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Effect of hybrid polypropylene-steel fibres on strength characteristics of UHPFRC

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Abstract. This study intends to produce an ultra-high performance fibre reinforced concrete (UHPFRC) made with hybrid fibres (i.e., steel and polypropylene). Compressive and tensile strength characteristics of the hybrid fibres UHPFRC are considered. A total of 14 fibre-reinforced composites (FRCs) with different fibre contents or types of fibres were prepared and tested in order to determine a suitable hybrid fibre combination. The compressive and tensile strengths of each concrete at 7 days were determined. The results showed that a hybrid mix of micro-polypropylene and steel fibres exhibited good compromising performances and is the ideal reinforcement mixture in a strong, cost-effective UHPFRC. In addition, maximum compressive strength of 167 MPa was achieved for UHPFRC using 1.5% steel fibres blended with 0.5% macro-polypropylene fibres.

Keywords: ultra-high performance fibre reinforced concrete; steel fibre; polypropylene fibre; hybrid fibres; compressive strength; tensile strength

1. Introduction

Ultra-high performance fibre reinforced concrete (UHPFRC) has been used in Europe and North America for sometime, and its application has started to see success in Asia in recent years (Huang *et al.* 2018). UHPFRC is suitable for use where special-purpose concrete is needed for structures (high-rise buildings, slender bridges, arches, anti-seismic elements, etc.) (Hannawi *et al.* 2016, Zhou *et al.* 2018, Qi *et al.* 2019). This innovative concrete is special, with a very high compressive strength exceeding 150 MPa, high stiffness, and excellent durability (Shi *et al.* 2015, Habel *et al.* 2016). Generally, these characteristics are supported by: (1) using a high cement content of approximately 800-1,000 kg/m^3 (Shi *et al.* 2015); (2) incorporating a dosage of quartz powders (such as silica fume, nano silica, etc.) to achieve more durable concrete through pozzolanic reaction and dense solid particle packing (Wille *et al.* 2012, Shi *et al.* 2015); (3) employing an extremely low water-to-binder ratio; (4) increasing the superplasticizer-to-binder ratio; (5) using quartz sand with particle size ranging from 150 to 600 μm; (6) exclusion of coarse aggregate to increase the homogeneity of concrete; and (7) addition of fibres (Shi *et al.* 2015).

The aim of using fibres in concrete is primarily to enhance the concrete's ductility. According to the Association Française de Génie Civil (AFGC; French Association of Civil Engineering), UHPFRC should be designed to achieve at least 8 MPa tensile strength (AFGC, 2013). Huang *et al*. (2018) reported that steel fibres can greatly enhance toughness of concrete cast with 0.2 w/c ratio, especially when 2% fibre by volume of concrete is added. Also, Wille *et al*. (2011) found that increasing the amount of straight steel fibres from 1.5% to 2% increased the uniaxial direct tensile strength of concrete by 12%. This observed improvement in tensile strength is in agreement with results previously obtained by Song and Hwang (2004), who found that flexural strength of UHPFRC increased with the incorporation of fibres. As such, it can be seen that fibres are very useful for the purpose of reducing concrete brittleness. This ability to improve concrete's strength and moderate its brittleness by incorporating fibres and high strength concrete makes fibre-reinforced concrete (FRC) and UHPFRC the most highly regarded advancement in cement composite technology (Mehta and Monteiro 2006, Wille *et al.* 2014, Yu *et al.* 2014a).

The behaviour of fibre-reinforced composites under uniaxial tension is usually described by the tensile stress-elongation curve shown in Fig. 1 (Naaman and Reinhardt 2006, Park *et al.* 2012, Wille *et al.* 2014). Generally, FRCs are classified based on their tensile response after first cracking, which includes strain-hardening and strain-softening.

For strain-hardening composites (Fig. 1(a)), the peak in tensile stress at the end of the linear stress-strain relationship is defined as the first cracking stress and strain,

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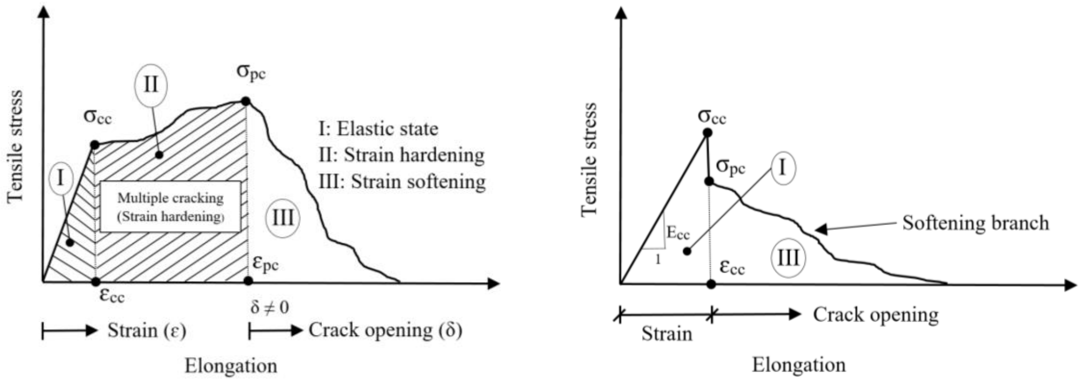

(a) Strain-hardening FRC (b) Strain-softening FRC

Fig. 1 Tensile behaviour of strain-hardening and strain-softening FRC (Naaman and Reinhardt 2006, Park *et al.* 2012, Wille *et al.* 2014)

denoted by σ_{cc} and ε_{cc}, whereas the stress and strain where softening starts to occur is characterized by σ_{pc} and ε_{pc}. The FRC material is considered as strain-hardening if its maximum post-cracking strength (σ_{pc}) is higher than the first-cracking stress (σ_{cc}) (Wille *et al.* 2011, Wille *et al.* 2014). The energy absorption capacity of a composite (g) is represented by the shaded area under the curve prior to softening (Wille *et al.* 2014). The region in zone II shows the additional energy absorption due to multiple cracking, which occurs up to the post-cracking coordinate (σ_{pc}, ε_{pc}).

Fig. 1(b) shows the typical behaviour of strain-softening FRC. Similar to the response curve of strain-hardening material, strain-softening FRC shows a linear stress-strain relationship with slope E_{cc} up to the first cracking point (zone I). However, immediately after the first cracking, the composite shows a softening response and crack localization (zone III).

Polypropylene (PP) fibres are a type of synthetic plastic fibres that is finding increasing construction material nowadays. PP fibres play a major role in controlling the plastic shrinkage cracking which occurs during the plastic state of concrete (Banthia and Gupta 2006). Many researchers are beginning to appreciate PP fibres' ability to provide some toughening and impact resistance (Toutanji *et al.* 1998, Song *et al.* 2005, Nili and Afroughsabet 2010). A new and improved form from earlier versions of steel fibre-reinforced concrete is "hybrid fibre reinforced concrete", created by incorporating steel and PP composite fibres into concrete. This hybrid reinforcing mechanism can be explained through the fibre modulus. While the inclusion of steel fibres increases the ultimate strength and impact resistance of the composite, the inclusion of flexible synthetic fibres increases the strain capacity and toughness (Qian and Stroeven 2000, Pakravan *et al.* 2017). Moreover, the hybrid fibres are effectively mobilized to resist cracks at different strains during loading (Pereira *et al.* 2012). In addition to the attractive engineering properties (Yao *et al.* 2003, Ganesan *et al.* 2017, Afroughsabet *et al.* 2018), hybrid fibre reinforced concrete offers construction cost savings by reducing the amount of steel fibres in the concrete (Pakravan *et al.* 2017).

