the bituminous slab covering a distance of 230mm at a speed  
183 of 42 (±1) times/min (16.1 cm/s) along the centre line of the slab, for 460 minutes under dry  
184 conditions.

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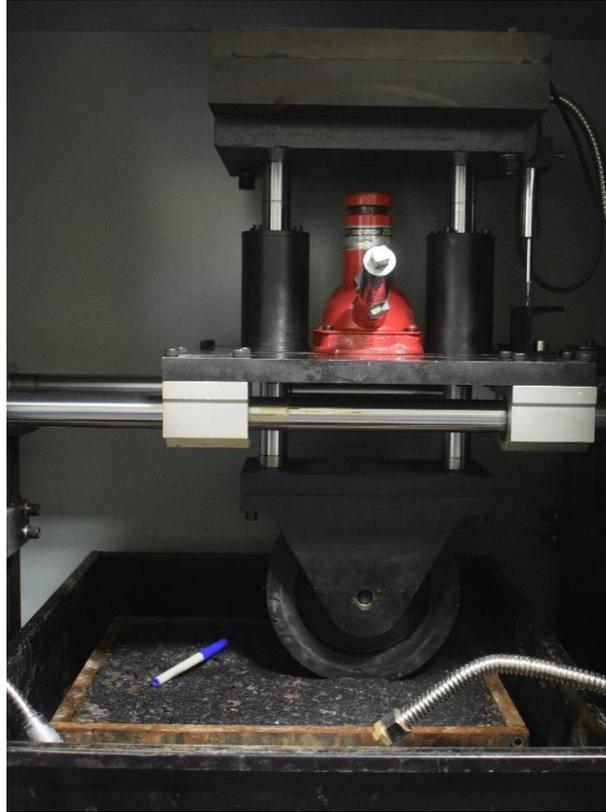


Figure 3. Wheel-tracking test equipment

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### 3.4.3 Scanning electron microscopy (SEM) analysis

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

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#### 205 3.4.4 Water sensitivity test

206 The ability of a bituminous mixture to resist moisture distress is critical to its long-term  
207 performance [38]. These mixtures are identified as being sensitive to moisture if the laboratory  
208 specimens fail in a water sensitivity test. In this research, the water sensitivity test was conducted  
209 in accordance with BS EN 12697-12 [39]. This test exposes any loss of adhesive bond between  
210 the aggregate and bitumen of cylindrical specimens, due to the existence of water. During the test,  
211 the compacted specimens were divided into two groups; the first group for dry testing, the second  
212 for saturated testing. The specimens in the dry group were tested without moisture conditioning as  
213 they were kept in the mould (after compaction) for one day at room temperature (20°C), extruded  
214 and left at room temperature for another seven days before the ITSM test. The specimens in the  
215 second group were saturated as part of the moisture pre-condition protocol. Each specimen (after  
216 one day in the mould at room temperature), was extruded and immersed in a water bath at 20°C  
217 for four days and then transferred to the vacuum container. A combination of vacuum pressure and  
218 duration (6.7kPa for 30 min) was applied to achieve the required degree of saturation. After  
219 completing the vacuum process, the specimens were kept in the vacuum container for another 30  
220 minutes, removed from the container and placed on a flat surface at 40°C for three days, before  
221 being tested. Five sets of each sample were tested for each mixture type. Water sensitivity was  
222 calculated using the stiffness modulus ratio (*SMR*) as shown in equation (1):

$$223 \quad SMR = (wet\ stiffness / dry\ stiffness) \times 100 \quad (1)$$

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226 3.4.5 Semi-circular bending test

227 The European Standard specifies the use of the Semi-Circular Bending (SCB) test to determine  
228 tensile strength, or fracture toughness, of bituminous mixtures to assess for potential crack  
229 propagation. This test involves determining the resistance of bituminous mixtures to crack  
230 propagation during dynamic loading. Slab samples of length 400mm, width 305mm and depth  
231 50mm, were prepared and compacted using a steel roller compactor which simulated pavement  
232 compaction in the field. After full curing, three cylindrical specimens measuring 150mm in  
233 diameter and 50mm in height, were cored from each slab using an electrical extruder. Each  
234 specimen (core) was then cut into two equal halves (semi-circular specimens), through the middle,  
235 each half cut in the centre with a notch of 10mm depth and 0.35mm width to act as a pre-crack.  
236 These specimens were loaded under three-point bending in such a way that the middle of the base  
237 of the specimens were subject to tensile stress (Figure 4). During the test, deformation increases  
238 at a constant rate of 5 mm/min. The corresponding load increases to a maximum value ( $F_{max}$ ),  
239 directly related to the fracture toughness of the specimens.

