2017

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

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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

Publication Details

Balanji, E. K. Z., Sheikh, M. Neaz. & Hadi, M. N. S. (2017). Behaviour of high strength concrete reinforced with different types of steel fibres. Australian Journal of Structural Engineering, 18 (4), 254-261.

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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.

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

1 Introduction

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

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

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

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

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

2 Experimental program

2.1 Materials

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

2.2 Mix proportions and casting process

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

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

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

3 Results

3.1 Failure modes of the HSC with and without steel fibres

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

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

3.2 Compressive strength of HSC with and without steel fibres

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

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

3.3 Split tensile strength of HSC with and without steel fibres

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

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

4 Conclusions

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

Acknowledgement

The authors thank the University of Wollongong, Australia for the research facilities. The authors also acknowledge the technical assistance provided by Senior Technical Officer Mr. Fernando Escribano. The first author thanks the Ministry of Higher Education and Research, Iraq for his PhD scholarship.

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TABLES AND FIGURES

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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

Table 2:Mix proportions for 1 m^3 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	

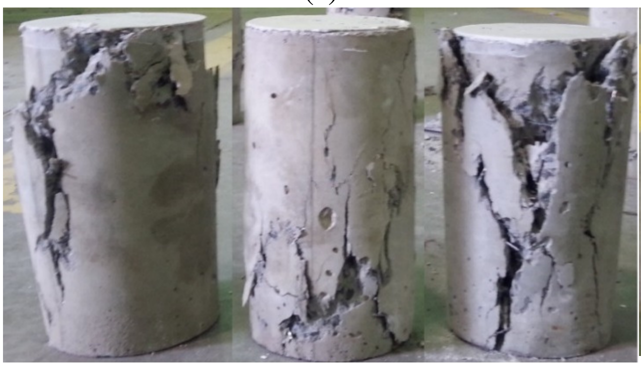
Figure 1: The shape of steel fibres.

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.

