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Flexural behavior of high-strength concrete beams reinforced with a strain hardening cement-based composite layer

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HIGHLIGHTS

- HSC beams reinforced with a SHCC layer.
- The flexural behavior of HSC beams containing steel fibers.
- SHCC layer increased the load-bearing capacity of the beams.
- Steel fibers increased the beam ductility and load-bearing capacity.

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ABSTRACT

High-strength concrete (HSC) is often used in construction. High-strength concrete exhibits high compressive strength, but the flexural strength and cracking are problems for this material. Strain-hardening cement-based composites were recently developed as a repair material for improving crack control and flexural strength. This paper details the behavior of high-strength concrete beams reinforced with a strain hardening cement-based composite (SHCC) and steel fibers. A new method for improving concrete beam flexural behavior was explored by laying a layer of SHCC in the concrete beam in situ. The flexural behavior of HSC beams containing steel fibers was also studied using a high fiber content. Three types of beams were cast, and a series of tests were conducted. The flexural results indicated that the added SHCC layer increased the load-bearing capacity of the beams. Adding steel fibers significantly increased the load-bearing capacity of the beam.

1. Introduction

Concrete is a brittle material that more effectively resists compressive than tensile forces. Most concrete failures and deterioration are due to its brittle nature. Cracks form in concrete materials due to shrinkage, thermal effects and processing. Internal cracks propagate and reach exposed surfaces due to load-induced tensile stresses and allow deeper penetration for existing external cracks. The crack width increases with increasing applied loads [1]. Cracking increases the permeability to water, air and aggressive agents that attack reinforcing steel, which reduces the durability of reinforced concrete structures. Adding fibers could be a solution to control cracks. Included fibers can bridge the brittle matrix to increase fracture resistance [2–7]. Concrete possessing unique properties from strain hardening cementitious composites included to limit crack widths have been reported. Cracking or spalling can be reduced by replacing concrete with a cementitious composite surrounding the conventional steel reinforcement to prohibit the migration of aggressive substances [8].

SHCCs, also called engineered cementitious composites (ECCs), are a new category of high-performance fiber-reinforced cementitious composites tailored using micromechanics theory that exhibit high durability and ductility [9–12]. Superior durability has been observed for SHCCs under various environmental and mechanical loads due to the high compatibility of their deformation with existing concrete, tensile ductility, and self-controlled micro-crack width [13,14]. SHCCs have undergone major advances in both development and applications since their introduction. The performance of SHCCs for seismic and non-seismic structural applications has been assessed via various experiments [15–17]. These experiments revealed that structural performance was enhanced by the material properties. Compared to normal concrete, where a single crack develops into a failure plane, SHCC has good characteristics for developing multiple stable micro-cracks bridged by fibers [18]. High-strength concrete beams with

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a steel fiber content of 1% demonstrate an increased displacement at failure. Additionally, the number of cracks at a comparable load level was reduced, and the flexural rigidity before the yield stage increased [19]. The factors affecting the flexural strength of different concretes have been reported. Concrete with improved confinement conditions exhibited better flexural behavior with increasing age [20]. Strengthening the reinforced concrete beams with reinforced SHCC layer significantly enhanced the post peak behavior. Additionally, unreinforced SHCC layers cause brittle failures [21]. Crack control and loading bearing capacity of normal strength concrete had been improved by using SHCC in combination with high strength reinforcing steel bars. SHCC strengthening to beams had been applied to beam after initial gain of concrete strength at 7 days [22]. Engineered cementitious composites had significant improvement on ability to control cracks with larger deflections. The ultimate strength and improvement of deflection in composite beams are mainly dependent on the tensile and compressive ductility of matrix [23].

Most literature regarding the application of SHCC on flexural elements is related to normal strength concrete and using SHCC on the concrete in hardened state. This work investigates the behavior of hybrid concrete beams using both an SHCC layer around main steel reinforcement and steel fibers in high-strength concrete to highlight the structural behavior. High-strength concrete beams were cast as controls, and a steel fiber content of 1.5% was added to check the structural behavior of high-strength steel fiber-reinforced concrete. A new control beam modification was performed using an SHCC layer with main steel reinforcement. The SHCC layer was laid in such a way that it is covering reinforcing bar with total thickness of 25 mm leaving cover of concrete. Load deflection behavior, strain variation with load and mode of failure for all three types of beams is presented and results of these three types of beams are compared.

