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Behaviour of high strength concrete reinforced with different types of steel fibres

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Behaviour of high strength concrete reinforced with different types of steel fibres

Abstract

This paper reports the results of an experimental investigation on the behaviour of High Strength Concrete (HSC) reinforced with different types of steel fibre (copper-coated micro steel fibres, deformed macro steel fibre and hybrid steel fibre). A total of 40 cylindrical specimens with 100 mm diameter and 200 mm height were cast and tested for compressive and split tensile strengths. Three groups of steel fibre reinforced HSC specimens were prepared. The first group included 2, 3, and 4% by volume of copper-coated micro (CM) steel fibre; the second group included 1, 2 and 3% by volume of deformed macro (DM) steel fibre; and the third group included 1.5% (1% CM + 0.5% DM), 2.5% (1.5% CM + 1% DM), and 3.5% (2% CM + 1.5% DM) by volume of hybrid (H) steel fibre. Plain HSC specimens without steel fibre were also prepared. The experimental results showed higher improvements in the compressive and split tensile strengths of the HSC with the inclusion of 3, 2, and 2.5% by volume of CM, DM and H steel fibres, respectively, compared to the plain HSC.

Disciplines

Engineering | Science and Technology Studies

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1 **Behaviour of high strength concrete reinforced with different types of steel**
2 **fibres**

3

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29 **Behaviour of high strength concrete reinforced with different types of steel**
30 **fibres**

31

32 **ABSTRACT:** This paper reports the results of an experimental investigation on the behaviour of
33 High Strength Concrete (HSC) reinforced with different types of steel fibre (copper-coated
34 micro steel fibres, deformed macro steel fibre and hybrid steel fibre). A total of 40 cylindrical
35 specimens with 100 mm diameter and 200 mm height were cast and tested for compressive and
36 split tensile strengths. Three groups of steel fibre reinforced HSC specimens were prepared. The
37 first group included 2%, 3%, and 4% by volume of copper-coated micro (CM) steel fibre; the
38 second group included 1%, 2% and 3% by volume of deformed macro (DM) steel fibre; and the
39 third group included 1.5% (1% CM + 0.5% DM), 2.5% (1.5% CM + 1% DM), and 3.5% (2%
40 CM + 1.5% DM) by volume of hybrid (H) steel fibre. Plain HSC specimens without steel fibre
41 were also prepared. The experimental results showed higher improvements in the compressive
42 and split tensile strengths of the HSC with the inclusion of 3%, 2%, and 2.5% by volume of
43 CM, DM and H steel fibres, respectively, compared to the plain HSC.

44 **Keywords:** Concrete, Compressive strength, Split tensile strength, Micro steel fibre, Macro
45 steel fibre, Hybrid steel fibre.

46 **1 Introduction**

47 The use of High Strength Concrete (HSC) as a construction material has become very popular due
48 to its economic advantages. One of the most common structural applications of HSC is in the
49 construction of columns of high rise buildings, where normal strength concrete (NSC) results in
50 larger cross-sectional areas together with higher costs (Foster, 2001). However, the HSC is brittle
51 and has low ductility (Foster & Attard, 2001). One of the techniques to reduce the brittle failure and
52 improve the ductility of concrete is the inclusion of steel fibre. The inclusion of steel fibre into
53 concrete leads to enhancements in the mechanical properties such as compressive strength, tensile
54 strength, shear strength, impact resistance and toughness of the concrete (Wafa & Ashour, 1992;
55 Khaloo & Kim, 1997; Gao et al, 1997; Zollo, 1997; Song & Hwang, 2004; Hadi, 2007; Thomas &
56 Ramaswamy, 2007; Yazici et al, 2007; Ramadoss & Nagamani, 2008; Behnood et al, 2015; Balanji
57 et al, 2016).

