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Full-scale pipes using dry-cast steel fibre-reinforced concrete

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HIGHLIGHTS

- Engineering properties of DCSFRC have been explored.
- Steel fibre type and dosage for precast pipes have been determined.
- Full-scale DCSFRC pipes were successfully fabricated.
- DCSFRC precast pipes achieved ultimate loads greater than the required strength.
- Steel fibres could be an alternative to conventional steel cages in precast concrete pipes.

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ABSTRACT

The mechanical properties of dry-cast steel fibre-reinforced concrete (DCSFRC) were investigated in the present study. Four commercially available steel fibres were added at rates of 0, 20, 40 and 60 kg/m^3. Full-scale 300 mm diameter precast pipes were fabricated using the tested DCSFRC mixtures to examine its potential for such application. In addition, plain (PC) and conventionally reinforced concrete (RC) precast pipes were fabricated and tested for comparison. As expected, results showed that the mechanical properties of DCSFRC were enhanced as the fibre dosage increased. Generally, hooked-end fibres with the highest aspect ratio led to highest tensile and flexural strengths. Furthermore, DCSFRC precast pipes achieved ultimate loads greater than the required strength for Class V pipes according to the ASTM C76 standard. The post-peak behaviour of DCSFRC pipes was comparable or superior to that of conventional RC pipes. Findings of this research indicate that discrete steel fibres could be an adequate alternative to the labour intensive and time-consuming steel cages normally used for reinforcing precast concrete pipes.

1. Introduction

Precast reinforced concrete (RC) pipes have been in widespread use in North America in the conveyance of sewage and storm water for several decades. They generally have shown reliable long-term performance. However, the manufacturing cost is a challenge facing precast RC pipes production. Specifically, manufacturing the pipe's reinforcing steel cage from conventional steel bars, which requires special bending, welding and placement machinery, is costly and time consuming. Therefore, it is hypothesized that using discrete steel fibres as the primary reinforcement for concrete pipes instead of conventional steel cages could overcome this disadvantage without compromising the overall quality of the product.

Recently, structural applications of steel fibre-reinforced concrete (SFRC) have been increasing. For instance, SFRC has been used in tunnel linings [20,54], slabs on grade [47], pavements on metal decks [39], seismic retrofitting and rehabilitation of various concrete structures [38,46,32,52,21]. However, only about 5% of the total amount of FRC that is produced annually is used in precast members [16].

Steel fibres (SF) enhance the post-cracking behaviour of hardened concrete through maintaining some of its load-carrying capacity after crack formation. Moreover, during fracture, energy is consumed in the de-bonding, pulling-out, and rupture of fibres leading to higher concrete toughness [16]. The overall improvement in the engineering properties of concrete owing to SF addition is a function of several variables, including the fibre shape, length, aspect ratio, volume fraction with respect to the total concrete volume, and the quality of the hosting matrix [18].

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Several studies have investigated the use of SF in precast concrete pipes (e.g. [36,29,22,23,1]. MacDonald and Trangsrud [36] and Haktanir et al. [29] reported fabricating SFRC pipes with different types of steel fibres. However, the load versus deformation curves and analysis of the effect of the fibre type and dosage on the post-cracking behaviour were not explored. In their work, De La Fuente and De Figueiredo [22] and De La Fuente et al. [23] reported the fabrication and testing of SFRC pipes having internal diameters ranging from 600 to 1000 mm with a steel fibre contents from 10 to 40 kg/m^3. The targeted pipe strengths were class C60 and C90 according to EN 1916 [25]. These classes correspond to ultimate crushing loads of 60 and 90 N per meter of pipe length per millimetre of pipe internal diameter. Class C60 coincides with the lowest strength class (Class I) specified in ASTM C76 [5], while class C90 falls between Class II and III.

Abolmaali et al. [1] reported the fabrication and testing of SFRC pipes having internal diameters ranging between 400 and 1200 mm with steel fibre contents from 13 to 66 kg/m^3. The targeted pipe strength was Class III pipe according to ASTM C76. However, none of the studies mentioned above investigated SFRC pipes with internal diameter of 300 mm. This is important since newly developed plastic pipes can primarily compete with concrete pipes in the range of small diameters. Thus, it is paramount to explore the mechanical behaviour of pipes with such diameter (D_i = 300 mm). Furthermore, none of the above studies reported on the concrete strain values measured at critical pipe sections. Such values are much needed for the numerical modelling of SFRC pipes.

A commonly used method for producing concrete pipes in Canada is the Dry Cast/Vibration method [44]. In this method, a low frequency-high amplitude mechanical vibrator is used to distribute and densely compact the dry concrete mixture in the form. The form is removed immediately since the newly formed pipe can support its own weight. This requires a special type of concrete usually called "dry-cast concrete", which is defined as concrete having a slump in the range of 0–25 mm [2].

Therefore, the present study investigates the mechanical properties of dry-cast concrete incorporating different types of commercially available steel fibres at different addition rates. Moreover, the flexural behaviour of full-scale 300 mm diameter DCSFRC pipes was explored in comparison to that of PC and RC pipes with similar diameter.

