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Influence of fibre type on flexural behaviour of self-compacting fibre reinforced cementitious composites

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ABSTRACT

This paper investigates the flexural properties of self-compacting fibre reinforced cementitious composites that contain high fly ash volume. Seven types of fibres were compared at the same volume fraction and in similar matrices containing high-volume fly ash and having a high compressive strength of around 85 MPa at 28 days. Third-point bending test was conducted on beam specimens to obtain their load–deflection curves, and investigate their fracture behaviour, flexural strength, deflection and toughness. The results showed that using straight steel and micro-polyvinyl alcohol fibres produced composites demonstrating stable deflection-hardening with multiple-cracking phenomenon. This behaviour resulted in high flexural strength, along with large maximum deflection and toughness values, which are important for applications in cementitious composites. This study indicates that fibres with both sufficiently high aspect ratio and high tensile strength are necessary for achieving deflection-hardening in self-compacting cementitious composites with high-strength matrices containing high-volume fly ash.

1. Introduction

A strain-hardening behaviour in direct tensile testing has been observed in fibre reinforced cementitious composites (FRCC) with aligned long fibres [1,2] or randomly oriented short fibres [3,4]. This behaviour is associated with a multiple cracking process where a series of small cracks are developed. This process results in a large increase in the toughness of a material [5], which is important for the serviceability and durability of the structures under different loading conditions [6,7].

Most conventional FRCC that have a typical concrete matrix and 0.1–3% by volume of short randomly oriented fibre only show a strain-softening behaviour and fail with one single crack under tension [8]. The strain-hardening behaviour can be obtained only when the fibre volume fraction exceeds a critical value [9,10]. This critical value depends on various factors including the strength of the matrix, the dimension, shape and orientation of the fibres and the fibre–matrix bond properties and so forth [10–12]. Different strain-hardening cementitious composites have been developed, including slurry infiltrated fibre concrete (SIFCON) [3,13], slurry infiltrated mat concrete (SIMCON) [14], engineered cementitious composites (ECC) [4] and the like [15–17].

As shown in Fig. 1, the ductility in FRCC can also be identified by a deflection-hardening and multiple-cracking behaviour in a flexural test [18], noting that a deflection-hardening cementitious composite may not necessarily exhibit strain-hardening under direct tension [19]. FRCC that show multiple cracking under tension or flexure have been classified as ductile fibre reinforced cementitious composites (DFRCC) [20]. In other words, DFRCC includes both strain-hardening and deflection-hardening cementitious composites. However, it is generally accepted that high performance cementitious composites (HPFRCC) include only strain-hardening cementitious composites [19]. Due to this deflection-hardening multiple-cracking behaviour, DFRCC show higher values in flexural strength, ductility (larger maximum deflection), and toughness compared with conventional FRCC.

Theoretical analysis has indicated that the volume content and the type of fibre are critical for DFRCC [10,12]. There have been some reports on the effect of fibre type on the flexural behaviour of FRCC [18,21–24]. One common issue with the investigation of the flexural behaviour of FRCC, as pointed out by Kim et al. [18], is that much research has been based on different non-standard testing procedures applied to specimens with different dimensions. This causes the difficulty of comparing results obtained by different authors. Kim et al. investigated the effect of fibre type

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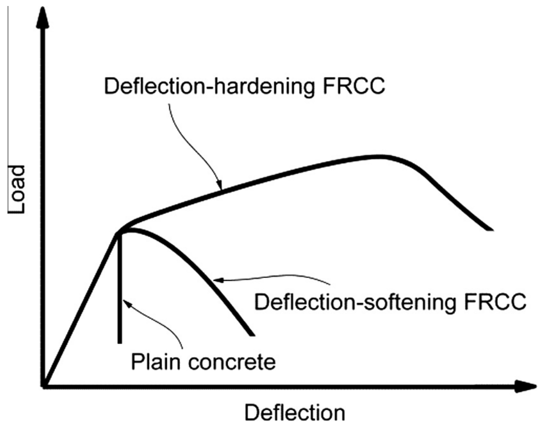

Fig. 1. Typical load–deflection curves of FRCC in flexure.

and content on the flexural behaviour of DFRCC [18]. They carried out third-point bending tests according to ASTM C1609 and showed that the beams reinforced with twisted steel fibres have the best performance out of four types of investigated fibre reinforcement.