58
59 The main function of steel fibre in concrete matrix is to transfer the stress from the matrix to the
60 fibre by frictional stress at the fibre-matrix interface, which causes debonding of the fibre from the
61 matrix. The frictional stress and debonding behaviour are significantly affected by the type, volume
62 content and aspect ratio (length to diameter ratio) of the fibres (Li & Chan, 1994). It was found that
63 steel fibres in cement-matrix led to adhesive bond failure at the fibre-matrix contact surface (Chan,
64 1994). However, copper-coated steel fibres in cement-matrix caused cohesive bond failure between
65 fibre and matrix in the transition zone due to the chemical reaction between the copper and the
66 cement material (Li & Chan, 1994; Chan & Li, 1997; Li & Stang, 1997). Thus, the inclusion of
67 copper-coated steel fibres into HSC may be more effective in improving the strength and ductility
68 of HSC. However, only a limited number of studies exist on the behaviour of copper-coated steel
69 fibre reinforced concrete (Balanji et al, 2016).

70

71 The fracture in concrete is a gradual process, which includes multi-scale cracks (micro and macro
72 cracks). Under incremental applied load, micro cracks grow and then join to create macro-cracks
73 (Yao et al, 2003; Yoo et al, 2014; Huang et al, 2015). Afterwards, macro-cracks propagate under
74 further increase in the applied load and eventually lead to a rapid fracture. The inclusion of macro
75 fibres *i.e.*, a fibre with a length higher than 10 mm and diameter $\geq 50 \mu\text{m}$, into concrete can arrest
76 macro-cracks (Sharma *et al*, 2013). However, inclusion of micro fibre *i.e.*, a fibre with a length less
77 than 10 mm and a diameter in the range between $25 \mu\text{m}$ to $40 \mu\text{m}$, into concrete can arrest micro-
78 cracks (Sharma *et al*, 2013). A number of research studies focused on the effect of different types,
79 volume content and aspect ratio of macro fibres on the mechanical properties of the concrete (Zollo,
80 1997; Brandt, 2008). It was found that 2% by volume of macro fibres is adequate to obtain
81 reasonable workability of fresh concrete and higher strength improvement in the hardened concrete.

82

83 The use of one type of fibre (either macro or micro) can only provide reinforcement to the concrete
84 to a limited extent. The use of hybrid fibre, which is a combination of two or more types of fibres,
85 can enhance the mechanical properties of the HSC effectively. However, only a limited number of
86 research studies are available in the literature regarding hybrid steel fibre reinforced HSC (Dazio et
87 al, 2008; Ding et al, 2010; Balanji et al, 2016).

88

89 The main objective of this experimental study is to investigate the optimum amount of micro, macro
90 and hybrid steel fibres in terms of compressive strength and split tensile strength of steel fibre
91 reinforced HSC. The main parameters investigated are the fibre type (copper-coated micro steel
92 fibres, deformed macro steel fibres, and hybrid steel fibres) and volume content of the steel fibres.

93

94 **2 Experimental program**

95 **2.1 Materials**

96 In order to produce High Strength Concrete (HSC) mixes with and without steel fibres, the
97 materials used included Ordinary Portland Cement (OPC) Type I (ASTM, 17), fly ash, fine
98 aggregate with a maximum size of 4.75 mm, coarse aggregate with a maximum aggregate size of 10
99 mm, super-plasticizer and three types of steel fibres. The first type of steel fibre was copper-coated
100 micro (CM) steel fibre, which was supplied by Ganzhou Daye Metallic Fibres (GDFM, 2015). The
101 second type of steel fibre was deformed macro (DM) steel fibre, which was provided by Fibercon
102 Co. Ltd (Fibercon, 2015). The third type of steel fibre was hybrid (H) steel fibres, which was a
103 combination of CM steel fibres and DM steel fibres. Table 1 shows the nominal properties of steel
104 fibres that were provided by the manufacturers. These properties conform to A820M-11 (ASTM,
105 2011). Figure 1 shows the shape of CM, DM and H steel fibres used in this study.

