Construction and Building Materials 164 (2018) 477–488

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Key mechanical properties and microstructure of carbon fibre reinforced self-consolidating concrete

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HIGHLIGHTS

- The mechanical performance of carbon fibre reinforced self-consolidating concrete (CFRSCC) was focused.
- The microstructure of CFRSCC was examined to observe the distribution and failure mode of carbon fibres.
- The optimum content of carbon fibres for producing CFRSCC was determined.

ARTICLE INFO

Article history:
Received 26 July 2017
Received in revised form 6 December 2017
Accepted 25 December 2017

Keywords:
Carbon fibres
Fibre distribution
Load-deflection behaviour
Scanning electron micrograph
Self-consolidating concrete
Strength
Toughness

ABSTRACT

This paper presents the key mechanical properties and microstructure of different carbon fibre reinforced self-consolidating concrete (CFRSCC) mixtures. Two different water-to-binder (W/B) ratios of 0.35 and 0.40 were used to produce ten CFRSCC mixtures including 0–1% carbon fibres by volume of concrete. The key mechanical properties such as compressive strength, splitting tensile strength, flexural strength or modulus of rapture, and toughness or fracture energy of CFRSCCs were determined. In addition, the load-deflection behaviour was studied for all CFRSCCs. The microstructure of all CFRSCCs was also observed via scanning electron micrographs (SEMs) of the fracture surface to examine the distribution and failure mode of carbon fibres in self-consolidating concrete. Test results revealed that the increased amount of carbon fibres decreased the compressive strength of CFRSCC by 36.6–58.9% depending on W/B ratio and curing age. However, the higher amount of carbon fibres increased the splitting tensile strength of CFRSCC by 13.1–17% at different W/B ratios and curing ages. Also, the flexural strength and toughness of CFRSCC was increased by 3.6% and 41.4%, respectively, for 0.25% carbon fibres. The load-deflection behaviour diagrams showed that the CFRSCC with 0.25% carbon fibres had the best post-peak response under loading. Furthermore, the SEMs exhibited that the CFRSCCs with 0.35 W/B ratio were denser with lesser pores than the CFRSCCs with 0.50 W/B ratio. Carbon fibres were well-distributed in concrete when the fibre content was 0.25%. It was also observed from SEMs that carbon fibres failed either by pullout or breakage under loading.

1. Introduction

Self-consolidating concrete (SCC) is a special concrete that flows under its own weight when placed in the formwork [1–5]. SCC has the ability to fill all the gaps completely in the formwork and go around the congested reinforcement without segregation and bleeding [6–8]. In order for the concrete to be classified as SCC, the concrete has to fulfill the requirements of three workability properties such as filling ability, passing ability, and segregation resistance [9–11]. SCC has been described as "the most revolutionary development in concrete" over the last three decades [10]. This special concrete provides manifold advantages such as faster construction, reduced need for skilled construction workers, lower noise level in construction site, more construction safety, lesser air pollution, easier placing, better finishing, and greater durability [12–14]. SCC was indeed developed in Japan to compensate for the shortage of skilled laborers in concrete industry [3,15]. In fact, it has been rendered efficient and beneficial from both technological and economical standpoints. SCC can be applied to construct different types of concrete structure. It can be used in small or big structures, simple or complicated buildings, horizontal or vertical structural members, and cast-in-place or precast con-

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https://doi.org/10.1016/j.conbuildmat.2017.12.172
0950-0618/

crete components. In the United States, approximately 40% of the precast concrete production uses SCC, while approximately 2–4% of the cast-in-place concrete production uses SCC [12]. In Canada and Switzerland, SCC has been used as a repair material because of its capability to flow and fill in the restricted areas [9,10]. However, carbon fibre-reinforced self-consolidating concrete (CFRSCC) has been used limitedly in real-world applications.

Adding fibres to concrete decreases its two workability properties such as filling ability and passing ability [7,16] and therefore it becomes relatively difficult to produce fibre-reinforced SCC [6]. For example, steel fibres can affect negatively the filling ability and passing ability of SCC [17,18]. Despite the adverse effects on workability, adding fibres to SCC may improve its mechanical properties [19]. Generally, concrete is a brittle material and its brittleness increases with increased strength [20]. Hence, high-strength SCC exhibits more brittleness than conventional concrete when fails under tensile load [21]. The brittleness of SCC can be minimized adding suitable fibres. The addition of discrete fibres to SCC reduces the crack opening at the loading stage and creates a crack bridging, which can alter the fracture behavior of the concrete at failure [22,23]. Therefore, the fibres are expected to play a dominant role in improving the mechanical properties of SCC.

Many studies have been carried out to investigate the mechanical properties of SCC including steel, polypropylene, glass, and natural fibres [15,16,19,22–24]. Carbon fibres have also been used in different types of concrete, though limitedly in SCC. Numerous studies have been conducted since 1970s to investigate the effectiveness of carbon fibres on the various properties of non-self-consolidating concrete [25–30]. Carbon fibre-reinforced concrete (CFRC) (without SCC properties) has been used in many projects because of its good thermal conductivity, lightweight (low density), and high modulus of elasticity [26,27]. The addition of carbon fibres to concrete can also offer significant improvement in its flexural strength, toughness, and splitting tensile strength [27,31]. In addition, the impact strength and cracking resistance of concrete are substantially improved in the presence of carbon fibres [28,31].