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

242

243 
$$\sigma_{max} = \frac{4.263 \times F_{max}}{D \times t} \text{ N/mm}^2 \quad (2)$$

244 where

245  $D$  = the diameter of specimen (mm).

246  $t$  = the thickness of specimen (mm).

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

248

249 
$$K_{IC} = \sigma_{max} \times f\left(\frac{a}{W}\right) N/mm^{3/2} \quad (3)$$

250 where,

251  $W$  = height of specimen (mm).

252  $A$  = notch depth of specimen (mm).

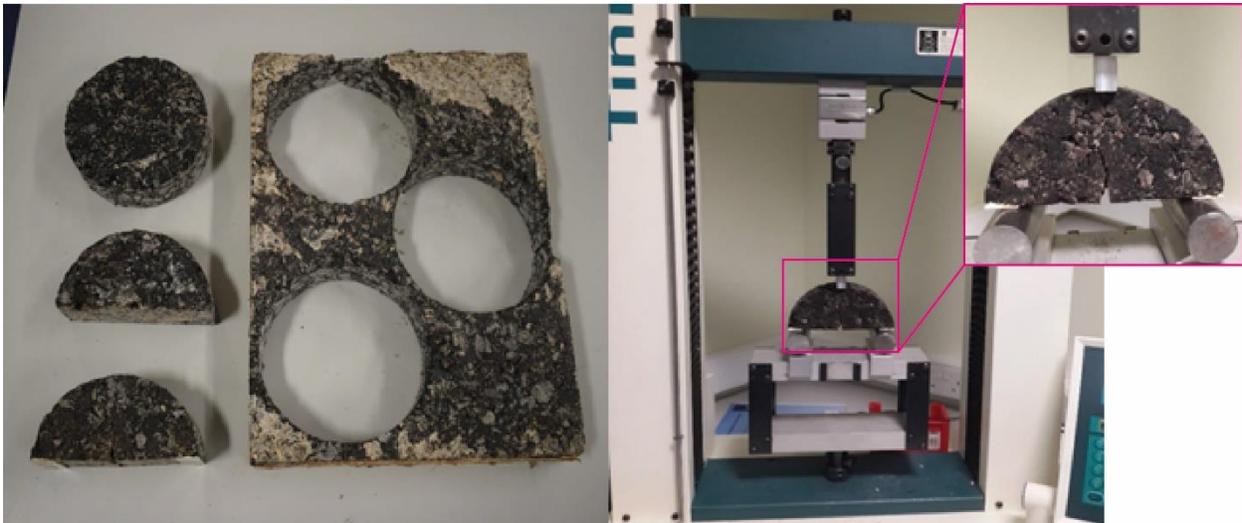
253  $\sigma_{max}$  = stress at failure of specimen (N/mm<sup>2</sup>).

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

255 5.956.

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260 Figure 4. Schematic of SCB specimen preparation and fracture test

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## 263 4. Results and analysis

### 264 4.1 ITSM

265 The Indirect Tensile Stiffness modulus is regarded as key when evaluating the effect of different

266 fibre lengths and contents on CMA mixture performance, taking into account the effect of curing

267 time and condition. Figure 5 shows that ITSM initially increases then decreases, with increasing  
268 fibre content, for all fibre lengths. The CMA mixture reinforced with 0.35% fibre content by  
269 weight of dry aggregate, had a higher ITSM than the other mixtures for all fibre lengths. This is in  
270 agreement with other researchers Chen, et al. [13] and Xu, et al. [41] who recommend that the  
271 optimum fibre content should be between 0.3% and 0.4%, based on the results from similar tests.  
272 14mm long fibres, cured for 2 days, developed the ITSM of the reinforced CMA mixtures to the  
273 maximum value. This indicates that the reinforced mixture with 14mm fibre length and 0.35%  
274 content, adheres well to the bitumen [20]. According to Liu, et al. [42], short fibres (10mm)  
275 cannot properly reinforce mixtures that have a larger size of aggregate (maximum 14mm) while  
276 long fibres (longer than the maximum size of the aggregate) can lead to loss in mixture strength  
277 because these fibres tend to lump together during the mixing process. The results found here were  
278 similar to those found in the literature [43]. Because of the use of an appropriate length of fibre  
279 (14mm in this research), the placement and distribution of this fibre in the bituminous mixture,  
280 produced enhanced interlocking between the fibre and the paste, hence the lateral strain was  
281 delayed and the mixture strength improved [44]. This optimisation process was only performed  
282 for the glass fibre, the optimized fibre length and content then adopted for all other fibre types.