2. Experimental investigation

2.1. Materials

2.1.1. Fine powder

Ordinary Portland cement (OPC) following the ASTM C150 requirements was used as the binder material and was partly replaced via silica fume. Class F fly ash was used to develop the SHCC. The median grain sizes were 13 μm for OPC, 8 μm for silica fume, approximately 15 μm for the class F fly ash and 133 μm for silica sand. The physical and chemical properties of the above fine powders are shown in Table 1. The particle size distributions of the fine powders are shown in Fig 1.

2.1.2. Fine and coarse aggregates

Two sands with different particle sizes were used to prepare mixes, crushed sand and fine sand. The fineness moduli were 1.47 and 4.66 for fine and crushed sand, respectively. Combining 65% and 35% fine and crushed sand, respectively, yielded a fineness modulus of 2.54. A coarse aggregate at most 10 mm in size was used to prepare the mixture. The physical properties of the fine and coarse aggregates are summarized in Table 2. The sand and coarse aggregate particle size distributions are shown in Fig. 2.

Table 1
Physical and chemical properties of cementitious materials.

Oxide composition (%)	Ordinary Portland Cement	Fly Ash	Silica Fume
SiO_2	20.2	50	93.2
Al_2O_3	5.49	28	0.2
Fe_2O_3	4.12	10.4	0.03
CaO	65.43	<6	0.72
MgO	0.71	<4	0.14
Na_2Oeq	0.26	1.5	0.07
SO_3	2.61	<2.5	<0.01
Loss on ignition (%)	1.38	4	5.4
Specific gravity	3.14	2.3	2.27
Fineness (m^2/kg)	373	300–600	19,000

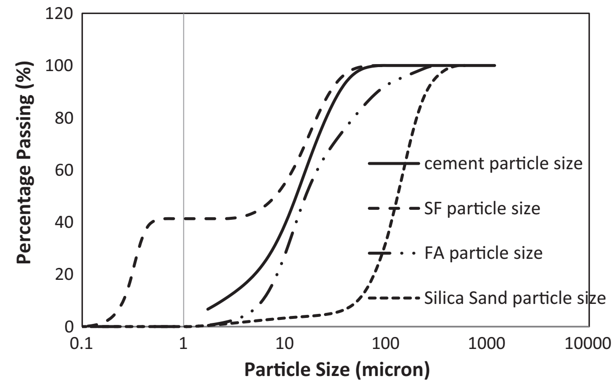

Fig. 1. Particle size distribution of cement, silica fume, fly ash and silica sand.

Table 2
Physical properties of fine and coarse aggregate.

Properties/Material	Specific Gravity	Absorption (%)	Unit Weight kg/m^3
White Sand	2.63	0.77	1725
Crushed Sand	2.68	1.52	1552
Coarse Aggregate (10 mm)	2.65	1.45	1570

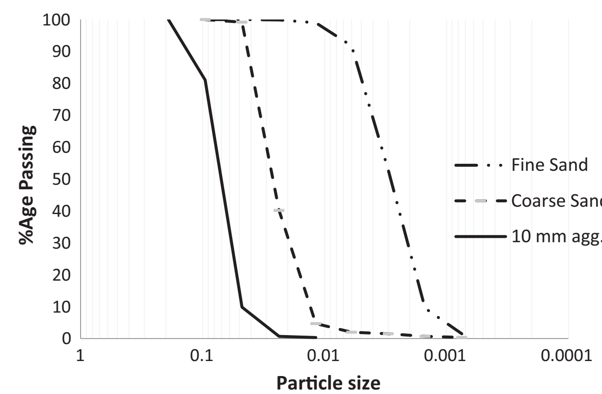

Fig. 2. Particle size distribution of fine and coarse aggregate.

2.1.3. Chemical admixtures

A modified polycarboxylic ether (PE) polymer (Glenium 51) with a specific gravity of 1.1 and a dry extract of 36% was used to produce ab required mixture. The PE dosage is expressed as a dry extract (D.E.) per cement weight. The optimized PE dosages were determined.

2.1.4. Fibers

Two types of fibers (steel and poly vinyl alcohol (PVA)) were used in this study. PVA fibers are normally used to develop SHCC and steel fibers are used in steel fiber-reinforced concrete. The fiber properties are summarized in Table 3. The physical appearances of the fibers are shown in Fig. 3.