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Structural performance of reinforced strain hardening cementitious composite pipes during monotonic loading

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HIGHLIGHTS

- The ultimate load and deflection diameter ratios increase 200% and 340% for SHCCP relative to RMP.
- SHCCP had thinner walls relative to normal reinforced concrete pipes.
- SHCCP could endure higher tensile strain than RMP.
- The multiple cracking characteristic of SHCC existed in SHCCP under TEBT.

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ABSTRACT

Strain Hardening Cementitious Composites (SHCC) is a kind of micromechanically designed cement-based composite with ultra high tensile ductility. It is used to fabricate an innovative concrete pipe to improve the structural performance of concrete pipe. The load-carrying capacity, deflection to diameter ratio, circumferential strain and crack patterns of reinforced SHCC pipes (SHCCP) in comparison to these of conventional reinforced cement mortar pipes (RMP) have been investigated under the Three-Edge Bearing Testing (TEBT). Results show that resulting from high tensile strength and high ductility of SHCC the ultimate load and deflection diameter ratios has increased about 200% and 340% for SHCCP relative to RMP. So, SHCCP had thinner walls relative to standard reinforced concrete pipes. SHCCP with diameter of 375 mm and wall thickness of 25 mm could bear the specified D_{ult} for Class III pipes according to ASTM C76. SHCCP also possessed high residual load-carrying capacity. SHCCP could endure higher tensile strain than RMP. The maximum tensile strain of the crown and the springline of SHCCP reached 10,000 $\mu\varepsilon$ and 6400 $\mu\varepsilon$. The multiple cracking characteristic of SHCC existed in SHCCP under TEBT. SHCCP exhibited high ductility so that it has the potential to be classified as a type of semi-rigid pipe.

1. Introduction

Concrete exhibits low cost, high compressive strength, fire prevention and high durability so that it is used widely as one of the most important engineering materials to manufacture pipelines. Steel fibers or synthetic fibers have been added into concrete pipes to improve their structural performances since steel fibers or synthetic fibers can help to increase tensile strength, toughness of concrete through bridging micro- and macro-cracks formed in the cementitious matrix. It is known that several standards on steel fiber reinforced concrete pipes (SFRCP) have been issued, i.e. European Standard EN 1916 [1] and ASTM C1765 [2]. MacDonald and Trangsrud [3] reported that the crushing strength of SFRCP increased with steel fiber inclusion. Haktanir et al. [4] tested SFRCP in comparison with plain concrete pipes and conventionally reinforced concrete pipes (RCP) under three-edge-bearing test (TEBT). It was found that longer steel fibers achieved greater improvement of the pipe strength than that of short fibers. The average strength and crack size of SFRCP having steel fibers of RC80/60-BN type at a dosage of 25 kg/m^3 turned out to be 82% greater and 6% greater than those of plain concrete pipes and RCP, respectively. A series of SFRCP with different steel fiber dosages have been tested and simulated by De Figueiredo et al. [5] and De La Fuente et al. [6,7]. They reported that SFRCP showed an equivalent performance to superior class pipes made with reinforced concrete. A fiber dosage of 40 kg/m^3 was considered as the optimum content [5]. De La Fuente et al. [6,7] developed a numerical model named as Mechanical Analysis of Pipes (MAP) based on the fictitious crack

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model to calculate the loading capacity and deformations of SFRCP. Abolmaali et al. [8] tested SFRCP having different pipe dimensions, fiber dosages and fiber properties. They reported that SFRCP achieved a comparable performance to that of RCP in terms of strength, stiffness, and ability to withstand large crack widths. Mohamed et al. [9] investigated the flexural behavior of full-scale 300 mm diameter dry-cast concrete pipes (DC-SFRCP) incorporating different types of commercially available steel fiber at different addition rates. DC-SFRCP achieved ultimate loads greater than the required strength for Class V pipes according to the ASTM C76 standard. The post-peak behavior of DC-SFRCP was comparable or superior to that of conventional RCP. Nehdi et al. [10] have studied the field performance of full-scale SFRC pipes when buried in soil and subjected to actual and simulated live loads.