106

107 **2.2 Mix proportions and casting process**

108 A total of 40 cylindrical specimens were prepared from ten HSC mixes. Four cylindrical specimens
109 of 100 mm x 200 mm from each mix were cast and tested. Mix R included plain HSC without steel
110 fibres. Mixes CM-1, CM-2 and CM-3 included 2%, 3%, and 4% by volume of CM steel fibres,
111 respectively. Mixes DM-1, DM-2, and DM-3 included 1%, 2% and 3% by volume of DM steel
112 fibres, respectively. Mixes H-1, H-2, and H-3 included 1.5% (1% CM + 0.5% DM), 2.5% (1.5%
113 CM + 1% DM), and 3.5% (2% CM + 1.5% DM) by volume of H steel fibres, respectively. The mix
114 proportions for 1 m³ of the HSC with and without steel fibres are presented in Table 2. The amount
115 of superplasticizer (high range water reducer) varied from 1.5% to 2% of the weight of binder
116 material (Cement + Fly ash).

117 A mixer with a capacity of 0.2 m³ was used to produce the HSC. First, the sand and coarse
118 aggregate were added into the mixer and mixed for 3 min. Then cement and fly ash were added and
119 mixed for another 3 min. The steel fibres were added into the mix (sand-coarse aggregate-cement-
120 fly ash) for about 3 min to obtain a homogenous dry mix. Finally, tap water was added into the
121 mixture along with super-plasticizer and mixed for an additional 3 min. The same process was
122 followed to produce all others concrete mix.

123

124 The fresh steel fibre reinforced HSC mixtures were poured into cylinder moulds and vibrated to
125 reduce air bubbles. After 24 hours, the specimens were demolded and cured in a water tank for 28
126 days. At the end of 28 days, the strength test (compression test and split tensile test) was performed
127 according to Australia Standards 1012.8-14 (AS, 2014).

128

129 **3 Results**

130 ***3.1 Failure modes of the HSC with and without steel fibres***

131 The typical failure modes of the HSC specimens tested under compression are shown in Figure 2. It
132 was observed that Mix R specimens failed in a brittle manner as shown in Figure 2 (a). However,
133 with the inclusion of steel fibres into HSC, the failure modes became a combination of compression
134 failure and bulging of the specimens in the lateral direction. The diagonal shear plane was observed
135 for all Mix CM specimens, as shown in Figure 2 (b). The lateral bulging was observed for all Mix
136 DM specimens, as shown in Figure 2 (c). The failure mode of all Mix H specimens was due to
137 bulging of the specimens in the lateral direction as shown in Figure 2 (d). It was observed from the
138 failure modes of the mixes tested under compression that Mix H specimens presented a better
139 performance compared to specimens of Mixes CM and Mixes DM.

140

141 The typical failure modes of the specimens tested under tension are shown in Figure 3. It was found
142 that Mix R specimens split into two parts, as shown in Figure 3 (a). However, the specimens
143 reinforced with steel fibres did not split under the tension load. The failure modes of Mix CM and
144 DM specimens were due to the propagation of large cracks parallel to the loading direction, as
145 shown in Figure 3 (b) and (c). The failure mode of Mix H specimens was due to small cracks
146 parallel to the load direction, as shown in Figure 3 (d). It was found that the average cracks width of
147 the Mix CM and DM specimens were about 15.5 mm and 5.8 mm, respectively. The difference in
148 cracks width between Mix CM and DM specimens could be because the length of CM steel fibre
149 was less than the length of DM steel fibre. For Mix H specimens, the average crack width was about
150 1.2 mm. The reason for the low crack width could be due to the combined contribution of CM and
151 DM steel fibres. Thus, it was observed that Mixes H specimens presented a better performance
152 compared to specimens of Mixes CM and DM.

153

154 ***3.2 Compressive strength of HSC with and without steel fibres***

155 The axial compression test was performed on two identical cylinders of 100 mm x 200 mm for each
156 mix. The results of the compressive strength of the HSC with and without steel fibres are presented
157 in Table 3. Figure 4 shows the effect of volume content of steel fibres on the compressive strength
158 of the HSC. It was observed that the compressive strength of the HSC was marginally influenced by
159 the inclusion of different types of steel fibre. The improvement in the compressive strength was up
160 to 6%. A higher improvement in the compressive strength of HSC was obtained for the inclusion
161 3% by volume of CM steel fibres. Although the compressive strength of HSC was not significantly
162 influenced by the addition of 1% and 3% of DM steel fibre, the inclusion of 2% by volume of DM
163 steel fibres into HSC showed a slight improvement in the compressive strength of the HSC. The
164 inclusion of 2.5% of H steel fibres into HSC showed a higher improvement in the compressive

165 strength.