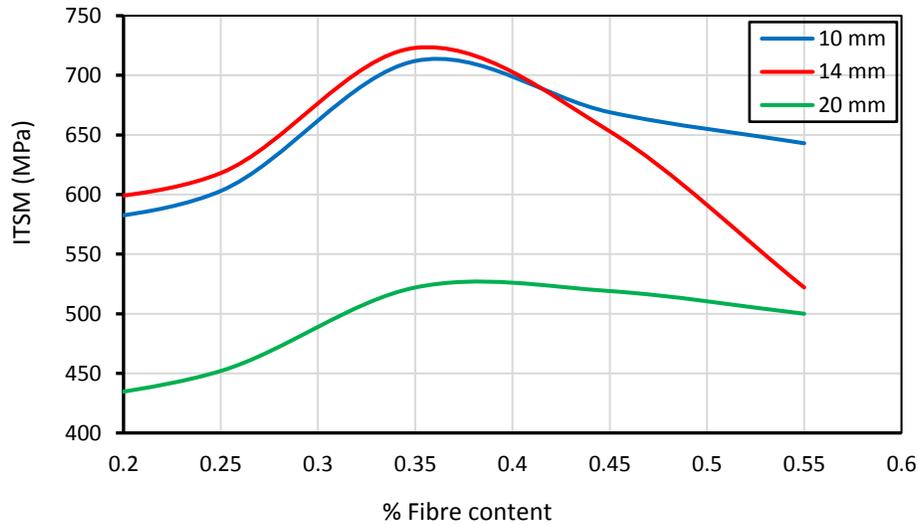


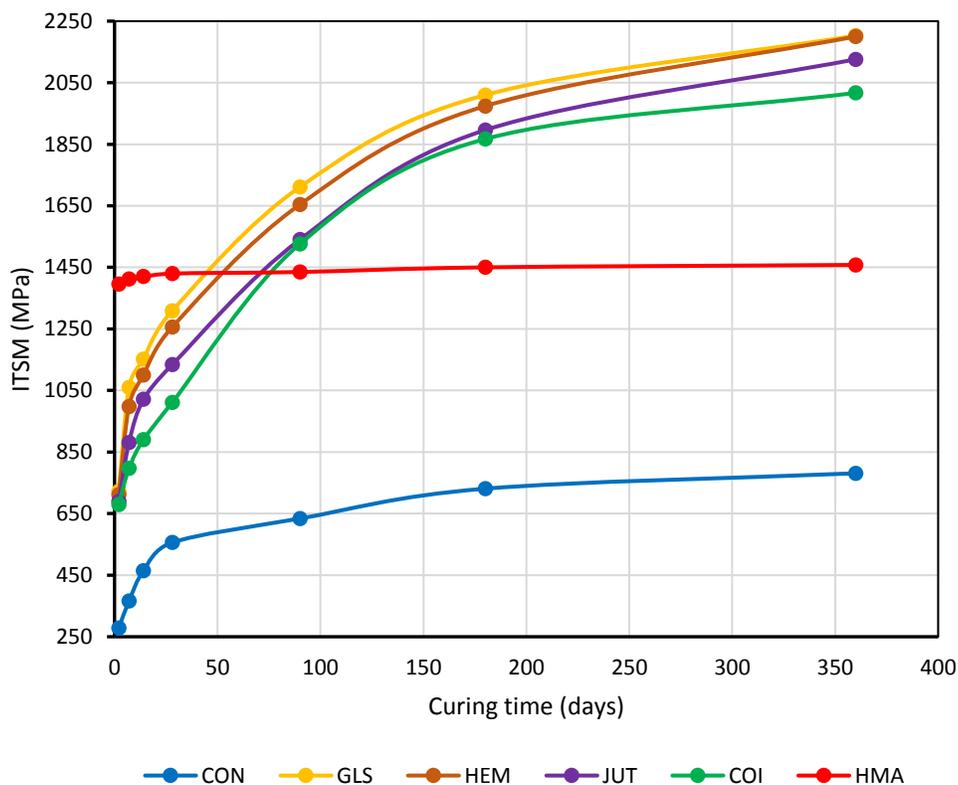
Figure 5. Glass fibre optimization at 20°C after 2 days