Although research have been conducted on the effects which steel and synthetic fibres have on the properties of

Table 1 Properties of fibres

Properties	Steel fibres		Polypropylene fibres	
	S6	S13	PP	mP
Fibre length (l_f, mm)	6	13	24	12
Fibre diameter (d_f, mm)	0.16	0.2	0.72	0.015-0.045
Tensile strength (MPa)	2,750	2,750	550	340
Modulus of elasticity (GPa)	200	200	8.2	3.5
Specific gravity	7.85	7.85	0.90-0.91	0.89-0.93
Price of materials (USD/kg)	6.70	6.10	9.70	3.60

conventional concrete, reports on the hybridization of these fibres for UHPFRC are limited. Since UHPFRC is required to withstand not only tensile strength but also the compressive strength, this duality creates a challenge when synthetic fibres are mixed into UHPFRC.Thus, this study aimed to produce UHPFRC made with hybrid fibres to study their strength properties. The criteria for strength for the UHPFRC produced in this study were taken from the AFGC's recommended minimum compressive strength of 150 MPa and minimum tensile strength of 8 MPa. There were two types of hybrid fibre combinations used in this investigation: steel/macro-PP and steel/micro-PP. All-steel and all-synthetic FRCs were also prepared for strength comparison.

2. Experimental details

2.1 Materials used for concrete preparation

In this study, UHPFRC was designed for self-compacting concrete applications. The concrete precursor used was a premixed concrete powder commercially available from the Siam Cement Group (SCG) company, comprising of cement, reactive powder, and micro silica sand, with a specific gravity of 2.99. A water: binder ratio of 0.11 was used for all concrete mixtures. A polycarboxylate superplasticizer, at 1.15% weight of binder, was also used to give a flowability to concretes made with

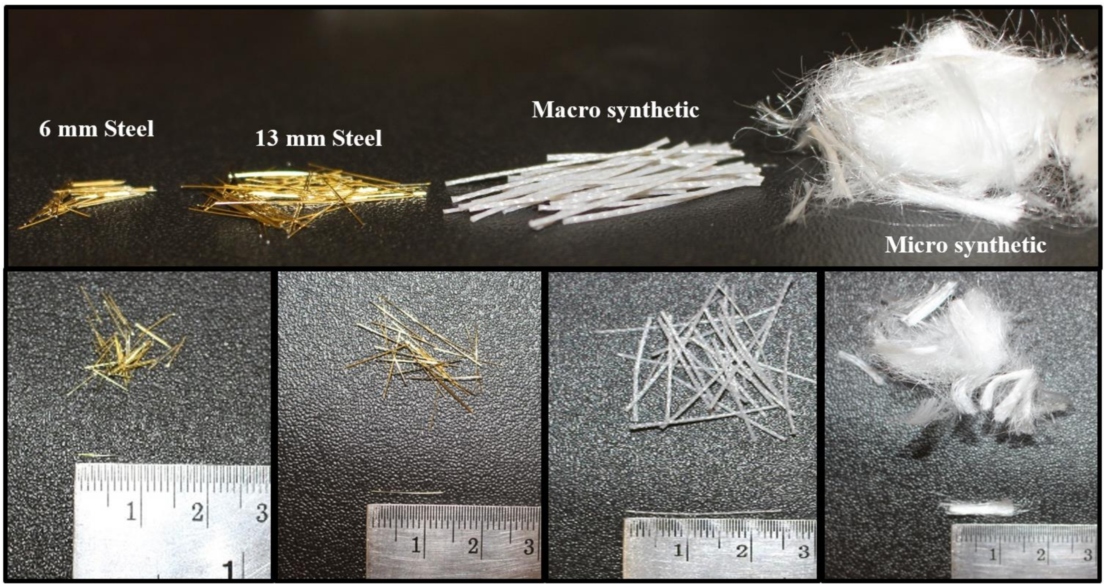

Fig. 2 Steel and synthetic fibres used for FRC preparation

Table 2 Volume fraction of fibres

Series	Mixture	Fibre content (% by volume of concrete)			
		S6	S13	PP	mP
I	CON	-	-	-	-
II	2S6	2%	-	-	-
	2S13	-	2%	-	-
III	1PP	-	-	1%	-
	2PP	-	-	2%	-
	0.5mP	-	-	-	0.5%
	1mP	-	-	-	1%
	2mP	-	-	-	2%
IV	1.5S6+0.5PP	1.5%	-	0.5%	-
	1S6+1PP	1%	-	1%	-
	0.5S6+1.5PP	0.5%	-	1.5%	-
V	2S13+0.1mP	-	2%	-	0.1%
	2S13+0.2mP	-	2%	-	0.2%
	2S13+0.3mP	-	2%	-	0.3%

extremely low water content.

Fibres used for making the UHPFRC were: (1) brass coated steel fibres, and (2) synthetic fibres. Fibre physical properties are listed in Table 1. Steel fibres were straight, smooth fibres made from cold-drawn wire, as shown in Fig. 2. They can be classified into two groups according to their aspect ratio (l_f/d_f): (1) S6 fibres with 6 mm of length and 0.16 mm of diameter (l_f/d_f=37.5), and (2) S13 fibres with 13 mm of length and 0.20 mm of diameter (l_f/d_f=65).

Also, two groups of synthetic fibres were used to produce UHPFRC. The first type was macro-polypropylene fibres (PP) with a tensile strength of 550 MPa. The other type was micro-polypropylene fibres (mP) with diameters ranging from 15 to 45 µm. As can be seen from Table 1, polypropylene fibres are lower in density (lower specific gravity) than steel fibres and have a lower tensile strength, about 340-550 MPa as compared to 2,750 MPa. The details of fibre volume fraction used for manufacturing fibre-reinforced composites are presented in Table 2.

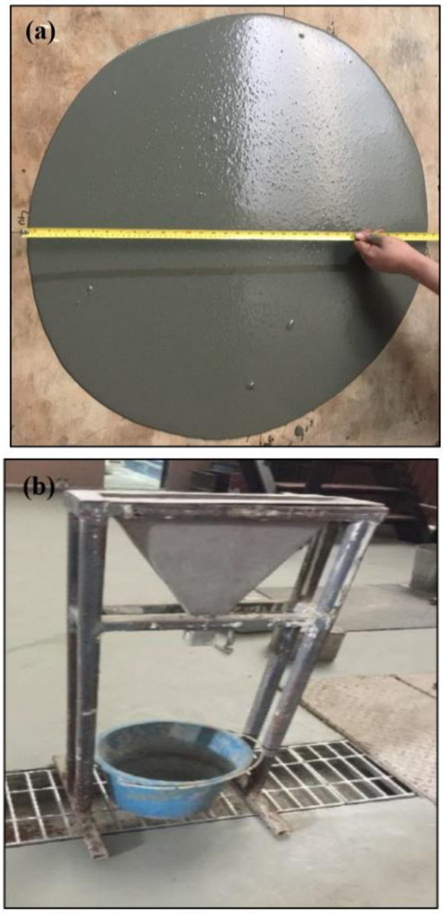

Fig. 3 Measurement of workability of concrete: (a) Slump flow and (b) V-funnel viscosity