Besides SFRCP, synthetic fiber reinforced concrete pipes have also been studied. Wilson and Abolmaali [11] investigated the feasibility of using a type of fiber manufactured from a blend of polypropylene resins to replace conventional steel rebars in concrete pipes. The fibers had a length of 54 mm, an equivalent diameter of 0.82 mm, and a tensile strength of 585 MPa. Their study showed that the synthetic fibers could be used as means of alternative reinforcing. Further, Park et al. [12] used hybrid steel fibers and polypropylene fibers to enhance the rubberized concrete pipe strength and ductility. They also have proposed the thin walled flexible concrete pipes with polypropylene fibers. It was found that discrete fibers could increase the shear capacity of concrete, delay the shear failure mode and significantly enhance the pipe's loading carrying capacity with the use of reduced steel reinforcement. Flexible concrete pipes showed superior stiffness than very flexible pipes such as HDPE pipes and corrugated metal pipe [13]. Peyvandi et al. [14,15] have performed an investigation on the efficiency of coarse polyvinyl alcohol (PVA) fibers (a diameter of 0.3 mm or 0.1 mm) or fine PVA fibers (a diameter of 0.026 mm) with volume fractions varying from 0.5% to 2% in enhancing the structural performance of concrete pipes. It was found that depending on load-bearing requirements, synthetic fibers could reduce the amount of steel reinforcement in concrete pipes by 50% or more. Direct joint shear tests also demonstrated that PVA fiber reinforcement enhances the joint shear capacity of concrete pipes.

Strain hardening cementitious composites (SHCC) is a kind of micromechanically designed cement-based composite with high tensile ductility. Stable, multiple fine cracking characteristics, instead of localized wide cracking characteristics is observed in SHCC. The ultimate tensile strain of SHCC reaches above 3.0% with the average crack width smaller than 0.1 mm under uniaxial tensile tests [16–18]. It is noted that the ultimate tensile strain of the conventional concrete is about 0.02%. The smaller crack width in SHCC is useful to solve problems such as leakage and steel reinforcement corrosion taken place in concrete pipes. Further, since SHCC can bear tensile stress, SHCC pipes (SHCCP) may exhibit higher load-carrying capacity than conventional concrete pipes. Until now applications of SHCC into steel reinforced concrete beams or columns have been studied [19,20]. But, little attentions has been paid on reinforced SHCCP. An et al. [21] introduced SHCC into a kind of sandwich pipes (SP) for ultra-deepwater submarine pipelines. SP was designed using SHCC as the core material enveloped with the inner and outer steel pipe. The collapse behavior of SP under external hydrostatic pressure was investigated experimentally and numerically. Baker et al. have filed a patent proposing cementitious pipe as a tubular wall of SHCC [22].

In this paper, a comprehensive experimental program is conducted on the hollow cylindrical SHCCP under the action of externally quasi-static compressive loads. The aim is to understand the mechanical behaviors of this new type of concrete pipe. The following studies has been performed: (i) Assessment of the load-carrying capacity of 375 mm diameter reinforced SHCCP in comparison to that of conventional RCP with similar diameter; (ii) Determination of the overall deformation behavior and strain at several critical locations such as the crown, the springline and the invert of SHCCP and RCP; (iii) Evaluation of the post-peak characteristics of SHCCP after the ultimate load has reached, i.e. residual load-carrying capacity; and (iv) Observation of the crack growth in SHCCP and RCP. To our knowledge, reinforced SHCCP has not been studied yet. The rest of paper is organized as follows. In the next section, preparation and testing methods for SHCC and reinforced SHCCP are presented. In Section 3, at first the basic mechanical properties of materials are gained. Then, structural performances of SHCCP and RCP such as ultimate carrying load, strain at several key positions of pipe cross-section, deflection of the crown, the invert and the springline are discussed. Based on the experimental data, SHCCP and RCP are classified according to ASTM C76-15 [23], and deflection-to-diameter ratio of SHCCP is compared with that of normal PVA fiber reinforced concrete pipes. Finally, crack patterns and its development in SHCCP are provided. The paper ends in Section 4 with conclusions.