166

167 The effect of the type of steel fibres (CM and DM) on the compressive strength of HSC was also
168 studied by considering the volume contents of 2% and 3% of both steel fibres. Figure 5 presents the
169 effect of the type of steel fibres on the compressive strength of HSC. It was found that the
170 compressive strength of HSC increased by 3% and 1% with the inclusion of 2% of CM steel fibres
171 and DM steel fibres by volume, respectively. However, the compressive strength of HSC increased
172 by 6% and 0.2% with the inclusion of 3% of CM steel fibres and DM steel fibres by volume,
173 respectively. For the same volume content, it was observed that the inclusion of CM steel fibres
174 leads to higher compressive strength of HSC compared to the compressive strength of the HSC for
175 the inclusion of DM steel fibres.

176

177 ***3.3 Split tensile strength of HSC with and without steel fibres***

178 The results of the split tensile strength of different types of steel fibre reinforced HSC are shown in
179 Table 4. Figure 6 presents the effect of the volume content of steel fibres on the split tensile
180 strength. It was found that the split tensile strength of the HSC significantly improved with the
181 inclusion of steel fibres. The split tensile strength in general increased with the increase in volume
182 content of steel fibres. The improvement in the split tensile strength ranged from 55% to 100%
183 compared to the reference specimens. The split tensile strength of the HSC increased by 55%, 74%,
184 and 76% with the addition of 2%, 3%, and 4% by volume of CM steel fibres, respectively,
185 compared to the reference specimens. In addition, the split tensile strength of the HSC increased by
186 57%, 77%, and 79% with the inclusion of 1%, 2%, and 3% by volume of DM steel fibres,
187 respectively, compared to the reference specimens. Also, the split tensile strength of the HSC
188 increased by 60%, 85% and 100% with the inclusion of 1.5%, 2.5%, and 3.5% by volume of H steel
189 fibres, respectively, compared to reference specimens.

190 The effect of the type of steel fibres (CM and DM) on the split tensile strength of HSC was also
191 studied by considering volume contents of 2% and 3% of both steel fibres. Figure 7 presents the
192 effect of the type of steel fibres on the split tensile strength of HSC. It was observed that the split
193 tensile strength of HSC increased by 55% and 78% for the inclusion of 2% of CM steel fibres and
194 DM steel fibres by volume, respectively. Whereas, the split tensile strength of HSC increased by
195 74% and 79% with for the inclusion of 3% of CM steel fibres and DM steel fibres by volume,
196 respectively. For the same volume content, it was observed that the inclusion of DM steel fibres
197 leads to higher split tensile strength of HSC compared to the split tensile strength of the HSC for the
198 inclusion of CM steel fibres.

199

200 **4 Conclusions**

201 In this study, a total of 40 cylindrical specimens were cast and tested to investigate the behaviour of
202 the HSC with and without different types of steel fibres. The influence of types (CM, DM, and H)
203 and volume content of steel fibres on the compressive and split tensile strength of HSC were
204 observed. The maximum improvement in the compressive strength of HSC was observed with the
205 inclusion of 3% of CM steel fibres, 2% of DM steel fibres and 2.5% of H steel fibres. Also, the
206 higher improvement in split tensile strength was observed with the inclusion of 4%, 3% and 3.5%
207 of CM, DM and H steel fibres, respectively.

208

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278
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293 21

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298 (b) DM and (c) H 24

299 Figure 7: The effect of the aspect ratio of steel fibres on the split tensile strength of HSC. 25

300

301

302

Table 1: Nominal properties of steel fibres provided by manufacturers.

Type of steel fibres	Length (l) (mm)	Diameter (d) (mm)	Aspect ratio (l/d)	Tensile strength (MPa)	Density of fibre (kg/m^3)
Copper-coated Micro (CM) steel fibre (GDFM, 2015)	6±1	0.2±0.05	30	>2600	7900
Deformed Macro (DM) steel fibres (Fibercon, 2015)	18	0.55	33	800	7865

303

Table 2: Mix proportions for 1 m³ of the HSC with and without steel fibres.