2.2 Concrete mixtures and samples preparation

Concrete mixing was done with slight modifications of

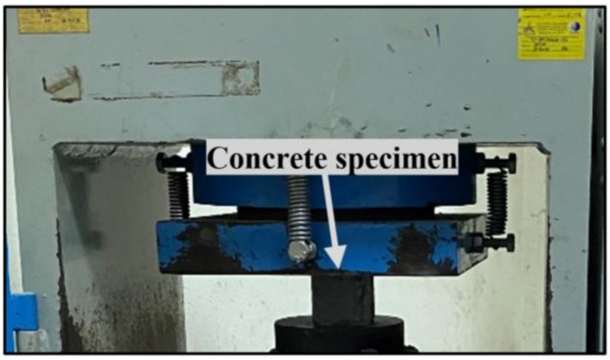

Fig. 4 Testing of compressive strength

ASTM C305 (ASTM 2014). The cement, reactive powder, and micro silica sand were first premixed. Then, water and superplasticizer were added into the premixed powder and mixed for 3 minutes. Finally, fibres were added and mixed for the last 5 minutes. As shown in Fig. 3, concrete slump was measured in accordance with ASTM C1611 (ASTM 2014) before concretes were casted into moulds. Concrete viscosity was evaluated via the *V*-funnel test, following the EFNARC testing method (EFNARC 2005), to ensure there were no segregation for any mixtures. After casting, concrete samples were covered with plastic sheets to prevent plastic-shrinkage cracking, which is caused by the loss of surface moisture by evaporation (Banthia *et al.* 2006). Samples were demoulded after 24 hours before being cured in a 90°C water bath for 72 hours. Finally, concrete was continuously immersed in water (23-25°C) for 72 hours until the age of 7 days.

Concrete mixtures were divided into five series as outlined in Table 2; note that mix proportions of all cases were the same except for type and volume fraction of fibres. Series I was concrete without fibres. Series II were specimens with 2% of steel fibres, which are normally used in UHPFRC. Series III were specimens with synthetic fibres investigated for their strength properties. Series IV and V were designed based on the experimental results of Series I-III; their fibre contents were designed to examine for the influences of hybrid steel/macro-PP and steel/micro-PP, respectively.

2.3 Strengths of concrete

UHPFRC were characterized by compression and tension test results. As shown in Fig. 4, compression tests were carried out on 50 mm cubic specimens according to ASTM C109 (ASTM 2016). Tensile tests were carried out under a direct tension test method, following the experimental work of Park *et al*. (2012). Tensile tests were conducted on dogbone-shaped samples with a cross section of 70 mm×70 mm as can be seen in Fig. 5. The samples were subjected to a controlled elongation at a speed of 0.4 mm/min using a Linear Variable Differential Transformer (LVDT; Fig. 5). Tensile testing measured the behaviour of FRC under uniaxial tension, which is helpful in determining the elastic and post-elastic deformations of concrete upon loading. In both cases, the results were obtained from three replications.

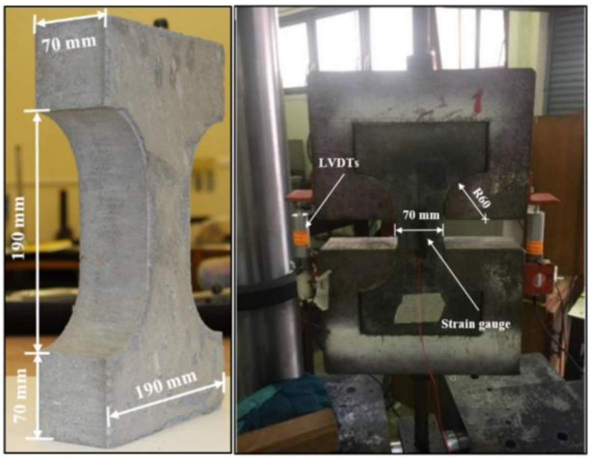

Fig. 5 A dogbone-shaped specimen and experimental set-up

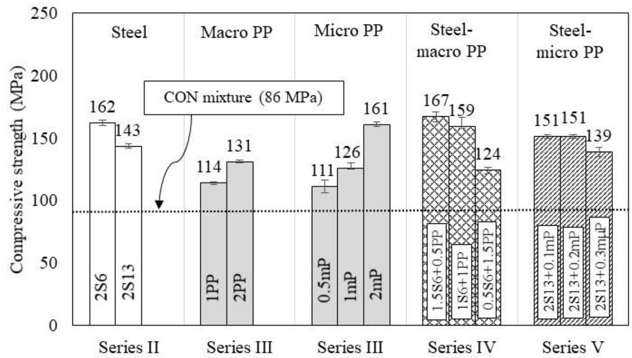

Fig. 6 Compressive strengths of composites made with different types of fibres

3. Results and discussion

It was found that there were no obvious differences for the workability of concretes having either different amounts of fibres or different types of fibres. The concretes showed a very narrow range of slump flows, between 855 to 901 mm. *V*-funnel viscosity test results ranged between 11 to 16 s, falling into EFNARC class VF2 which has a specific V-funnel test time range of 9 to 25 s (EFNARC, 2005). EFNARC also states that higher *V*-funnel flow times indicate a concrete's higher resistance to segregation.

Fig. 6 shows the compressive strengths, and Table 3 the uniaxial tension test results, of the composites made with different types of fibres in this study. As seen from Fig. 6, 2S6 mixture provides higher compressive strength than other single-fibre mixtures. The results of specimens in Series III show that the compressive strength increases with the increase in synthetic fibre volume, and mixtures with micro-PP fibre give higher compressive strength than that of macro-PP fibre. Regarding the hybrid steel-macro fibres mixtures, although the total fibre volume was kept constant at 2%, the compressive strength decreased with the decrease in steel fibre volume. In addition, based on the results of Series V, the addition of 0.3% mP to the hybrid mixture with 2% S13 decreased the compressive strength. The results will be also discussed in sections 3.1 to 3.4.

It should be emphasized again that, according to AFGC code (AFGC, 2013), FRC mixtures are considered as

Table 3 Tensile properties of concrete

Series	Mixture	Tension test results			UHPFRC	Additional cost from series I (USD/m^3)	Relative cost with 2S6 mixture (%)
		σ_{cc} (MPa)	σ_{pc} (MPa)	ε_{pc} (%)			
I	CON	3.8±0.1	-	-	-	0	-
II	2S6	8.3±0.1	7.7±0.2	0.32	Yes	1,140	0
	2S13	7.8±1.0	6.9±0.2	0.14	-	1,036	-9
III	1PP	4.1±0.1	3.2±0.1	0.32	-	96	-92
	2PP	4.5±0.2	1.6±0.1	0.37	-	192	-83
	0.5mP	5.8±0.3	0.2±0.1	0.59	-	18	-98
	1mP	6.0±0.6	1.2±0.2	0.63	-	36	-97
	2mP	4.2±0.2	0.9±0.3	0.63	-	72	-94
IV	1.5S6+0.5PP	8.2±0.4	6.4±0.4	0.43	Yes	903	-21
	1S6+1PP	6.6±0.5	4.0±0.4	0.42	-	666	-42
	0.5S6+1.5PP	6.9±0.5	5.2±0.2	0.91	-	429	-62
V	2S13+0.1mP	7.5±0.1	8.1±0.3	0.60	Yes	1,040	-9
	2S13+0.2mP	7.6±0.1	8.6±0.2	0.52	Yes	1,043	-8
	2S13+0.3mP	6.9±0.2	7.4±0.2	0.46	-	1,047	-8

Note: Measured data are shown as the main ± standard error derived from three replications. Significance of any differences in the means was evaluated by analysis of variance (ANOVA) or Kruskal-Wallis test (KWT), accepting significance at the $p < 0.05$ level.