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287 The results of the ITSM tests are shown in Figure 6 for both reinforced and unreinforced CMA  
 288 mixtures. The results for HMA are also presented for comparison purposes. Each set of specimens  
 289 was tested at various curing times; 2, 7, 14, 28, 90, 180 and 360 days. The results indicate that  
 290 average stiffness modulus values increase significantly, with curing time, at early to medium ages  
 291 (2 to 28 days), followed by a reduction in the curve of the slope due to reaching a definitive level,  
 292 this achieved after about 28 days of curing. This behaviour is due to the bitumen emulsion emitting  
 293 volatile components, allowing the CMA mixtures to be cured and reach their final strength [29].  
 294 The HMA presents no significant stiffness modulus change over time [45, 46]. It can also be seen  
 295 from Figure 6 that the significant development in ITSM specifically depends on the fibres as these  
 296 provide a three-dimensional reinforcement for the CMA mixtures [20, 26, 29, 41, 47]. Therefore,  
 297 the stiffness modulus of CMA mixtures, reinforced with natural and synthetic fibres, reached or  
 298 exceeded the stiffness of HMA between 40 to 80 days, depending on the fibre type. Conventional  
 299 (unreinforced) CMA mixture still has low stiffness in comparison to HMA, after one year of  
 300 curing. For all types of fibre, the reinforced CMA mixtures provide almost the same, or slightly

301 higher, stiffness modulus compared to the HMA mixture, over medium curing times (28-90 days).  
 302 This means that roadwork activities should be able to guarantee adequate performance in a short  
 303 to medium time after construction, if natural and synthetic fibre-reinforced CMA mixtures are  
 304 used. When it is possible to have a longer curing time, the natural and synthetic fibre-reinforced  
 305 CMA mixtures are able to ensure high performance, significantly exceeding the performance of  
 306 the HMA mixture.



307  
 308 Figure 6. Effect of curing time on stiffness modulus  
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310  
 311 Regarding the range of curing times investigated, the increase in ITSM value as a function of  
 312 curing time ( $t$ ), can be represented with a logarithmic regression, according to the following  
 313 equation (4):

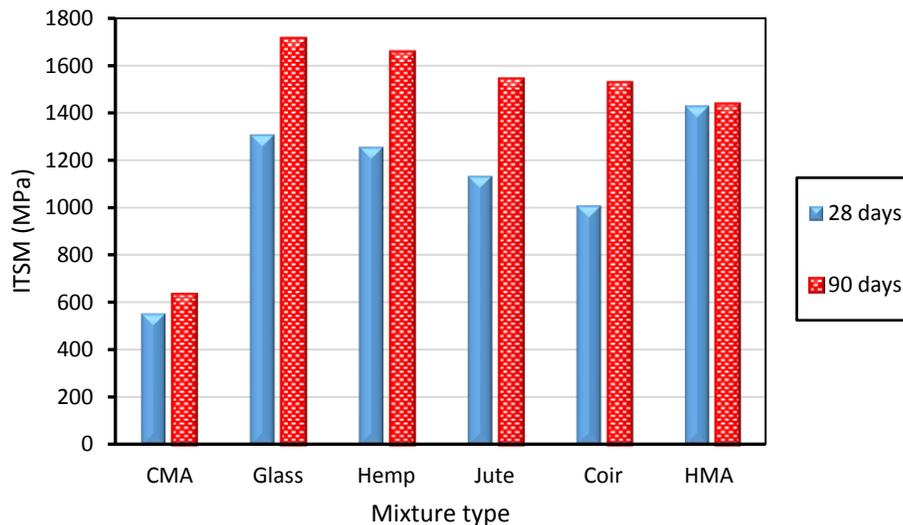
314 
$$ITSM = a \ln(t) + b \quad (4)$$

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

318 Table 2. Logarithmic regression parameter values  
 319

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

320  
 321 The comparison between the conventional and reinforced CMA mixtures, shows that glass fibre  
 322 gives the highest ITSM. Figure 7 shows the ITSM results for samples at 28 and 90 days of curing.  
 323 These times have been selected to illustrate the capacity of such mixtures to withstand traffic loads  
 324 within medium curing times. All in all, the CMA mixture containing natural and synthetic fibres,  
 325 could be an alternative for HMA, as the stiffness modulus reached a similar value within 28 days.