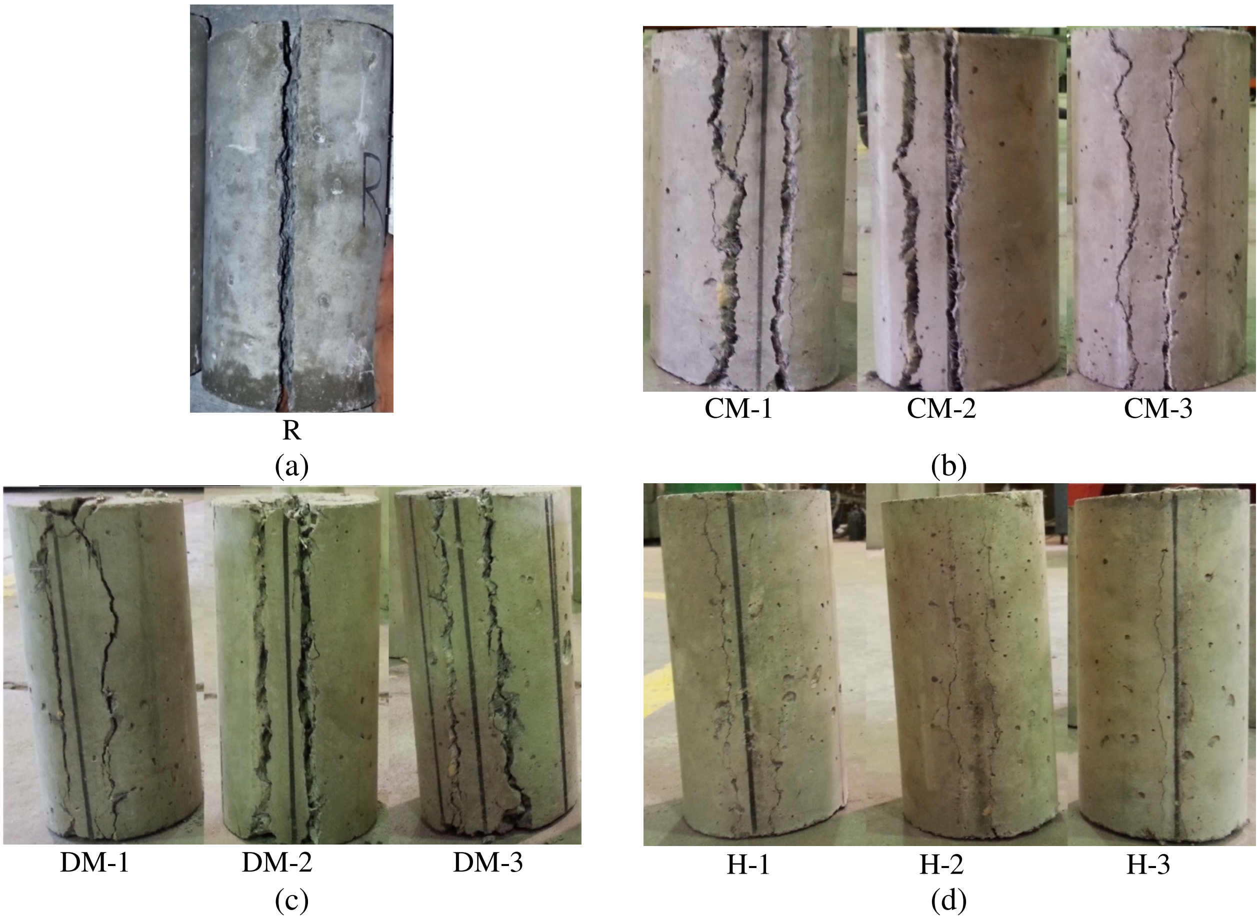


Figure 3: Typical failure modes of mixes tested under split tensile: (a) R, (b) CM, (c) DM and (d) H.