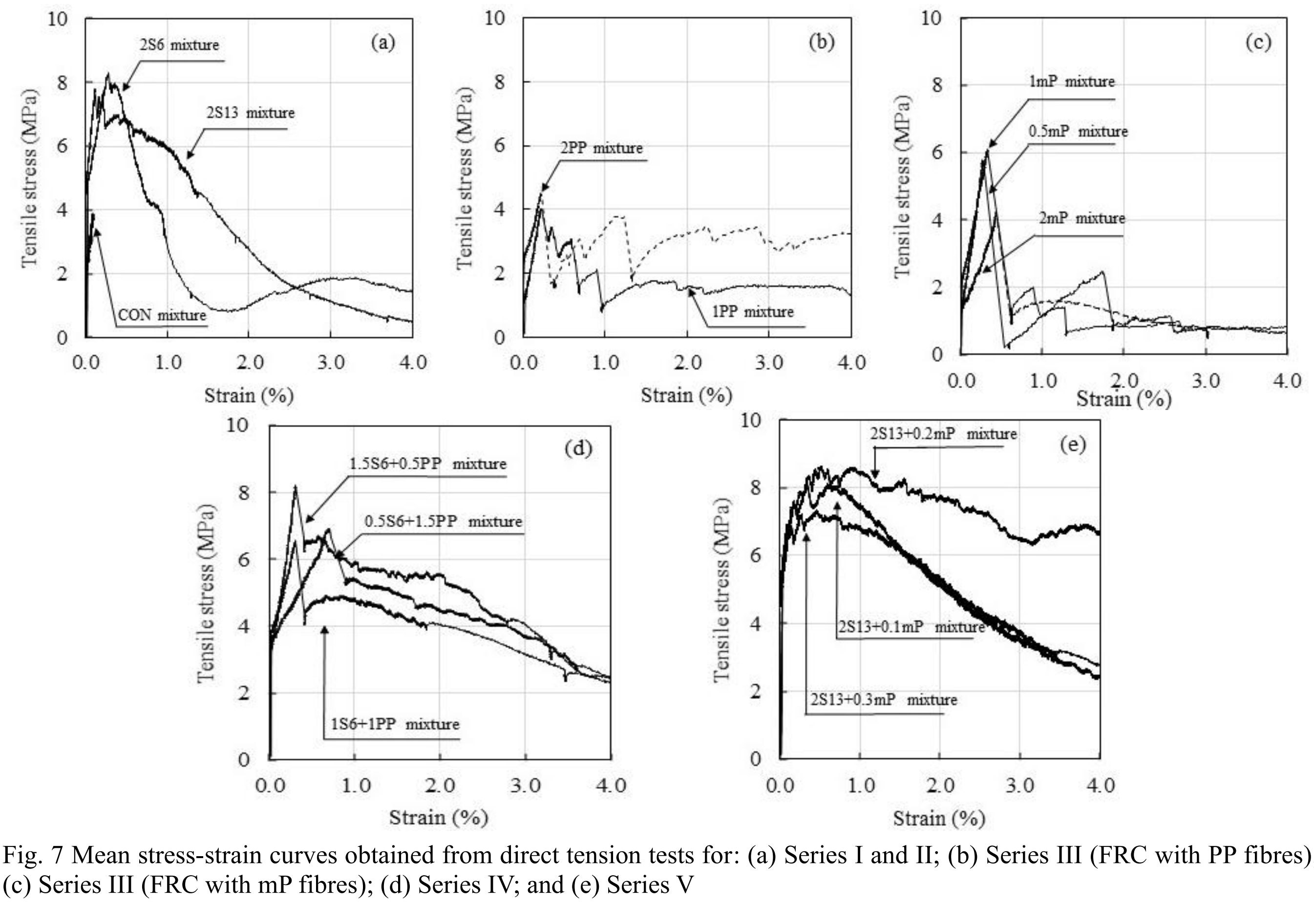

Fig. 7 Mean stress-strain curves obtained from direct tension tests for: (a) Series I and II; (b) Series III (FRC with PP fibres); (c) Series III (FRC with mP fibres); (d) Series IV; and (e) Series V

UHPFRC if their compressive strength are >150 MPa and tensile strength >8 MPa. Table 3 also shows the possible cost savings for various fibre-reinforced concretes when compared to conventional UHPFRC (2S6 mixture).

Fig. 7 shows the tensile stress-strain curves of the prepared concrete and different FRCs. The shape of their stress-strain relationship is helpful in determining failure phenomena of each composite under tensile load. The ductility of the composites is expressed in terms of the energy absorption capacity (g), which is the area under the tensile stress-strain relationship up to the stress prior to tension softening (Figs. 8 and 9).

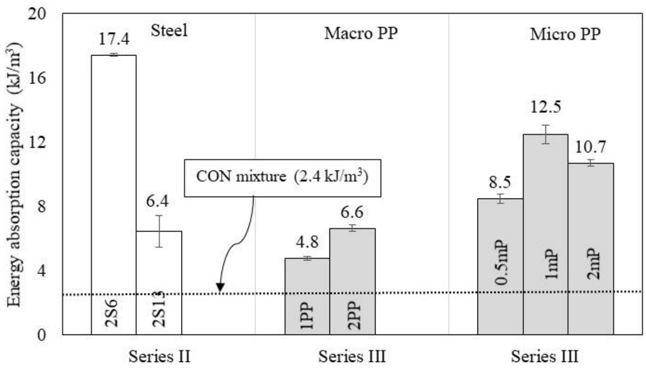

Fig. 8 Energy absorption capacity of single FRCs

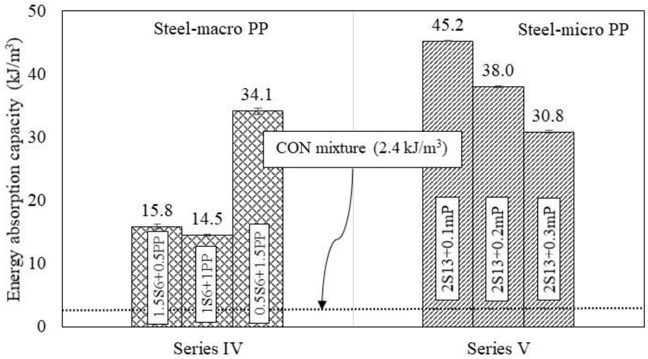

Fig. 9 Energy absorption capacity of hybrid FRCs

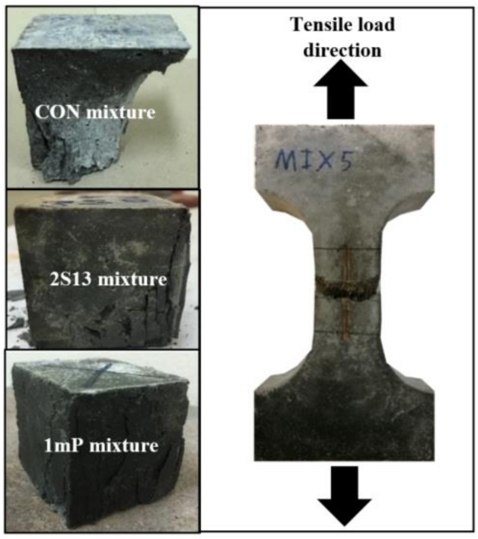

Fig. 10 Failure modes in concrete under stress

The experimental results have shown that fibres help to increase the strengths and improve the ductility of concrete. Under compression, failure modes vary with the presence of fibres, unlike under uniaxial tension where the direction of the fracture plane is always transverse to the loading direction as shown in Fig. 10. Unlike plain concrete, FRC does not fail suddenly after the growth of the first crack. FRC continues to carry considerable loads even after first cracking, and additional stress is required to break the fibre-reinforced composite through a process that involves stress transfer between the fibre and the matrix, which mainly depends on the pull-out resistance of fibres and matrix-fibre bond strength (Mehta *et al.* 2006).