Mix	Water (kg/m ³)	Cement (kg/m ³)	Fine aggregate (kg/m ³)	Coarse aggregate (kg/m ³)	Fly ash (kg/m ³)	Volume contents		
						Cooper- coated Micro (CM) steel fibres (%)	Deformed Macro (DM) steel fibres (%)	Hybrid (H) steel fibres (%)
R	151	504	708	1062	35	-	-	-
MI-1	151	504	704	1056	35	2	-	-
MI-2	151	504	702	1054	35	3	-	-
MI-3	151	504	701	1051	35	4	-	-
MA-1	151	504	706	1059	35	-	1	-
MA-2	151	504	704	1056	35	-	2	-
MA-3	151	504	702	1054	35	-	3	-
HY-1	151	504	705	1058	35	-	-	1.5 (1% CM + 0.5% DM)
HY-2	151	504	703	1055	35	-	-	2.5 (1.5% CM + 1% DM)
HY-3	151	504	702	1052	35	-	-	3.5 (2% CM + 1.5% DM)

Table 3: Results of compressive strength of HSC with and without steel fibres.

Mix	Cylinder specimens	Compressive strength (MPa)	Average compressive strength (MPa)
R	1	66.8	65.0
	2	63.2	
CM-1	1	68.1	66.7
	2	65.3	
CM-2	1	69.5	68.9
	2	68.3	
CM-3	1	65.4	65.8
	2	66.2	
DM-1	1	64.2	64.5
	2	64.8	
DM-2	1	65.5	65.8
	2	66.1	
DM-3	1	65.0	65.1
	2	65.2	
H-1	1	66.2	65.2
	2	64.2	
H-2	1	70.1	68.4
	2	66.7	
H-3	1	71.0	68.0
	2	65.1	

Table 4: Results of split tensile strength of HSC with and without steel fibres.

Mix	Cylinder specimens	Split tensile strength (MPa)	Average split tensile strength (MPa)
R	1	3.5	3.9
	2	4.3	
CM-1	1	6.0	6.1
	2	6.1	
CM-2	1	7.1	6.8
	2	6.5	
CM-3	1	6.6	6.9
	2	7.2	
DM-1	1	5.7	6.2
	2	6.6	
DM-2	1	6.5	7.0
	2	7.4	
DM-3	1	7.0	7.0
	2	7.0	
H-1	1	6.3	6.3
	2	6.2	
H-2	1	7.3	7.2
	2	7.1	
H-3	1	8.0	7.8
	2	7.6	



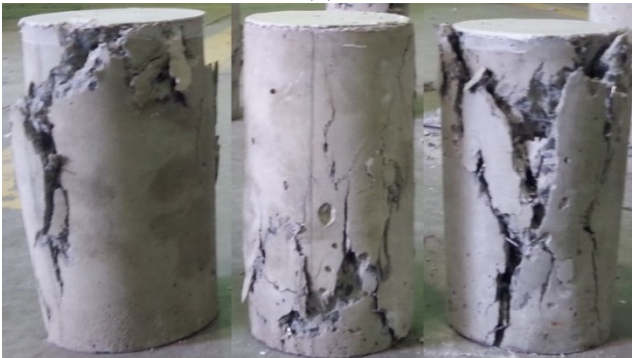
Figure 1: The shape of steel fibres.



R
(a)



CM-1 CM-2 CM-3
(b)



DM-1 DM-2 DM-3
(c)

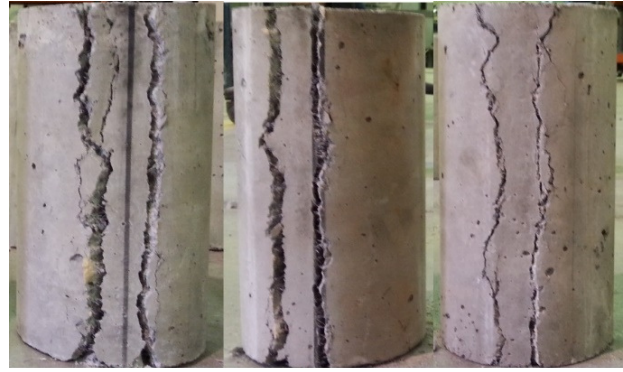


H-1 H-2 H-3
(d)

Figure 2: Typical failure modes of HSC mixes tested under compressive load: (a) R, (b) CM, (c) DM and (d) H.