326 Figure 7. Stiffness modulus after 28 and 90 curing days  
 327  
 328

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

#### 335 336 *4.2 Rutting*

337 The test results in Figures 8 and 9 show the variation in accumulated rutting depth, under  
338 cumulative loading cycle times, at 45°C and 60°C, respectively. The reinforced CMA mixtures  
339 have significantly reduced accumulated rutting (permanent deformation). The accumulated rutting  
340 in CMA with synthetic fibres (glass) is slightly lower than for the CMA with natural fibres at both  
341 test temperatures. Glass, hemp, jute and coir fibres have a reduced rut depth by 766%, 636%,  
342 610%, and 462%, at 45°C after 20000 cycles (27600 seconds), respectively. These figures also  
343 show that at the initial stage of the test, there is a rapid increase in rutting induced by the  
344 consolidation of the mixtures under the vertical pressure of wheel loading [41]. It was observed  
345 that after a certain number of load repetitions, this rate of rutting depth decreased and sometimes  
346 followed a horizontal line, this mainly due to the high shear strength of the reinforced CMA  
347 mixtures under shear stress [41, 47]. At this stage, the increase in rate of rutting depth with time,  
348 tends to be almost horizontal, indicative of the high stiffness modulus of the bituminous mixture.  
349 In contrast, the development of rutting for the conventional CMA mixture is faster initially  
350 followed by a gentle decrease. The faster the rutting development rate, the earlier the road  
351 pavement enters into its failure stage [48]. In this case, it is highly probable that the serviceable  
352 life of bituminous pavements will be shortened.

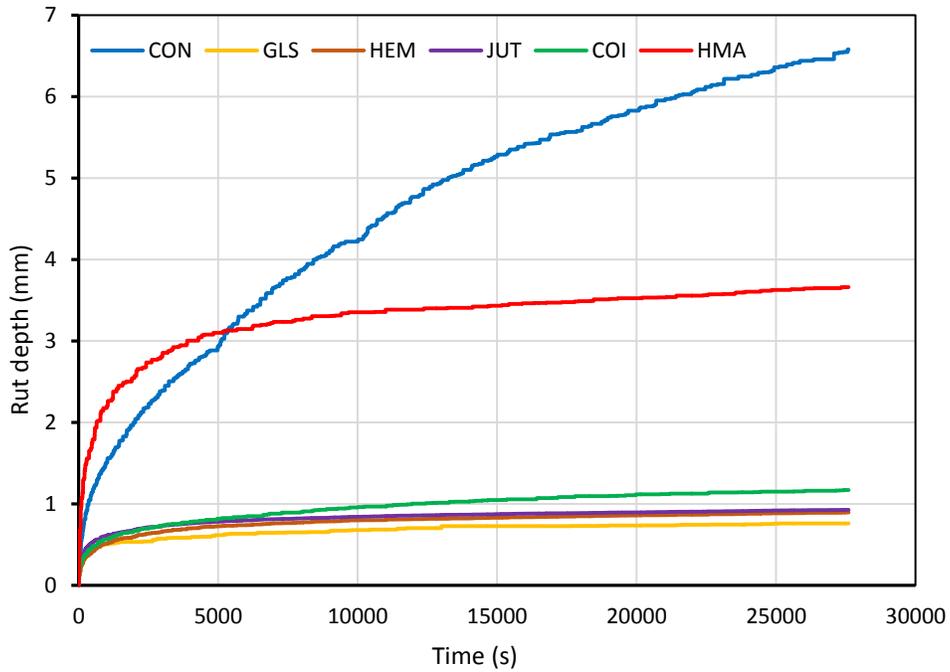


Figure 8. Rut depth at 45°C

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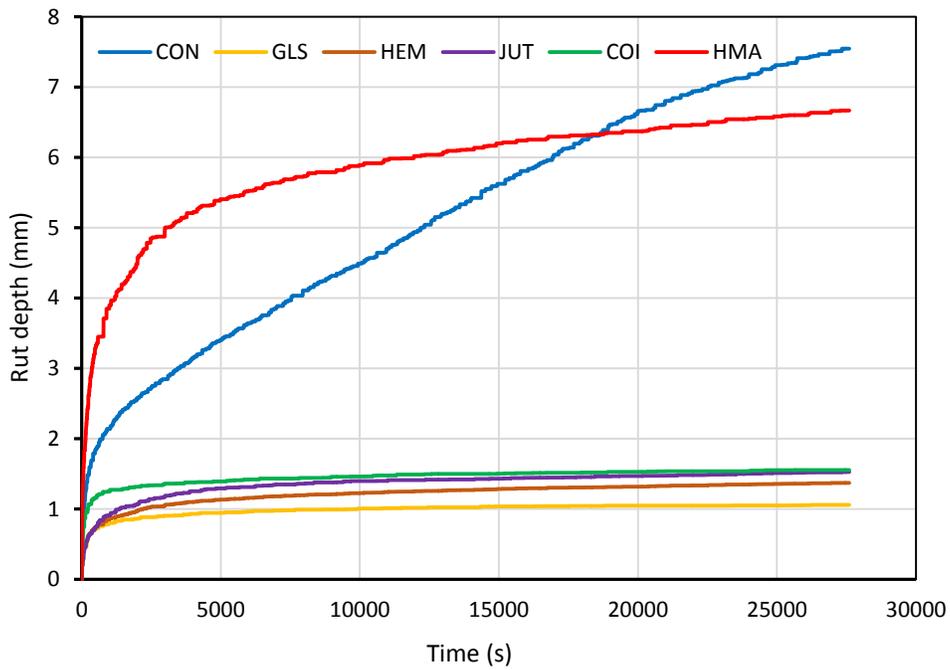