In the post-cracking stage, where a large strain capacity is present, fibres play an important role in controlling the growth of cracks in concrete (Hannawi *et al.* 2016). The rapidly bridging of cracks can lead to failure of the concrete. The inclusion of fibres delays concrete failure by arresting crack propagation when the concrete is under load (Shaikh and Taweel 2015, Afroughsabet *et al.* 2019). This also helps to sustain the concrete's available load-carrying area even at high stress levels (Li *et al.* 2018). As a result, higher strengths and ductility are observed in FRCs (Mehta *et al.* 2006, Sharma and Bansal 2019).

As described earlier in this section, the expression for fibre enhancement behaviour under stress is known by term "general concept". The mechanism of multiple fibre UHPFRC systems are complex, especially when synthetic fibres are presented. In this study, there were many different types of fibres used, including steel fibres, polypropylene fibres, and hybrid fibres, each of which have various effects on the performance of FRCs according to their volume fractions and characteristics (e.g., size, shape, length and stiffness). The following is a summary of these investigation's findings:

3.1 FRC made with steel fibres

As expected, unreinforced concretes showed brittle behaviour, with a compressive strength of 86 MPa. Usually, when a UHPFRC reaches its final lateral strain under compression, the sample will fail suddenly in an explosive manner (Hassan *et al.* 2012). Also, the unreinforced concrete broke easily under further tensile loading immediately after first cracking, seen in Fig. 7(a). It should be noted that the direct tensile strength of the CON mixture was 3.8 MPa, which was approximately 4.4% of its compressive strength; however, this is about 7-11% of the compressive strength of normal concrete (Mehta *et al.* 2006).

The incorporation of steel fibres gives concrete a ductile failure mode, S6 and S13 fibres, into the mixture. Steel fibre-reinforced composites remained in a tough state after compression failure. Despite the FRC no longer being able to withstand the applied stress, the concrete sample remained intact (Fig. 10). Fig. 7(a) shows the stress-strain curves for FRC containing steel fibres. The composites exhibited a strain-softening behaviour in tension. After peak stress, stress values started to decrease as the fibres began to pull out from the cement-based matrix (Yao *et al.* 2003, Hassan *et al.* 2012). Compared to the CON mixture, FRC with steel fibres had a tensile strength which was about 105-118% higher. Also, the increase in energy absorption capacity was about 6.3 and 3.5 times for the 2S6 and 2S13 mixtures, respectively. Steel fibre reinforced concrete also saw an improvement in compressive strength over unreinforced concrete. Specifically, the mixture containing 2% S6 fibre exhibited a compression strength that was approximately 88% higher than that of CON concrete. Due to steel's high elastic modulus and stiffness, steel fibres increase the strengths and strain capacity of the FRCs by reinforcing mechanisms previously discussed. In addition, it

Table 4 Compressive strength of different FRC with volume fraction of fibre (V_f)=2%

Reference	Steel fibre			Compressive strength (MPa)
	d_f (mm)	l_f (mm)	V_f (%)	
Yoo *et al*. (2015)	0.2	13	2.0	152.5
Yu *et al.* (2014b)	0.2	13	2.0	139.3
	0.16	6	2.0	120.8
Yoo *et al*. (2014b)	0.2	13	2.0	201.8

should be noted that up to 200 MPa compressive strength concrete can be produced with steel fibres as seen from Table 4.

In the current study, a 2% S6 and concrete mixture was shown to have compressive and tensile strengths of 162 MPa and 8.3 MPa, respectively, which meet the requirements of AFGC code for UHPFRC. However, the 2% S13 and concrete mixture tested did not meet AFGC's UHPFRC specifications. Although Le Hoang and Fehling (2017) suggested that fibres with higher slenderness (S13 fibre, l_f/d_f=65) are more effective for fibre-to-matrix bonding, the use of fibres with high aspect ratio usually results in poor fibre dispersion, which may cause problems which lead to the deterioration of compressive strength (Yoo *et al*. 2014a, Midhun *et al.* 2018).

3.2 FRC made with synthetic fibres

Test results on synthetic fibre FRC showed improved compression strengths over unreinforced CON, as shown in Fig. 6. Compressive strengths of 86, 114, and 131 MPa were obtained for the mixtures made with 0%, 1% and 2% of macro-PP fibres, respectively. Although concrete compressive strength improved by the inclusion of macro-PP fibres, the increase in tensile strength was small. Among the single-fibre reinforced composites, samples made with macro-PP fibres exhibited the lowest toughness, as can be seen in Fig. 8.

The FRCs with macro-PP fibres that were tested did not have enough bonding strength between the matrix and macro synthetic fibres to resist the bond stress taken by the matrix. Hannawi *et al*. (2016) have also confirmed that low fibre-to-matrix bonding is one of the disadvantages of composites made with synthetic fibres. Based on observations of the microstructure, they found more air bubbles in the fibre-matrix interfacial zone than compared to composites made with steel fibres. This may explain why only marginal improvements in tensile strength and ductility were observed for the plastic fibres FRCs, especially the macro-PP fibre-reinforced composite.

Similar behaviour was observed when micro-PP fibres were used. The inclusion of micro-PP fibres had a large effect on concrete compressive strength, with the 2mP concrete showing a compressive strength of 161 MPa (Fig. 6), which exceeds the minimum required strength to be classified as UHPFRC; unfortunately, the same composite's tensile strength was much lower than the required 8 MPa (Table 3). Overall, the addition of 0.5%, 1% and 2% micro-PP fibre by volume of concrete increased the tensile strength by approximately 53%, 58%, and 11%, respectively. In addition, in all cases, the toughness was 3.5 to 4.2 times that of the CON mixture.

Although the synthetic-fibre reinforced composites exhibited a "strain-softening" behaviour as seen in Figs. 7(b) and 7(c), they gave marginal toughness gains when compared to steel-fibre reinforced composites. According to Wille *et al*. (2014), this type of tensile stress-strain curve is classified as the lowest class of FRC. In addition, it should be noted that the tensile strength of the synthetic-fibre reinforced composites was still low, even in the presence of high fibre volume.

Results indicate that micro-PP fibre FRC's compressive strength becomes higher and tensile strength lower as the volume fraction of micro-PP fibre increases. The improvement in compressive strength may have been due to the micro-aggregate effect contribution of the micro-PP fibres, similar to effects previously observed in the case of basalt fibres added to composite cement (Punurai *et al.* 2018). As a result, the interfacial bonding strength between micro fibres and the matrix were too strong, thus making the fibres break before the stress is transferred to the matrix (Mehta *et al.* 2006). In addition, it is believed that the stronger the fibre-matrix bond, the higher the number of fibre strands will remain non-active (Robins *et al.* 2002; Mehta *et al.* 2006). These reasons can explain why a lower micro-PP fibre volume (< 2% by volume) is more effective in increasing the tensile strength of FRC.