2. Materials and methods

2.1. Raw materials and mix proportion

SHCC is often prepared with cement, fly ash, fine sand, fine PVA fibers and other admixtures without coarse aggregate [16–18]. So, in this paper SHCCP and RCP to study are not concrete. In order to differentiate RCP, hereinafter steel reinforced cement mortar pipes are denoted as RMP. PVA fibers[1] were 12 mm in length, 39 μm in diameter, with a young's modulus of 42.8 GPa, and relative density of 1300 kg/m^3. The fiber volume fraction in SHCC was 2.0% (26 kg/m^3). Dosages of other materials used were: 390.1 kg/m^3 of P.O. 42.5 cement,[2] 780.2 kg/m^3 of Class I fly ash,[3] 526.6 kg/m^3 of silica sand with maximum particle size of 0.3 mm, 362.8 kg/m^3 of water, 4.1 kg/m^3 of water reducing agent (WR)[4] and 0.3 kg/m^3 of viscosity modifier agent (VMA).[5] One circular reinforcement cage with a reinforcement area of 2.5 cm^2 per linear meter of pipe wall was embedded into pipes. The reinforcement cage was welded using ribbed steel rebar with a young's modulus of 210 GPa and yield strength of 600 MPa. The diameters of circumferential reinforcement and longitudinal reinforcement were 4 mm and 5 mm, respectively. RMP was prepared using the same mix proportion as SHCCP except that PVA fibers were not added.

2.2. Preparation of specimens

First, cement, sand and fly ash were dry-mixed for 1 min. Then the total amount of water and 80% of WR was added and mixed for 2 min. After that, PVA fibers were added into the rotating mixer within 3 min. Then the rest of WR and VMA were added and mixed for another 1 min. The flow value of the mixture was tested according to GB/T2419-2005 [24] and controlled to be about 210 mm. The fresh mixture was poured into the mould and vibrated for 2 min.

In terms of JSCE recommendations [25] and JGJ 70-2009 [26], dumbbell-shaped specimens shown in Fig. 1 and 70 mm cubic specimens were prepared for uniaxial tension test and compression test, respectively. SHCC and plain cement mortar specimens were prepared and demoulded after 1 day, then cured at 20 °C and RH 95% for 28 days. SHCCP and RMP had an inside diameter D_i of 375 mm (about 15 in.) and the wall thickness of 25 mm (1 in.). The length of SHCCP and RMP was 320 mm, which was larger than the minimum length of 300 mm for TEBT specified in AS 4139 [27]. The mould for preparation of pipes is shown in Fig. 2, consisting of the internal and external mould. Before pouring the fresh mixture into the mould, the reinforcement cage was fixed inside the mould to let the circumferential reinforcement position at 2/5 of the pipe wall from the inner surface of the pipe. The mould was vibrated for 2 min, and demoulded after 2 day. Pipe specimens were covered with wet clothes and cured at room temperature for 28 days. Prior to testing, specimens were dried in air at a temperature of 25 °C and at 70% RH for 4 days. Two duplicates of SHCCP and RMP were fabricated and tested.

2.3. Methods for uniaxial tension and compression

Uniaxial tension test or direct tension was performed to measure tensile properties of SHCC and plain cement mortar according to JSCE recommendation [25]. The setup is shown in Fig. 3. The specimen was placed in the test machine with a

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[2] Huaxin Cement Co. Ltd., Hubei Province, China.

[3] Huaneng Yangluo Power Plant, Hubei Province, China.

[4] ADVA152, GRACE Shanghai Branch, China.

[5] RHEOPLUS420, BASF in China.