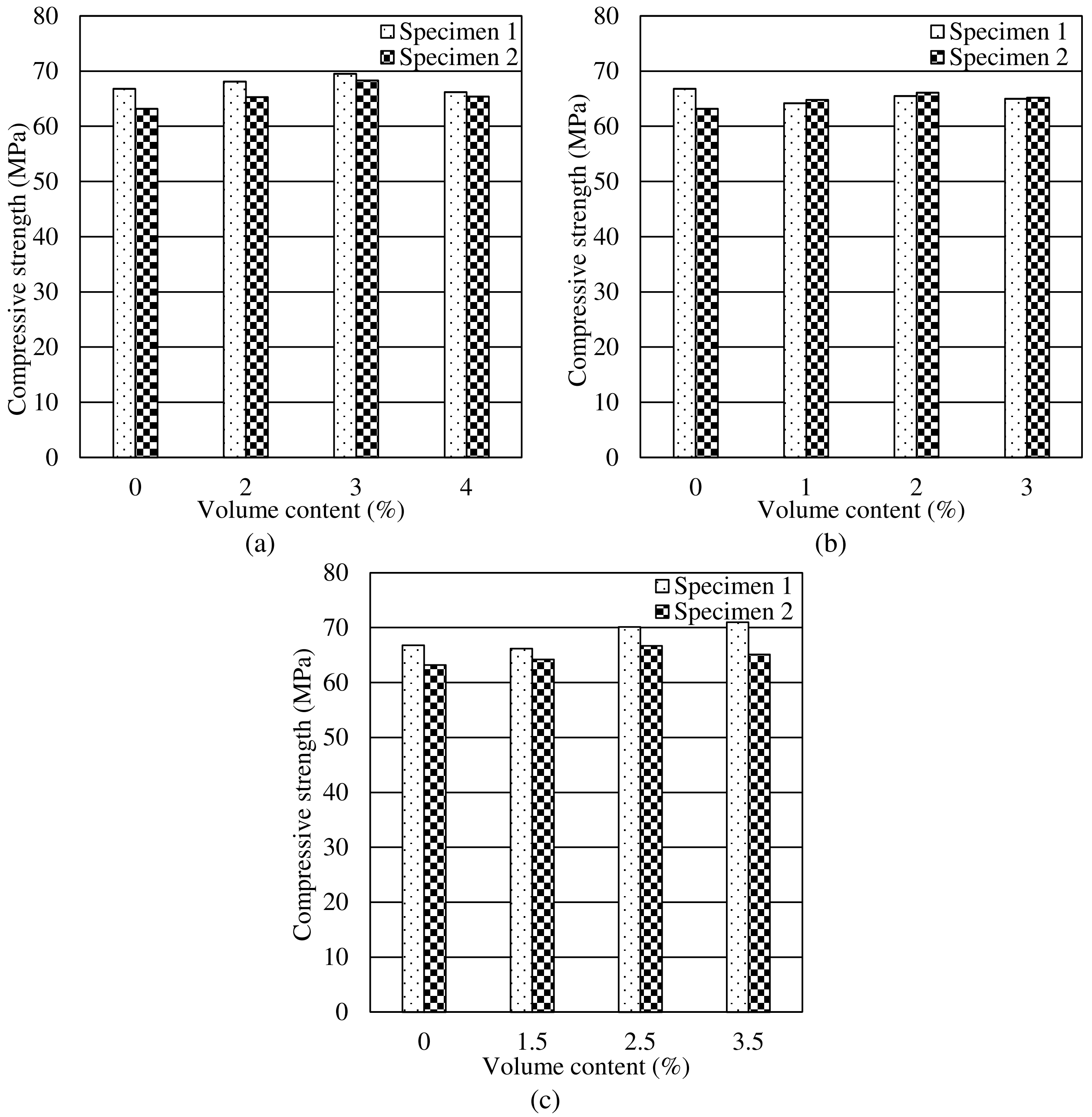


Figure 4: Effect of the volume content of steel fibres on the compressive strength of HSC: (a) CM, (b) DM and (c) H.

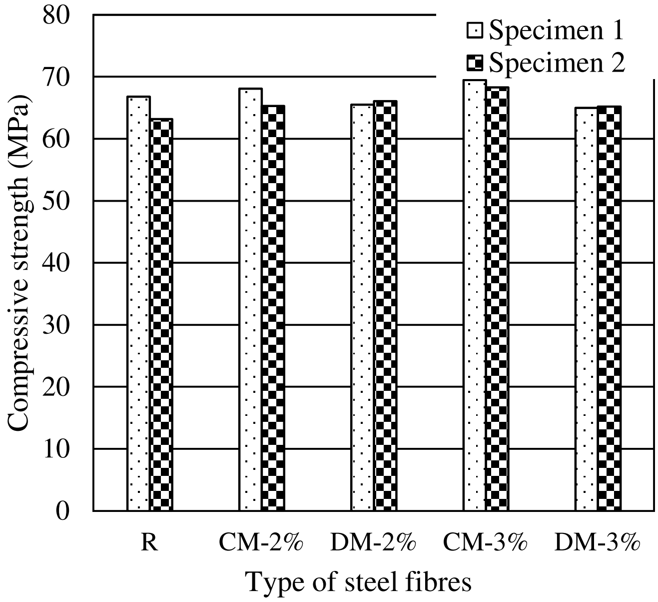


Figure 5: The effect of the type of steel fibres on the compressive strength of HSC.