3.3 Hybrid FRC made with steel/macro-PP fibres

Test results showed that steel/macro-PP fibres helped improve concrete strengths. In comparison to plain concrete, FRC made with steel/macro-PP fibres showed 44-94% improvement in compressive strength. Furthermore, the tensile strength of hybrid FRC varied from 6.6 to 8.2 MPa, which was about 74-116% higher that of plain concrete. However, increasing macro-PP fibre content was found to decrease compressive strength of the hybrid FRC made with steel/macro-PP fibres. It should be noted that maximum compressive strength was exhibited at 0.5% macro-PP fibres. The strength criteria for UHPFRC classification was successfully achieved by this mixture (1.5S6+0.5PP mixture). Moreover, the cost to produce this steel/macro-PP fibre hybrid UHPFRC is estimated to be 21% lower than the cost to produce the purely steel-reinforced 2S6 mixture.

For this series of composites, steel and macro-plastic fibres played different roles in increasing the strength and toughness of the composites. The interchanging effects of additional steel and macro-plastic fibres give rise to an optimal combination of the two in improving composite strength, up to and beyond UHPFRC strength specifications. Based on the existing knowledge of Robins *et al*. (2002), and Banthia and Gupta (2004), it is assumed that the improvement in bonding strengths between macro-PP fibres and the cementitious matrix is attributed to the strengthening of the matrix by the steel fibres. Therefore, the longer macro-PP fibres are able to effectively bridge over macro cracks, thus keeping crack widths in the post-cracking period small to withstand considerable stress. Unfortunately, there is a trade-off between energy

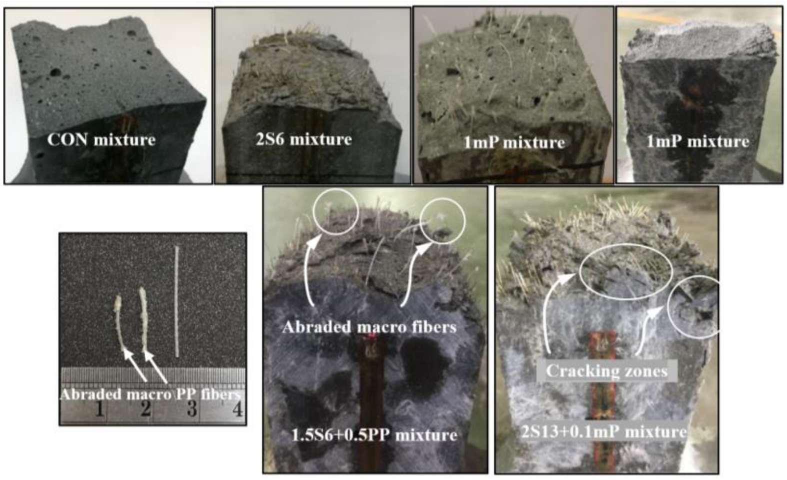

Fig. 11 Sample failure under uniaxial tension

absorption capacity and composite strength when adjusting the composition of steel/macro-PP hybrid composites. Low steel fibre contents (<1.5%) are required to create high energy-absorbing composites, where strength is low. The trade-off between strength and toughness of the composite was determined to be the reason for this behaviour (Naaman *et al.* 2006).

The tension stress-strain curve of the steel/macro-PP fibres hybrid FRC is presented in Fig. 7(d). It can be seen that the slope of the steel/macro-PP hybrid FRC stress-strain curve drops suddenly to a new value at the point of maximum applied stress. In this case, some of the bridging fibres may have ruptured instead of being pulled out of the matrix. Although the tensile strength was improved by the inclusion of steel/macro-PP fibres in the mix, the post-cracking strength of the composite was lower than its cracking strength ($\sigma_{pc}<\sigma_{cc}$). Therefore, these hybrid FRC concretes were classified as strain-softening composites, similar to the case of steel-fibre reinforced FRC (series II). Also of interest is the fact that the outer surface of the macro-PP fibres were abraded during the tension test as can be seen in Fig. 11. This indicated that pull-out hardening behaviour had occurred (Kabele 2007, Di Maida *et al.* 2015). In addition, it was noticed that the abrasion effect was more pronounced with the hybrid FRC than with the single fibre composite. This clearly shows that the presence of steel fibres in the composite was effective in improving the pull-out resistance of the macro-PP fibres.

3.4 Hybrid FRC made with steel/micro-PP fibres

In this study, micro-PP fibres were added to steel-fibre reinforced concrete in small amounts. Compared to the CON mixture, the inclusion of both S13 and micro-PP fibres resulted in an increase of tensile strength by about 95-126%. Under AFGC's requirements, the increased strength of steel/micro-PP fibres hybrid FRC met the requirements of UHPFRC classification. Optimum micro-PP fibre volume fraction was found to be about 0.1-0.2%. Specifically, the 2S13+0.2mP mixture achieved compressive and tensile strengths of 151 MPa and 8.6 MPa, respectively. When micro-PP fibre content of the hybrid FRC was increased to beyond 0.2%, the improvement in compressive and tensile strengths began to reduce. It is possible to believe that too much fibre content may cause poor fibre distribution, which reduces the FRC's ability to withstand external stresses (Yoo *et al.* 2014a).

As already noted, FRC made with a high volume of micro plastic fibres alone (series III) does not provide high tensile strength. Although micro-PP fibre FRC performed well in terms of its compressive strength, its tensile strength was lower than when compared to steel/micro-PP hybrid mixtures. On the other hand, steel fibre FRCs, represented by the 2S13 mixture, also did not meet compressive strength requirements for UHPFRC classification. In these tests, it was the steel/micro-PP hybrid FRCs that gave strength results adequate for UHPFRC classification. The high tensile strength of steel/micro-PP hybrid mixtures is due to the presence of stiffer and stronger fibres, which gives the system the ability to resist the growth of cracks (Park *et al.* 2014).

The stress-strain curves for hybrid FRC made with steel/micro-PP fibres are shown in Fig. 7(e). Special attention was given to the strain-hardening behaviour of the composites. The hybrid FRCs made from steel/micro-PP fibres showed strain-capacities (ε_{pc}) ranging from 0.46 to 0.60%. They were also found to have developed maximum post-cracking strengths between 7.4 and 8.6 MPa. Since the steel fibres embedded in the composite act as a barrier wall for crack arresting, more energy is needed to extend the cracks. Through this process, crack propagation is slowed down. In addition, the shape of the stress-strain curve in steel/micro-PP hybrid FRC shows that the composite is free from the risks of fibre slipping or fracturing. Besides providing an improved ductility over other UHPFRC, the hybrid FRCs were estimated to have a material cost that is approximately 8% lower than normal UHPFRC made from 2S6 steel fibres.

There are applications in which conventional concrete is just not suitable, and UHPFRC is needed for its superior properties instead. UHPFRC can be used for special construction purposes, and it is especially suitable for slender composite and precast concrete applications due to its unique properties (Kim *et al.* 2011, Li *et al.* 2019). This study has demonstrated that a low-cost UHPFRC can be produced with synthetic fibres. Table 3 shows the benefit of using PP fibres for reducing the cost of FRC production. When macro-PP fibres are used as a partial replacement for steel fibres, they represent significant cost savings. A 21% savings in fibre cost is achievable through the use of 0.5% macro-PP fibres, and yet there is practically no strength differences between 1.5S6+0.5mP and 2S6 mixtures according to test results. Although replacing steel fibre content with synthetic fibres is the effective way to bring down material costs, unfortunately, UHPFRC qualities cannot be produced by polypropylene fibres alone.