R
(a)



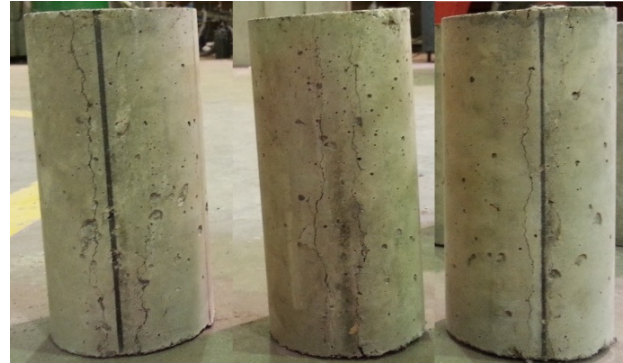
CM-1 CM-2 CM-3

(b)



DM-1 DM-2 DM-3

(c)



H-1 H-2 H-3

(d)

Figure 3: Typical failure modes of mixes tested under split tensile: (a) R, (b) CM, (c) DM and (d) H.

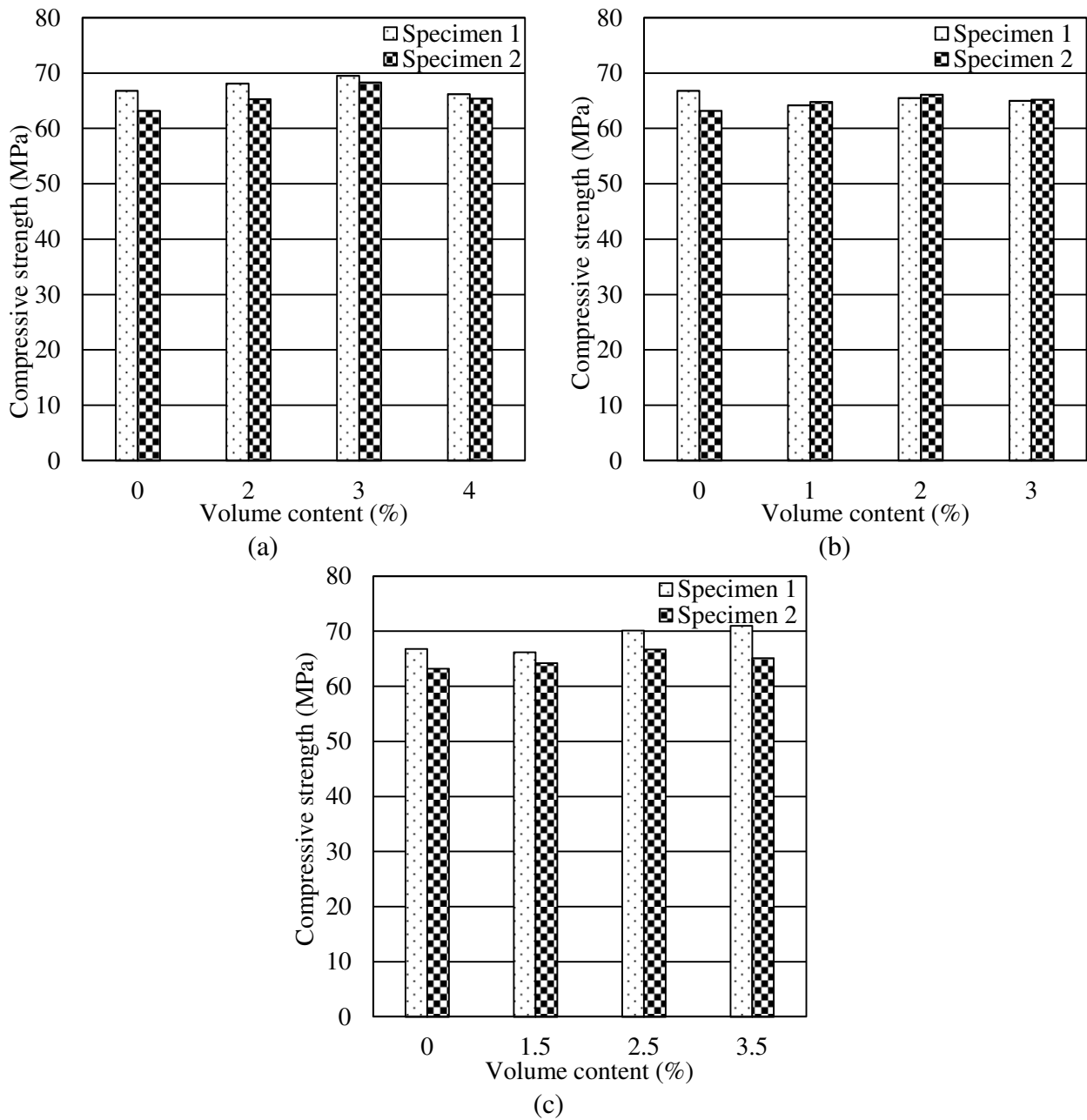