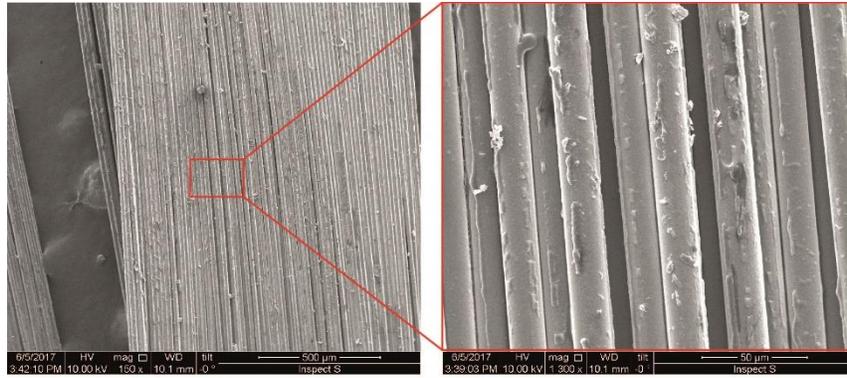
Figure 9. Rut depth at 60°C

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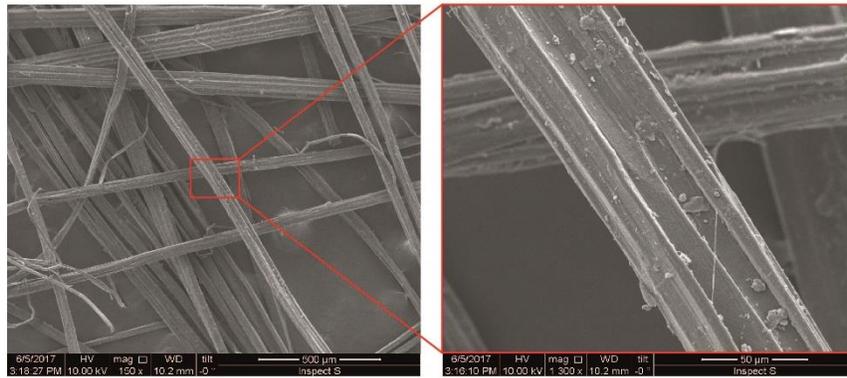
361 The significant reduction in rutting depth of the reinforced CMA mixtures could be partially due  
362 to the ability of the fibres to stabilize and hold the bitumen on their surface, thus resisting the flow  
363 of bitumen at high temperatures [47]. The fibres form a three-dimensional network in the  
364 bituminous mixture, this reinforcing the skeleton structure, resisting shear and tensile stresses and  
365 reducing fluidity [41, 47]. In summary, the analysis of rutting depth indicates that the mixtures  
366 containing natural and synthetic fibres significantly reduce rutting depth in comparison to  
367 conventional cold and hot mixtures.

368  
369 *4.3 Fibres microstructure characteristics*

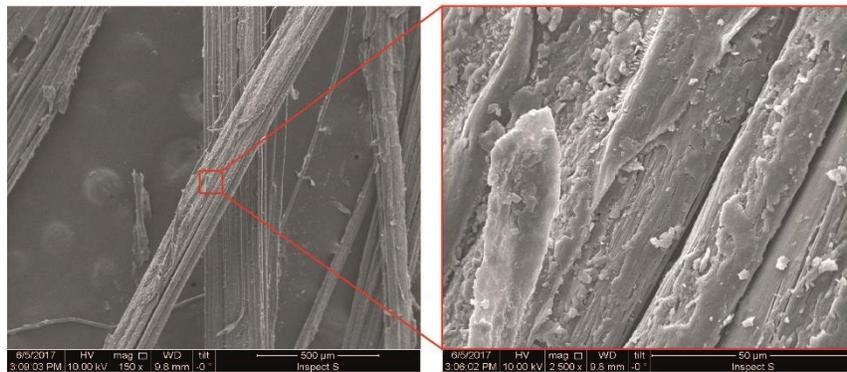
370 The SEM microstructure of fibres, shown in Figures 10a to d, reveals both the shape of the fibres  
371 and their surface roughness characteristics. Figure 10a shows a SEM image of the glass fibre where  
372 it is seen that the surface area has some protrusions resulting in a rough surface texture that can  
373 enhance the interlock between the mixture and fibres [49].