5. Conclusions

The primary objective of this study was to produce UHPFRC by using multiple fibre systems. AFGC requires a concrete to exhibit a compressive strength >150 MPa and a tensile strength >8 MPa to be classified as an UHPFRC. Based on the experimental results, the following is concluded.

1. The mixtures 2S6, 1.5S6+0.5mP, 2S13+0.1mP, and 2S13+0.2mP all classify as UHPFRC. All of these mixtures showed compressive strength improvements over their base concrete, which had a compressive strength of 86 MPa.
2. FRCs made from steel fibres alone depended on the fibre's aspect ratio to satisfy minimum UHPFRC requirements; the higher the compressive strength, the more slender the steel fibres need to be.
3. FRCs made with plastic fibres alone had insufficient fibre-matrix interfacial bonding, making these FRCs too weak with fibres slipping out at low stress levels and causing loss of most of the fibre's crack bridging ability. If plastic fibres are too strong, the fibres may break and not contribute to the dissipation of energy in the system.
4. In view of the results obtained from the hybrid UHPFRC made with steel and macro-PP fibres, the synthetic fibres play only a minor role in contributing to strength enhancement. Macro-PP fibres were found to provide the reinforcing mechanisms at higher loads only when steel fibres are added to the mixture.
5. In the case of steel and micro-PP fibre hybrid UHPFRC, the micro-PP fibres increases the strength of the matrix, but the steel fibres are more effective for halting crack propagation in the system. In addition, the hybrid FRCs made with steel and micro-PP fibres classify as strain-hardening materials. In consideration of strength properties and the cost-savings effects of minimizing fibre use, it can be concluded that the optimum micro-PP fibres content for hybrid UHPFRC is around 0.1% by volume.

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References

AFGC (2013), Recommendation: Ultra High Performance Fibre-Reinforced Concretes, French Association of Civl Engineering Structure Design, and Control, Bagneux, France.

Afroughsabet, V., Biolzi, L. and Monteiro, P.J. (2018), "The effect of steel and polypropylene fibers on the chloride diffusivity and drying shrinkage of high-strength concrete", *Compos. Part B. Eng.*, **139**, 84-96. https://doi.org/10.1016/j.compositesb.2017.11.047.

Afroughsabet, V., Geng, G., Lin, A., Biolzi, L., Ostertag, C.P. and Monteiro, P.J. (2019), "The influence of expansive cement on the mechanical, physical, and microstructural properties of hybrid-fiber-reinforced concrete", *Cement Concrete Compos.*, **96**, 21-32. https://doi.org/10.1016/j.cemconcomp.2018.11.012.

ASTM C109 (2016), Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens), American Society for Testing and Material, West Conshohocken, PA, USA.

ASTM C1611 (2014), Standard Test Method for Slump Flow of Self-Consolidating Concrete, American Society for Testing and Material, West Conshohocken, PA, USA.

ASTM C305 (2014), Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency, American Society for Testing and Material, West Conshohocken, PA, USA.

Banthia, N. and Gupta, R. (2004), "Hybrid fiber reinforced concrete (HyFRC): fiber synergy in high strength matrices", *Mater. Struct.*, **37**(10), 707-716. https://doi.org/10.1007/BF02480516.

Banthia, N. and Gupta, R. (2006), "Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete", *Cement Concrete Res.*, **36**(7), 1263-1267. https://doi.org/10.1016/j.cemconres.2006.01.010.

Di Maida, P., Radi, E., Sciancalepore, C. and Bondioli, F. (2015), "Pullout behavior of polypropylene macro-synthetic fibers treated with nano-silica", *Constr. Build. Mater.*, **82**, 39-44. https://doi.org/10.1016/j.conbuildmat.2015.02.047.

EFNARC (2005), The European Guidelines for Self-Compacting Concrete Specification, Production and Use, Surrey, UK.

Ganesan, N., Sahana, R. and Indira, P.V. (2017), "Effect of hybrid fibers on tension stiffening of reinforced geopolymer concrete", *Adv. Concrete Constr.*, **5**(1), 75. https://doi.org/10.12989/acc.2017.5.1.75.

Habel, K., Viviani, M., Denarié, E. and Brühwiler, E. (2006), "Development of the mechanical properties of an ultra-high performance fiber reinforced concrete (UHPFRC)", *Cement Concrete Res.*, **36**(7), 1362-1370. https://doi.org/10.1016/j.cemconres.2006.03.009.

Hannawi, K., Bian, H., Prince-Agbodjan, W. and Raghavan, B. (2016), "Effect of different types of fibers on the microstructure and the mechanical behavior of ultra-high performance fiber-reinforced concretes", *Compos. Part B. Eng.*, **86**, 214-220. https://doi.org/10.1016/j.compositesb.2015.09.059.

Hassan, A.M.T., Jones, S.W. and Mahmud, G.H. (2012), "Experimental test methods to determine the uniaxial tensile and compressive behaviour of ultra high performance fibre reinforced concrete (UHPFRC)", *Constr. Build. Mater.*, **37**, 874-882. https://doi.org/10.1016/j.conbuildmat.2012.04.030.

Huang, H., Gao, X., Li, L. and Wang, H. (2018), "Improvement effect of steel fiber orientation control on mechanical performance of UHPC", *Constr. Build. Mater.*, **188**, 709-721. https://doi.org/10.1016/j.conbuildmat.2018.08.146.

Kabele, P. (2007), "Multiscale framework for modeling of fracture in high performance fiber reinforced cementitious composites", *Eng. Fract. Mech.*, **74**(1-2), 194-209. https://doi.org/10.1016/j.engfracmech.2006.01.020.

Kim, D.J., Park, S.H., Ryu, G.S. and Koh, K.T. (2011), "Comparative flexural behavior of hybrid ultra high performance fiber reinforced concrete with different macro fibers", *Constr. Build. Mater.*, **25**(11), 4144-4155. https://doi.org/10.1016/j.conbuildmat.2011.04.051.

Le Hoang, A. and Fehling, E. (2017), "Influence of steel fiber content and aspect ratio on the uniaxial tensile and compressive behavior of ultra high performance concrete", *Constr. Build. Mater.*, **153**, 790-806. https://doi.org/10.1016/j.conbuildmat.2017.07.130.

Li, B., Chi, Y., Xu, L., Shi, Y. and Li, C. (2018), "Experimental investigation on the flexural behavior of steel-polypropylene hybrid fiber reinforced concrete", *Constr. Build. Mater.*, **191**, 80-94. https://doi.org/10.1016/j.conbuildmat.2018.09.202.

Li, Y., Tan, K.H. and Yang, E.H. (2019), "Synergistic effects of hybrid polypropylene and steel fibers on explosive spalling prevention of ultra-high performance concrete at elevated temperature", *Cement Concrete Compos.*, **96**, 174-181. https://doi.org/10.1016/j.cemconcomp.2018.11.009.

Mehta, P.K. and Monteiro, P.J.M (2006), *Concrete: Microstructure, Properties and Materials*, McGraw-Hill Education, New York, NA, USA.

Midhun, M.S., Rao, T.G. and Srikrishna, T.C. (2018), "Mechanical and fracture properties of glass fiber reinforced geopolymer concrete", *Adv. Concrete Constr.*, **6**(1), 29. https://doi.org/10.12989/acc.2018.6.1.029.

