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Structural performance of dry-cast rubberized concrete pipes with steel and synthetic fibers

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HIGHLIGHTS

- Excessive addition of rubber showed a significant reduction in the pipe strength.
- Hybrid fiber reinforcements enhanced the pipe strength and ductility effectively.
- Fine aggregates can be replaced with an equal volume of crumb rubber up to 3%.

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ABSTRACT

A study was conducted to address the enhancement of the structural performance of concrete pipes through the use of crumb rubber, steel, and synthetic (polypropylene) fibers. Based on the three-edge bearing (3EB) test according to ASTM standard C497, pipes with five different dry-cast concrete mixtures were produced and tested: (1) reinforced concrete pipe (RCP), (2) crumb rubberized concrete pipe (CRP), (3 and 4) steel or polypropylene fiber reinforced rubberized concrete pipe (SFP or PFP), and (5) hybrid fiber reinforced rubberized concrete pipe (HYP). This study investigates how the variation of the fiber volume fraction and crumb rubber content in the dry cast concrete mix affects the behavior of pipes with diameters of 600 mm (24 in.) and 900 mm (36 in.). The crumb rubber particles replaced from 3% to 20% (by volume) of fine aggregate in the mixture used for concrete pipes. A series of rubberized concrete mixes were employed with a variation in the fiber volume fraction (V_f) (steel: 0.17% and 0.33%, polypropylene: 0.13%, 0.33%, 0.52% and 0.65%). Thirty-one rubberized concrete pipes were developed by incorporating different dosages of steel and polypropylene fibers and their combinations. Test results revealed that hybrid fiber reinforcements (both steel and polypropylene fibers) were more effective than single type fiber reinforcement (steel or polypropylene fibers) in enhancing the rubberized concrete pipe strength and ductility. In order to reach the strength requirement for Class III (96 kN/m/m) and Class II (72 kN/m/m) according to ASTM C76, fine aggregates can be replaced with an equal volume of crumb rubber up to 3% and 5% in HYPs, respectively, for the rubberized concrete pipes produced with zero-slump concrete.

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1. Introduction

The disposal of waste tires has been a major issue in solid waste sites, with approximately 242 million of them disposed of each year as stockpile (whole tire) or landfill (shredded tire) in the United States (U.S.) after their natural lifetime [1]. Six hundred thousand tons of waste tires are disposed of in landfills each year in the European Union (EU) [2]. From a public health and environment perspective, the ability of tire stockpiles and landfills to become breeding grounds for vermin, and their leaching of toxins into the groundwater are especially worrisome. At its worst, it has been estimated that approximately one billion used tires were

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in uncontrolled stockpiles in the U.S [3]. In response to these concerns, many countries made it illegal to dispose of tires in landfills and established strict controls on size and operations of scrap tire collection facilities [4]. In order to solve the environmental concerns of tire disposal, the use of recycled tire rubber in concrete mixtures has been introduced as a possible alternative to conventional concrete mixes. After grinding tire rubber into small particle form (crumb rubber), it was suggested to use it in applications such as cementitious materials like concrete.

However, it was reported that rubberized concrete has a major weakness with respect to its reduction in strength with increasing percentage weight replacement of aggregate with rubber. Despite this, the product did show great potential in its lightweight, ductility, impact-resistance and environmental benefits. Several studies have been carried out to evaluate the effects of rubber in concrete. The reports have noted that compressive strength and modulus of elasticity for rubberized concrete decreased significantly with an increase in rubber replacement [5–8]. However, the loss in compressive strength with a small portion of replacement was not significant. Compressive strength of up to 27.6 MPa (4000 psi) can be reached by replacing the coarse aggregates in concrete with small amounts of tire derivative aggregates (TDA) ranging from 7.5% to 10%, with a maximum size of 50.8 mm (2 in.), along with the use of enhanced materials such as silica fume [5]. The rubber should not exceed 17–20% of the total aggregate volume to avoid significant reduction in the compressive strength [9].

Some research efforts have proposed that the benefits of using fibers in rubberized concrete outweigh the drawbacks, owing to improvements in the concrete's crack resistance, flexural strength and toughness [10]. Incorporation of steel fiber reinforcement in concrete mix increases flexural strength, and the increase of the steel fiber contents influenced the increase in flexural strength [11]. When steel fibers were used to reinforce rubberized concrete, a positive synergy effect was evidenced with regard to the resistance to cracking [12]. Steel fibers with adequate anchorage (the capacity of pull-out resistance) can be used to bridge cracks and prevent catastrophic collapse. Compared with steel fibers, synthetic fibers have not been reported as much as steel fibers. However, in general, synthetic fibers have been found to increase freeze–thaw resistance, toughness, impact resistance and crack control [13,14].

In the last two decades, fiber reinforced concrete pipes (FRCP), with fibers partially or totally replacing the steel reinforcement (steel cage), have been introduced into the North American pipe market for use in underground applications [15]. A performance-based specification for steel fiber reinforced concrete pipe (SFRCP) was developed in the American Society for Testing and Materials (ASTM) specification C1765-*Standard specification for steel fiber reinforced concrete culvert, storm drain and sewer pipe* [16] and European Standard EN 1916-*Concrete pipes and fitting, unreinforced, steel fibre and reinforced* [17]. It has been reported that the use of fibers (steel or synthetic) in concrete pipes is a competitive option for alternative reinforcement from a technical and economical point of view [18,19]. Instead of the traditional reinforcement of a circumferential steel cage, which resists the ultimate load subjected on the concrete pipe, the inclusion of fibers in concrete pipes is viable as long as the concrete mix design and fiber dosage are adequate [20].