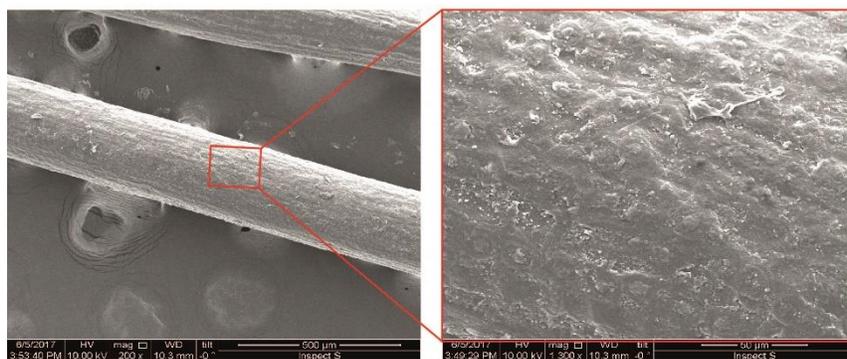
(a) Glass fibre



(b) Hemp fibre



(c) Jute fibre



(d) Coir fibre

Figure 10. Fibres and their microstructure

376 Figure 10b shows the surface morphology of the jute fibre. This fibre has an uneven surface with  
377 irregularities (more surface area), rough cavities on its outer surface and some voids. The presence  
378 of these cavities could improve the quality of the fibre/mixture interface [50]. The surface of the  
379 hemp fibre (Figure 10c) is observed as a rough surface with strip protrusions, which provide good  
380 structural stability. The SEM images of coir fibres, presented in Figure 10d, show a uniform fibre  
381 formation. There are however, small irregularities on the fibre surface that create an irregular  
382 morphology. This fibre has globular particles that show as protrusions fixed in specific pits of the  
383 fibre surface area.

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

#### 389 *4.4 Water sensitivity test*

390 The evaluation of water damage is an important factor because of the direct effect on the  
391 performance and service life of flexible pavements [26, 53]. The water sensitivity results revealed  
392 that all the natural and synthetic fibres significantly improved the moisture resistance of the CMA  
393 mixtures. Figure 11 shows that the addition of fibres increased the value of SMR. The mixtures  
394 with glass and hemp fibres show SMR values approximately the same as HMA mixtures. The  
395 CMA mixtures with natural and synthetic fibres, have better SMR values in comparison to the  
396 conventional CMA mixture. It is worth noting that the improved cohesion of the reinforced  
397 mixtures is the main reason for the improvement in performance against water action [5, 20, 29,  
398 41].

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

402

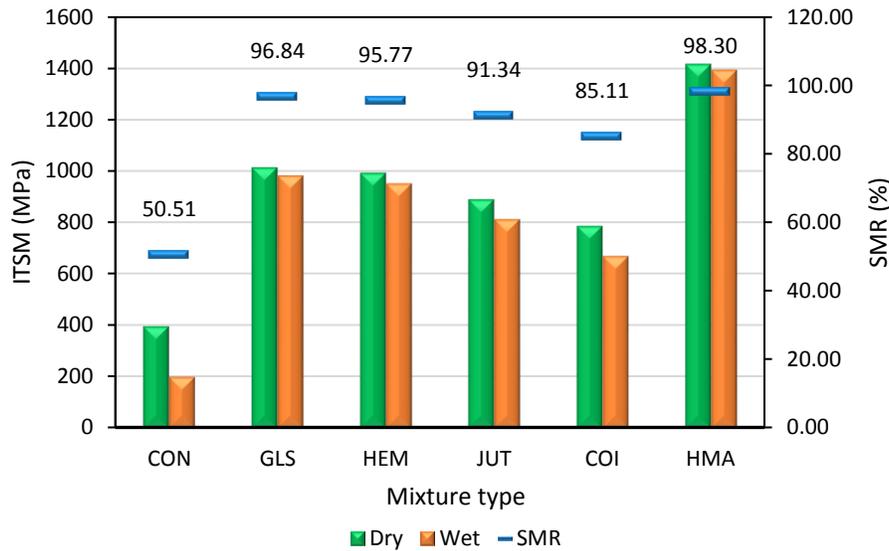


Figure 11. Water sensitivity results

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#### 4.5 Semi-circular bending test