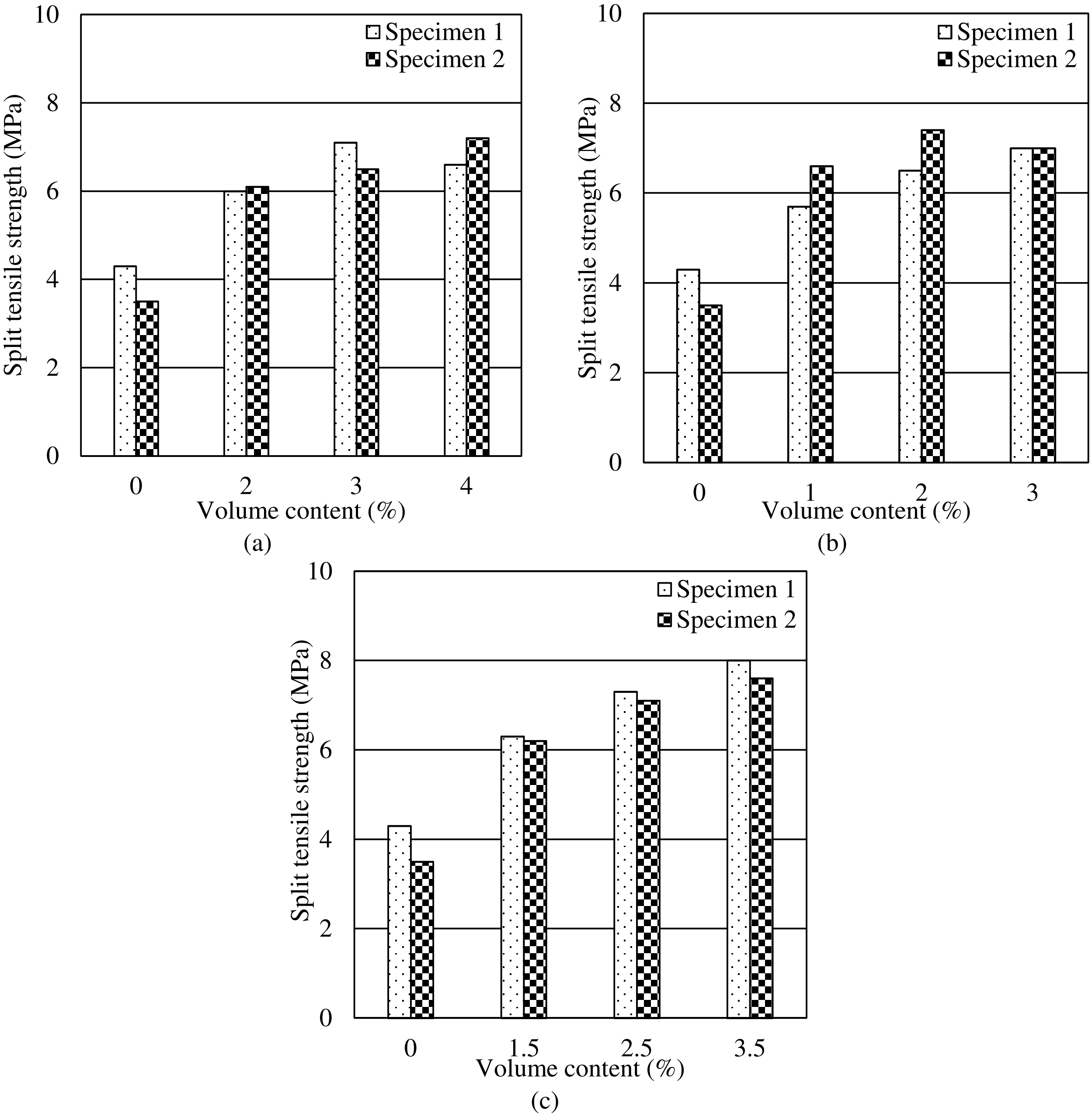


Figure 6: Effect of the volume content of steel fibres on the split tensile strength of HSC: (a) CM, (b) DM and (c) H

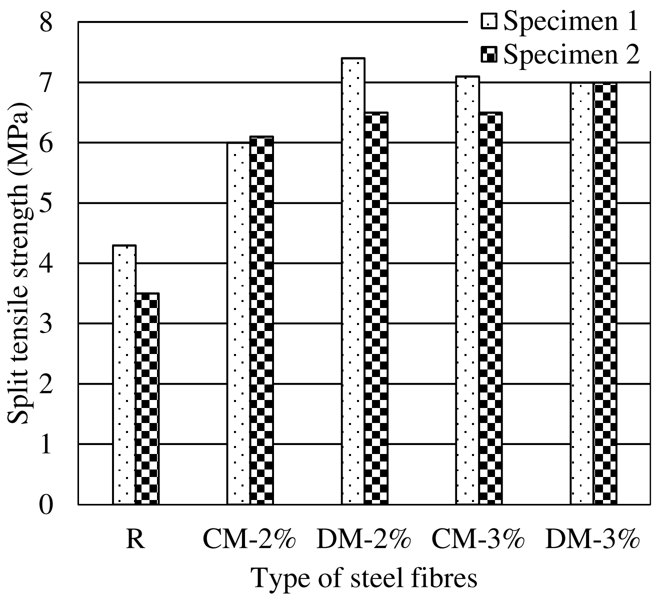


Figure 7: The effect of the aspect ratio of steel fibres on the split tensile strength of HSC.