Naaman, A.E. and Reinhardt, H.W. (2006), "Proposed classification of HPFRC composites based on their tensile response", *Mater. Struct.*, **39**(5), 547-555. https://doi.org/10.1617/s11527-006-9103-2.

Nili, M. and Afroughsabet, V. (2010), "The effects of silica fume and polypropylene fibers on the impact resistance and mechanical properties of concrete", *Constr. Build. Mater.*, **24**(6), 927-933. https://doi.org/10.1016/j.conbuildmat.2009.11.025.

Pakravan, H.R., Latifi, M. and Jamshidi, M. (2017), "Hybrid short fiber reinforcement system in concrete: A review", *Constr. Build. Mater.*, **142**, 280-294. https://doi.org/10.1016/j.conbuildmat.2017.03.059.

Park, S.H., Kim, D.J., Ryu, G.S. and Koh, K.T. (2012), "Tensile behavior of ultra high performance hybrid fiber reinforced concrete", *Cement Concrete Compos.*, **34**(2), 172-184. https://doi.org/10.1016/j.cemconcomp.2011.09.009.

Park, S.H., Ryu, G.S., Koh, K.T. and Kim, D.J. (2014), "Effect of shrinkage reducing agent on pullout resistance of high-strength steel fibers embedded in ultra-high-performance concrete", *Cement Concrete Compos.*, **49**, 59-69. https://doi.org/10.1016/j.cemconcomp.2013.12.012.

Pereira, E.B., Fischer, G. and Barros, J.A. (2012), "Effect of hybrid fiber reinforcement on the cracking process in fiber reinforced cementitious composites", *Cement Concrete Compos.*, **34**(10), 1114-1123. https://doi.org/10.1016/j.cemconcomp.2012.08.004.

Punurai, W., Kroehong, W., Saptamongkol, A. and Chindaprasirt, P. (2018), "Mechanical properties, microstructure and drying shrinkage of hybrid fly ash-basalt fiber geopolymer paste", *Constr. Build. Mater.*, **186**, 62-70. https://doi.org/10.1016/j.conbuildmat.2018.07.115.

Qi, J., Wang, J. and Feng, Y. (2019), "Shear performance of an innovative UHPFRC deck of composite bridge with coarse aggregate", *Adv. Concrete Constr.*, **7**(4), 219-229. https://doi.org/10.12989/acc.2019.7.4.219.

Qian, C.X. and Stroeven, P. (2000), "Development of hybrid polypropylene-steel fibre-reinforced concrete", *Cement Concrete Res.*, **30**(1), 63-69. https://doi.org/10.1016/S0008-8846(99)00202-1.

Robins, P., Austin, S. and Jones, P. (2002), "Pull-out behaviour of hooked steel fibres", *Mater. Struct.*, **35**(7), 434-442. https://doi.org/10.1007/BF02483148.

Shaikh, F.U.A. and Taweel, M. (2015), "Compressive strength and failure behaviour of fibre reinforced concrete at elevated temperatures", *Adv. Concrete Constr.*, **3**(4), 283-93. http://dx.doi.org/10.12989/acc.2015.3.4.283.

Sharma, R. and Bansal, P.P. (2019), "Efficacy of supplementary cementitious material and hybrid fiber to develop the ultra high performance hybrid fiber reinforced concrete", *Adv. Concrete Constr.*, **8**(1), 21-31. https://doi.org/10.12989/acc.2019.8.1.021.

Shi, C., Wu, Z., Xiao, J., Wang, D., Huang, Z. and Fang, Z. (2015), "A review on ultra high performance concrete: Part I. Raw materials and mixture design", *Constr. Build. Mater.*, **101**, 741-751. https://doi.org/10.1016/j.conbuildmat.2015.10.088.

Song, P.S. and Hwang, S. (2004), "Mechanical properties of high-strength steel fiber-reinforced concrete", *Constr. Build. Mater.*, **18**(9), 669-673. https://doi.org/10.1016/j.conbuildmat.2004.04.027.

Song, P.S., Hwang, S. and Sheu, B.C. (2005), "Strength properties of nylon-and polypropylene-fiber-reinforced concretes", *Cement Concrete Res.*, **35**(8), 1546-1550. https://doi.org/10.1016/j.cemconres.2004.06.033.

Toutanji, H., McNeil, S. and Bayasi, Z. (1998), "Chloride permeability and impact resistance of polypropylene-fiber-reinforced silica fume concrete", *Cement Concrete Res.*, **28**(7), 961-968. https://doi.org/10.1016/S0008-8846(98)00073-8.

Wille, K., El-Tawil, S. and Naaman, A.E. (2014), "Properties of strain hardening ultra high performance fiber reinforced concrete (UHP-FRC) under direct tensile loading", *Cement Concrete Compos.*, **48**, 53-66. https://doi.org/10.1016/j.cemconcomp.2013.12.015.

Wille, K., Kim, D.J. and Naaman, A.E. (2011), "Strain-hardening UHP-FRC with low fiber contents", *Mater. Struct.*, **44**(3), 583-598. https://doi.org/10.1617/s11527-010-9650-4.

Wille, K., Naaman, A.E., El-Tawil, S. and Parra-Montesinos, G.J. (2012), "Ultra-high performance concrete and fiber reinforced concrete: achieving strength and ductility without heat curing", *Mater. Struct.*, **45**(3), 309-324. https://doi.org/10.1617/s11527-011-9767-0.

Yao, W., Li, J. and Wu, K. (2003), "Mechanical properties of hybrid fiber-reinforced concrete at low fiber volume fraction", *Cement Concrete Res.*, **33**(1), 27-30. https://doi.org/10.1016/S0008-8846(02)00913-4.

Yoo, D.Y., Banthia, N., Kim, S.W. and Yoon, Y.S. (2015), "Response of ultra-high-performance fiber-reinforced concrete beams with continuous steel reinforcement subjected to low-velocity impact loading", *Compos. Struct.*, **126**, 233-245. https://doi.org/10.1016/j.compstruct.2015.02.058.

Yoo, D.Y., Kang, S.T. and Yoon, Y.S. (2014a), "Effect of fiber length and placement method on flexural behavior, tension-softening curve, and fiber distribution characteristics of UHPFRC", *Constr. Build. Mater.*, **64**, 67-81. https://doi.org/10.1016/j.conbuildmat.2014.04.007.

Yoo, D.Y., Shin, H.O., Yang, J.M. and Yoon, Y.S. (2014b), "Material and bond properties of ultra high performance fiber reinforced concrete with micro steel fibers", *Compos. Part B. Eng.*, **58**, 122-133. https://doi.org/10.1016/j.compositesb.2013.10.081.

Yu, R., Spiesz, P. and Brouwers, H.J.H. (2014a), "Mix design and properties assessment of ultra-high performance fibre reinforced concrete (UHPFRC)", *Cement Concrete Res.*, **56**, 29-39. https://doi.org/10.1016/j.cemconres.2013.11.002.

Yu, R., Spiesz, P. and Brouwers, H.J.H. (2014b), "Static properties and impact resistance of a green Ultra-High Performance Hybrid Fibre Reinforced Concrete (UHPHFRC): experiments and modeling", *Constr. Build. Mater.*, **68**, 158-171. https://doi.org/10.1016/j.conbuildmat.2014.06.033.

Zhou, M., Lu, W., Song, J. and Lee, G.C. (2018), "Application of ultra-high performance concrete in bridge engineering", *Constr. Build. Mater.,* **186**, 1256-1267. https://doi.org/10.1016/j.conbuildmat.2018.08.036.

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