Figure 4: Effect of the volume content of steel fibres on the compressive strength of HSC: (a) CM, (b) DM and (c) H.

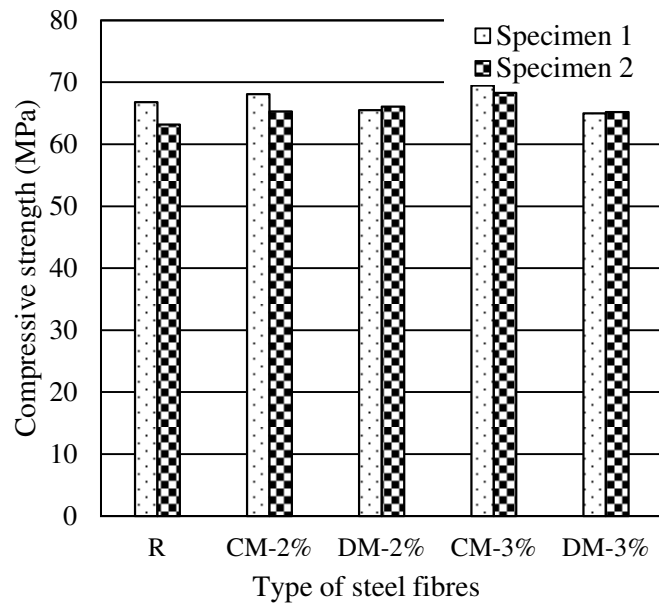


Figure 5: The effect of the type of steel fibres on the compressive strength of HSC.