Carbon fibres are advantageous over many well-known fibres such as cellulose, polypropylene, glass, and steel. Cellulose fibres are very sensitive to the moisture and therefore they may cause warping in cement composites due to the changes in humidity [32]. This problem can be avoided when carbon fibres are used in cement based composites. Also, carbon fibres are more suitable than polypropylene, glass and steel in respect of finishability, weatherability, mixability, thermal resistance, and long-term chemical stability in aggressive environments [33]. However, limited studies have been carried out to investigate the potential use of carbon fibres in SCC, particularly emphasizing the microstructure and mechanical properties of CFRSCC. Few recent studies reported that the incorporation of carbon fibres in SCC improves its mechanical and electrical properties [18,34,35]. Yet more research is required to study the effects of carbon fibres on the mechanical performance of SCC. In particular, comprehensive research is needed to understand how the distribution of carbon fibres influences the mechanical properties of SCC. It could also be vital to understand the failure mechanism of carbon fibres under tensile or flexural loading in relation to the mechanical performance of SCC. This study highlights the distribution of carbon fibres in SCC found from scanning electron micrographs (SEMs) and their effects on the key mechanical properties such as compressive strength, splitting tensile strength, flexural strength, toughness, and load-induced deflection. The failure modes of the carbon fibres, as observed in SEMs, are also discussed in this study.

2. Research significance

The effect of carbon fibres on the mechanical properties of SCC has not been investigated comprehensively. Incorporating carbon fibres in SCC can produce a high quality special concrete known as carbon fibre reinforced self-consolidating concrete (CFRSCC). CFRSCC offers the benefits of both carbon fibre-reinforced concrete and SCC. The main objective of this study was to investigate the effect of pitch-based carbon fibres on the mechanical properties of SCC. Also, the microstructure of CFRSCC was observed to examine the distribution and failure mode of carbon fibres. The research findings can be useful to produce CFRSCC commercially for use in new or aged concrete structures.

3. Materials and methods

3.1. Concrete constituents

Normal (Type I) portland cement (C), crushed limestone coarse aggregate (CA), manufactured fine aggregate (FA), silica fume (SF), high-range water reducer (HRWR), pitch-based carbon fibres (CFs) and normal tap water (W) were used in this study. The manufactured fine aggregate conformed with the specification OPSS 1002 [36]. Table 1 shows the major properties of concrete constituent materials. Fig. 1 shows some of the pitch-based carbon fibres used in the present study. The diameter and length of the selected carbon fibres was 17 μm and 10 mm, respectively. Hence, the aspect ratio of the carbon fibres was 588. The dimensions of carbon fibres were selected based on a previous study conducted by Safiuddin et al. [28]. The main objectives of selecting such dimensions were to minimize the clumping of fibres during mixing and the negative effect of fibres on the flowing ability (filling ability and passing ability) of concrete. Also, the selected length of carbon fibres was intended to maximize the bridging of cracks, resulting in enhanced mechanical performance. The carbon fibres selected had a protective coating. This coating was applied on fibre surface during production to prevent the physical damage of carbon fibres during handling and processing. It also reduces the physical damage of carbon fibres during concrete mixing.

3.2. Mixture proportions of concretes

A total of ten non-air-entrained SCC mixtures incorporating 0–1% pitch-based carbon fibres by volume of concrete were produced in this study. Silica fume was used in all SCC mixtures as a supplementary cementing material. The amount of silica fume was kept constant at 10% by weight of the binder (C + SF). Silica fume facilitated the dispersion of carbon fibres in SCC. Two control SCC mixtures with no fibres and eight SCC mixtures with different fibre contents were produced. Table 2 presents the details of concrete mixture proportions. The CFRSCC and control mixtures were divided into two groups based on the water-to-binder (W/B) ratio. The first group (series 1) had a W/B ratio of 0.35 and the second group (series 2) had a W/B ratio of 0.40. HRWR was added to the CFRSCC mixtures to enhance

Table 1
Major properties of concrete constituents.

Material	Properties
Normal (Type I) portland cement (C)	Relative density: 3.15
Crushed limestone coarse aggregate (CA)	Maximum aggregate size: 10 mm Saturated surface-dry based relative density: 2.74 Absorption: 1.13 wt%
Manufactured fine aggregate (FA)	Maximum aggregate size: 5 mm Relative density: 2.68 Absorption: 1.15 wt%
Pitch-based carbon fibres (CFs)	Relative density: 1.85 Tensile strength: 1770 MPa Tensile modulus: 180 MPa Length: 10 mm Diameter: 17 μm
High-range water reducer (HRWR)	Relative density: 1.064 Solid content: 33 wt%
Silica fume (SF)	Relative density: 2.2
Normal tap water (W)	Total solids: 430 mg/L Density ≈ 000 kg/m^3