However, among the numerous experimental studies conducted in the literature references, limited studies have been performed on the effect of a combination of rubber and fibers (steel or synthetic, or both) on dry cast concrete mixtures (with zero slump) used widely in concrete pipe production. The limited information available on the behavior of rubberized concrete pipes reinforced with fibers still leaves things unclear. The objective of this research is to investigate the possibility of producing concrete pipes where crumb rubber as a partial replacement of fine aggregates, and the inclusion of steel fiber and polypropylene fiber, can interact properly without reduction of pipe strength.

2. Experimental program

2.1. Concrete mixture

A zero-slump concrete mixture (known as dry-cast concrete) was used for the precast concrete pipe production in this study. The resulting concrete water-cement ratio (w/c) was 0.45 with zero slump. The control concrete mix used in this experimental study provided compressive strength of 27.6 MPa (4000 psi) at 28 days after casting. The materials used in dry cast concrete mixture were: 226 kg/m^3 (380 lb/yd^3) of Type I/II Portland cement, 990 kg/m^3 (1670 lb/yd^3) of coarse aggregate (crushed stone) with maximum particle size of 19 mm (0.75 in.), 1010 kg/m^3 (1700 lb/yd^3) of sand (fine aggregate) with maximum particle size of 3.75 mm (0.15 in.), 74 kg/m^3 (125 lb/yd^3) of fly ash (ASTM Class F) and 101 kg/m^3 (170 lb/yd^3) of water. The rubberized concrete mixes had fine aggregates replaced by crumb rubber of equal volume (3%, 5%, 10%, 15% and 20%). Half of the total amount of fibers was added into the mixer manually to ensure uniform distribution of the fibers in the mixture. Before water was added, the materials of crumb rubber and aggregates (coarse and fine) and were dry-mixed for 3 min with half of the fibers. In order to make dispersion of fibers sufficient, a further 3 min of mixing was conducted after half of the water and cement was added. Finally the rest of the water and fibers were added to the mixture and mixed again for 3 min.

2.2. Crumb rubber and macro fibers

Recycled rubber obtained from used vehicle tires was shredded. Crumb rubber particles range from 4.75 mm (No. 4 Sieve) to 0.075 mm (No. 200 Sieve) and have a specific gravity of 0.53 (absorption rate: 5.1%). Since the mineral aggregates have a higher unit weight than the crumb rubber particles, addition of crumb rubber reduces the unit weight of the mixture.

The steel fibers used in this study were low carbon drawn steel wires (tensile strength of 1200 MPa = 174 ksi). The fibers are 35 mm (1.38 in.) in length, 0.5 mm (0.02 in.) in diameter, with a young's modulus of 210 GPa (30458 ksi), and relative density of 7.85 (7847 kg/m^3 = 13226 lb/yd^3). In order to enhance bond strength between the fibers and concrete, steel fibers have different geometries such as deformed fiber, crimped-end, hooked-end and flat-end. Steel fibers with hooked ends (glued into bundles) were used in this study.

Synthetic fibers used in this study were produced from a blend of 100% virgin polypropylene resin, and complied with ASTM C1116-*Standard specification for fiber reinforced concrete* [21]. This was a mono-filament and embossed fiber (an embossed depth from peak to valley: 0.005–0.006 mm). The fiber length was 54 mm (2.1 in.) with a tensile strength of 586 MPa (85 ksi). Masterfiber MAC Matrix has previously been used in applications such as slab-on-grade and shotcrete as a replacement for welded wire reinforcement and other secondary reinforcement. The mechanical and geometric properties of the fibers are shown in Table 1.

2.3. Pipe production methods and equipment

All pipes were produced at a Hanson Pipe and Precast Plant in Texas (U.S.) using packerhead equipment. In this method as shown in Fig. 1, three-piece jackets (a metal pipe form, end-joint steel ring and steel cage in the bottom steel ring) were placed onto the rotating table. A circular roller head (called packerhead) rotated along the length of the pipe creating the inside diameter of the pipe, then concrete was poured into the jacket simultaneously. The spin of the packerhead forced the concrete mixture out circumferentially by radial compaction while the core was vibrated. The metal pipe form (pipe jacket creating the outside diameter) was removed after concrete pouring since the dry cast method enabled the immediate demolding of the jacket. Demolded pipes were placed in a steam curing chamber with a temperature of 60 °C (140°F) for 12 h and subjected to three-edge bearing tests after 28 days of production. A low-pressure steam with high humidity and high temperature is introduced into a chamber which allows circulation of steam around the entire pipe (Fig. 1).

Thirty-one test series for both 600 (24 in.) and 900 mm (36 in.) inside-diameter pipes (pipe length: 2440 mm = 8 ft) each were created with a combination of crumb rubber (volume contents) and two different fibers (fiber types and volume contents). Based on the classification in ASTM C76-*Standard specification for reinforced concrete culvert, storm drain, and sewer pipe*, Class III/B-wall pipes were manufactured. Precast concrete pipe is often specified in terms of a generalized class system representing the minimum D-load capacity which a reinforced concrete pipe should satisfy. The classes are designated in ASTM C 76 as shown in Table 3.

The wall thickness of 600 (24 in.) and 900 mm (36 in.) inside-diameter pipes are 75 (3 in.) and 100 mm (4 in.), respectively. Crumb rubber with replacement ratios by volume of sand (fine aggregate) of 3% (30 kg/m^3 = 51 lbs/yd^3), 5% (51 kg/m^3 = 85 lbs/yd^3), 8% (81 kg/m^3 = 136 lbs/yd^3), 10% (101 kg/m^3 = 170 lbs/yd^3), 15% (152 kg/m^3 = 255 lbs/yd^3) and 20% (202 kg/m^3 = 340 lbs/yd^3) were examined in this

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