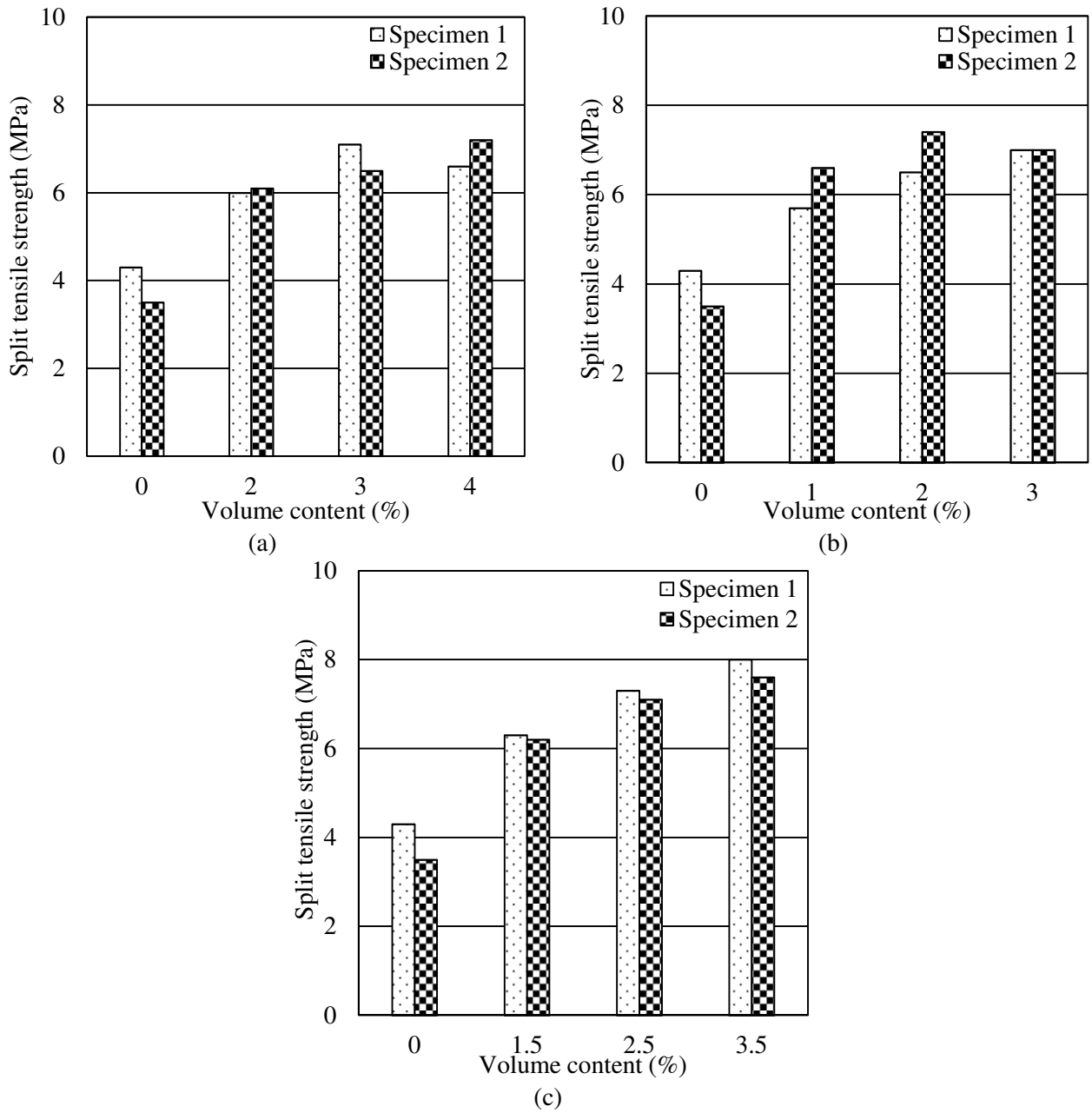


Figure 6: Effect of the volume content of steel fibres on the split tensile strength of HSC: (a) CM, (b) DM and (c) H

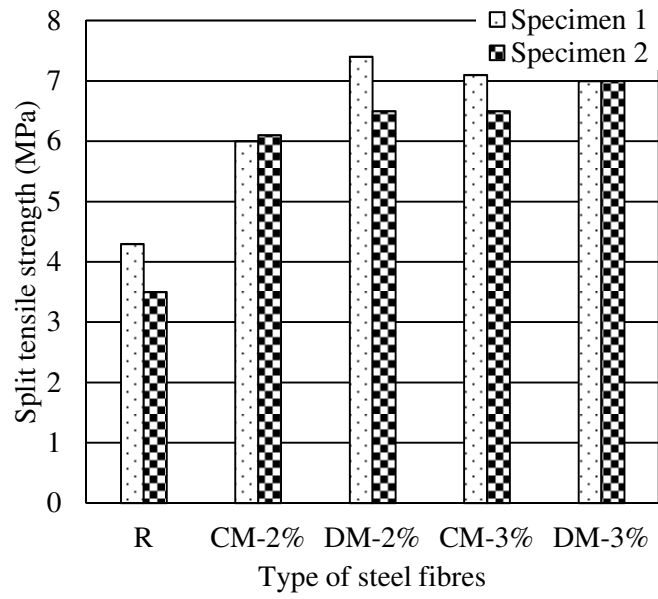


Figure 7: The effect of the aspect ratio of steel fibres on the split tensile strength of HSC.