The efficiency of fibre reinforcement also depends upon the matrix composition. Fly ash has been more and more frequently used as a component in the matrix composition of FRCC [24–28]. It is becoming evident that the usage of fly ash not only reduces the production costs of FRCC but also could improve the property of the materials. For instance, Zhang et al. [28] showed that the incorporation of fly ash improved the workability of mixtures, which could facilitate the dispersion of fibre at a relatively high content. Kayali [24] found that the usage of high-volume fly ash enhanced the bonding between the steel fibre and matrix, and hence improved the mechanical properties of the steel fibre FRCC. Wang and Li [26] indicated that high-volume fly ash was in favour of attaining high tensile strain capacity for ECC reinforced with polyvinyl alcohol (PVA) fibres.

Most research on DFRCC deals with mixtures with normal workability. Thus, compaction which is usually done by vibration is required. Recently, self-compacting concrete has drawn worldwide attention because self-compactability reduces the labour cost and increases casting efficiency while resulting in high performance [29]. FRCC with self-compactability in the fresh state and having high performance in the hardened state are highly desirable for civil structural applications. Therefore, self-compacting DFRCC have begun to attract the attention of some researchers. For example, self-compacting ECC with polymer fibre have been developed by Kong et al. [30]. Felekoglu et al. have studied self-compacting micro-concrete composites reinforced with 1%, by volume, polymeric fibre, using a non-standard three-point loading flexural test on $40 \times 40 \times 160$ mm beams [23]. They found that high strength concrete with high strength fibres provides best performance in flexural strength and toughness.

This paper presents an investigation into the effect of fibre type on the flexural behaviour of self-compacting FRCC tested according to ASTM C1069, and focuses on the influence of fibre types in achieving deflection-hardening. In the limited existing reports [18,31] on the flexural behaviour of FRCC based on the testing configuration in ASTM C1609, nearly all composites showed deflection-hardening behaviour. Those reports [18,31] have essentially compared the flexural behaviour of different deflection-hardening composites reinforced with different types of fibres. The transition from deflection-softening to deflection-hardening with the changing of fibre type has not been indicated using universal standard experiments such as ASTM C1069. Hence, to capture this transition, as many types of fibres as possible have been considered in this study. This included fibres of different dimensions ranging from micro-fibres to macro-fibres and fibres of different materials that varied from steel to polymeric. Hooked end steel fibres have been widely used in FRCC. The flexural behaviour of the composites reinforced with those fibres has been well documented by Kim et al. [18,31]. Although macro-PVA and straight steel fibres have been separately investigated in Refs. [18,31], respectively, the comparison between their influence on the flexural behaviour of the composites has not been sufficiently dealt with. These two types of fibres have similar dimension, and thus the comparison between them could offer insight into the influence of the material nature of the fibre. Hence, these two types of fibres were particularly covered in the present investigation.

Throughout the investigation, the fibre volume fraction has been fixed at 2%. The matrices are similar high strength pastes containing high-volume fly ash and having a compressive strength of around 85 MPa at 28 days. The flexural behaviour of the composites with different fibre types has been compared in terms of the fracture mode, ductility, flexural strength, residual strength and toughness.

2. Experimental program

2.1. Materials

The chemical compositions of the cement and the fly ash are shown in Table 1. The composite materials considered in this work were reinforced with the following fibres: brass-coated straight steel fibre (SS), enlarged end steel fibre (EES), crimped steel fibre (trade name Xorex), macro-polyvinyl alcohol fibre (MAPVA), micro-PVA fibre (MIPVA) with surface oil coating, straight polypropylene fibre (trade name 3M), and crimped polypropylene fibre (trade name HPP). The properties of the fibres and their shapes are presented in Table 2 and Fig. 2, respectively.

2.2. Specimen preparation

The mix proportions are shown in Table 3. The mixtures are named after the type of fibre included. To assess the effect of fibre type, the fibre volume fraction is kept constant at 2%. Fly ash takes up to 50% by mass of total cementitious materials within the mixtures. Due to its spherical shape, fly ash is able to increase the workability of concrete [32]. With the inclusion of the large amount of fly ash coupled with the usage of superplasticiser, all the mixtures have maintained self-compactability at a low water-to-cementitious-materials ratio of 0.19–0.20.

Cement and fly ash were first placed into the mixer and dry-mixed for about 5 min. Then, water with dissolved superplasticiser was added gradually and mixed for another 10–15 min. Shortly after that, the fibres were added and mixed for 5 more minutes. Thixotropy of the mixtures has been experienced, and long mixing time (15–20 min) has been used to minimize the thixotropy as

Table 1
Chemical composition of the cement and the fly ash by mass percentage (%).

	Cement	Fly ash
SiO_2	21.1	67.5
Al_2O_3	5.2	23
Fe_2O_3	4.3	4.5
CaO	64.2	<1
MgO	1.2	<1
Na_2O	0.05	0.5
K_2O	0.47	1.5
SO_3	2.6	0.1