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

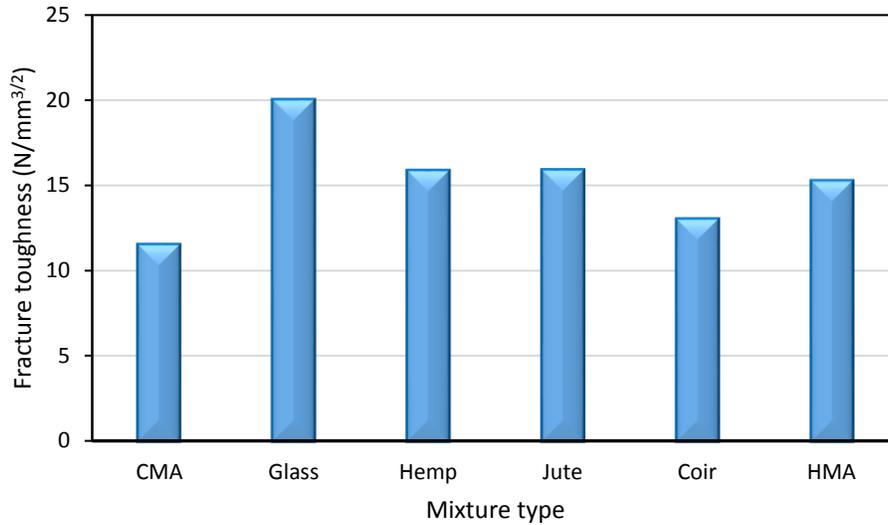


Figure 12. Effect of fibre-reinforced CMA on fracture toughness

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419 Figure 13 shows the load-displacement curve for the hot and cold mixtures. The load-displacement  
420 curves from the samples tested at 5°C, show that the fracture behaviour of bituminous mixtures  
421 was linear under these conditions, due to the elastic behaviour of bituminous mixtures at low  
422 temperatures [28].

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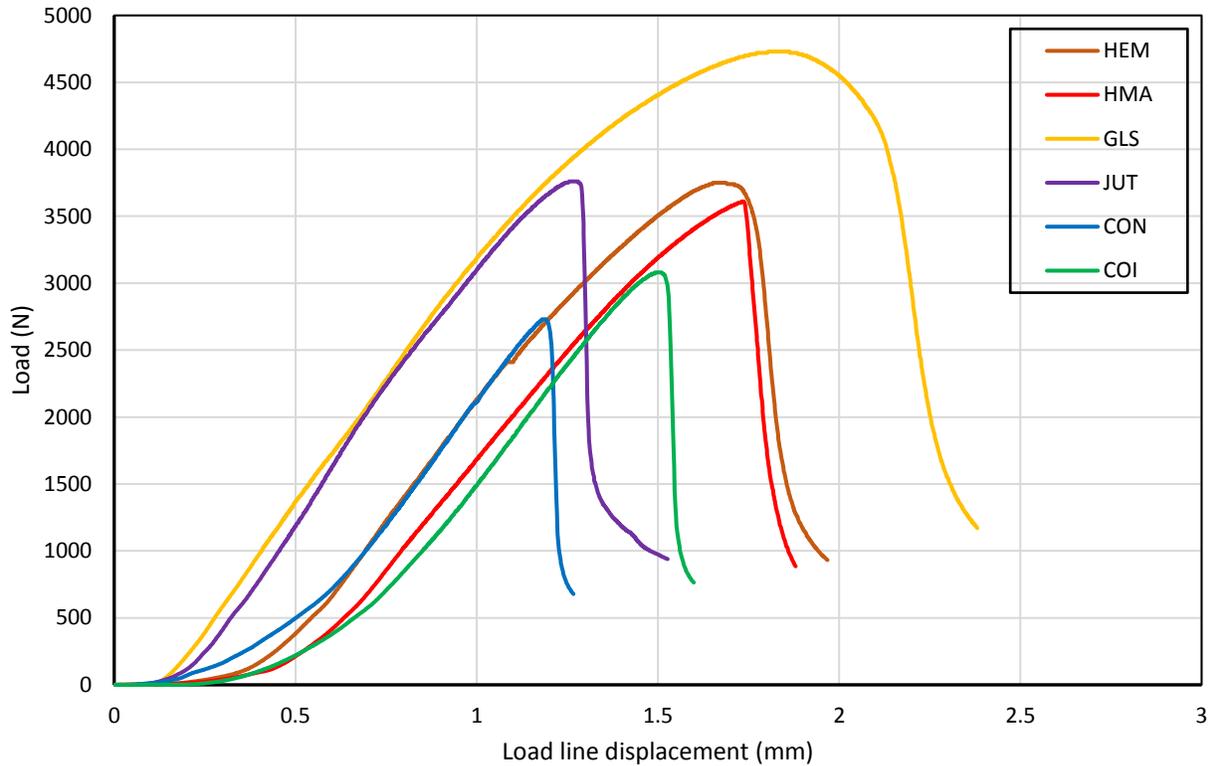


Figure 13. Typical load-displacement curves

## 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

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

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

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