2. Research significance

This paper is part of a large on-going study that aims at developing technical recommendations and design guidelines for DCSFRC pipes. It explores engineering properties of DCSFRC to evaluate its applicability in the precast pipe industry. Adequate type and dosage of steel fibres for manufacturing full-scale DCSFRC precast pipes were identified. Feasibility was demonstrated through full-scale testing of 300 mm diameter DCSFRC pipes incorporating different steel fibre types and dosages in comparison to conventional PC and RC pipes. This paper provides valuable data on DCSFRC pipes to the precast concrete pipe industry, which can enhance its productivity

3. Experimental program

3.1. Materials and mixture proportions

A commercial precast pipe dry-cast concrete mixture was adapted for the fabrication of laboratory specimens. A total of 15 mixtures including a control mixture were cast. High early-strength Portland cement and ground granulated blast furnace slag (GGBFS) were used in the binder formulation. Gravel with a maximum nominal size of 13 mm was used as the coarse aggregate. Natural sand with a fineness modulus of 2.82 was used as the fine aggregate. The water-to-cementitious materials ratio (w/cm) for all mixtures was 0.38. A polycarboxylate superplasticizer was added at a rate of 0.16% by mass of the cementitious materials. A non-ionic surfactant-dispersing admixture was added at a rate of 0.20% by mass of the cementitious materials. Four commercially available steel fibres were used. Steel fibres were either collated (Type A and B) or dispersed (Type C and D). The steel fibre dosage in the tested concrete mixtures (W_f) was 20, 40, and 60 kg/m^3 (V_f = 0.25%, 0.50%, and 0.75% by volume fraction). The effect of synergistic hybridization between fibres A (short) and B (long) was also investigated. The composition of the tested DCSFRC mixtures and different properties of the used steel fibres are shown in Tables 1 and 2, respectively.

Table 1
Concrete mixture proportions.

Material	Mass/cement mass
Cement (SG = 3.15)	1.00
Blast furnace slag (SG = 2.9)	0.54
Fine aggregate (SG = 2.68)	5.00
Coarse aggregate (SG = 2.75)	4.17
Water (SG = 1.0)	0.58
Super plasticizer	0.34 l/m^3
Surfactant	0.43 l/m^3
Steel fibres (SG = 7.8)	0, 20, 40, 60 kg/m^3

SG = specific gravity.

3.2. Specimens preparation and testing

Cement, GGBFS, coarse and fine aggregates, as well as steel fibres were dry-mixed for 5 min using a drum mixer. The superplasticizer and surfactant were added to the mixing water. Water was then added gradually to the mixture and mixing continued for another five minutes. The average measured air content was 3.5%. All mixtures exhibited a zero slump. Cylindrical 100 mm × 200 mm and prismatic 150 × 150 × 500 mm specimens were cast from each batch. Specimens were cast and compacted in accordance with the common practice for SFRC (i.e. no rodding or internal vibration). In agreement with previous work on dry-cast concrete and SFRC pipes (e.g. [29,53] specimens' compaction was done using a vibrating table. The vibrating table had dimensions of 500 × 500 mm and a motor with frequency between 2600 and 3600 RPM. Its maximum load capacity is 140 kg. Immediately after casting, specimens were covered with plastic caps and wet burlap to prevent surface drying. All specimens were de-moulded after 24 h and moved to a moist curing room (T = 25 °C and RH = 98%) until the testing age.

At 28 days, the compressive strength (C_s), modulus of elasticity (E_s) and splitting tensile strength (T_s) were evaluated for the various mixtures according to the guidelines of ASTM C39 [4], ASTM C469 [6] and ASTM C496 [7], respectively. Each reported result represents the average values obtained on four identical specimens.

The flexural performance of DCSFRC prism specimens was evaluated as per the procedure of ASTM C1609 (ASTM C1609-12 [9]). A controlled displacement load was applied at a rate of 0.05 mm/min. The first crack load was identified as the load whereby the initial linear elastic slope of the load displacement plot ends, while the peak/ultimate load was considered as the maximum load of the load-mid span displacement curve. Three replicate prismatic specimens from each mixture were tested to evaluate the flexural performance. Tables 3 and 4 show the average and coefficient of variation (COV) for each of the conducted tests.

3.3. Full-scale pipe production and testing

Full-scale 300 mm DCSFRC pipes using discrete steel fibres as the main reinforcement were cast at a commercial precast plant in Oakville, Ontario. The plant uses the dry-cast production method. Pipes were cast vertically in a mould consisting of an inside core and an outside mold. Concrete was fed inside the mold under mechanical vibration. When the mould was filled, a circular ring descends onto the top of the concrete and applies pressure. The form was removed immediately after casting, as the newly formed pipe could support its self-weight. All pipes had an inside diameter D_i of 300 mm and a Type C wall (D_i/12 + 44 mm). Two duplicates of PC, RC, and DCSFRC pipes were also fabricated and tested. The targeted pipe strength was Class V pipe according to ASTM C76. RC pipes had one circular reinforcement cage with a reinforcement area of 1.5 cm^2 per linear meter of pipe wall. Table 5 shows the fabricated 300 mm diameter pipes, and their corresponding fibre type and dosage.

The mechanical performance and structural behaviour of concrete pipes were evaluated using the Three Edge Bearing Test (TEBT) as per the guidelines of ASTM C497 [8] as shown in Fig. 1. A line load was applied along the crown of the pipe using a displacement controlled universal materials testing system (MTS). A rigid steel beam was attached to the loading system. The upper bearing consisted of a 25 mm thick hard rubber strip attached to a rigid wood beam. Pipes were supported along their longitudinal axis on a lower bearing system consisting of 25 mm thick hard rubber strips attached to two rigid wood beams spaced at 50 mm apart. For