Construction and Building Materials 45 (2013) 36–44

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Enhancement of the structural efficiency and performance of concrete pipes through fiber reinforcement

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HIGHLIGHTS

- Performance of different synthetic fibers in dry-mix concrete were evaluated.
- High elastic modulus fiber enhanced engineering properties of Concrete pipe.
- The number of steel reinforcement layers can be reduced through the use of polyvinyl alcohol (PVA) fibers in concrete pipes.
- PVA fibers could enable reduction of pipe thickness, thus lowering of the overall weight of concrete pipes.

ARTICLE INFO

Article history:
Received 26 November 2012
Received in revised form 19 March 2013
Accepted 22 March 2013
Available online 25 April 2013

Keywords:
Concrete pipes
Sewers
Composite materials
Structural design
Fiber reinforced material
Steel

ABSTRACT

Fiber reinforcement systems are used towards development of pipes with more efficient structural designs, reduced steel reinforcement, increased cover thickness over reinforcement (and thus durability), reduced weight, streamlined geometry (for ease of handling and installation), and enhanced shear resistance. Comprehensive experimental investigations were undertaken to evaluate the efficiency of different synthetic fibers (aramid, AR-glass, carbon, and polyvinyl alcohol (PVA)) at various volume fractions (0.5–1.0 vol.%) in lean, zero-slump concrete materials used in dry-cast method of concrete pipe production. PVA fiber was used for use in concrete pipes due to its desired balance of reinforcement efficiency and stability in aggressive chemical (e.g. sanitary sewer) environments. The reinforcement efficiency of PVA fibers in concrete was attributed to its relatively high elastic modulus and desired interfacial bonding to cement hydrates. Industrial-scale structural evaluation of concrete pipes indicated that 30% improvement in load-carrying capacity of concrete pipes was realized with introduction of PVA fibers. This improvement enabled reduction of welded wire fabric steel reinforcement layer in concrete pipes from two to one, thus increasing the protective concrete cover thickness over steel and durability of concrete pipes under the aggressive exposure conditions of sanitary sewers. Theoretical models were also developed for predicting the contributions of PVA fibers to the structural performance of concrete pipes. Comparison between experimental results and theoretical predictions indicated that experimental results occur within ±10% of theoretical predictions. The thickness of concrete pipes could also be lowered with introduction of fibers, thus reducing of the overall weight, and thus the production, transportation and installation costs of concrete pipes.

1. Introduction

Concrete pipes, manholes, pump stations, wet wells, etc. represent close to half of the investment in the infrastructure for the 20,000 sewer systems in the United States [1]. Concrete has assumed a prevalent position in the sewer infrastructure by providing satisfactory performance over long periods of time. Some concrete aqueducts constructed by Romans about 2000 years ago to transport sewage are still in use [2,3]. The concrete-based sewer infrastructure complements desirable durability with structural efficiency and initial as well as life-cycle economy. Advances in fiber reinforcement technology have opened new prospects for design of highly efficient reinforced concrete infrastructure systems [4]. Today's concrete pipe designs, relying strictly on conventional steel reinforcement, have not yet taken full advantage of advanced fiber reinforcement systems towards achieving higher levels of structural efficiency and performance [5–7]. Among the four categories of fiber reinforcement used in concrete (steel, glass, synthetic (including carbon) and natural fibers [8,9], steel fibers have received the most attention for use in concrete pipes [10–14]. The

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0950-0618/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2013.03.084

present study focused on the use of synthetic fibers towards enhancement of the structural efficiency and performance of concrete.

The weight of concrete pipes limits their economically viable shipment distances, and adds higher installation and replacement costs. There are also serious concerns with the durability of reinforced concrete pipes in sanitary sewer environment. The excess reliance on conventional steel reinforcement frequently forces use of two steel layers to meet structural requirements; this reduces the thickness of concrete cover needed to protect steel against the highly corrosive environment of the sanitary sewer system. While steel fibers, due to their higher elastic modulus and relatively large energy dissipation during pullout would have produced higher mechanical properties, they would be susceptible to corrosion in the chemically aggressive environment of sanitary sewer. Reinforcement of concrete pipes with synthetic fibers offers the opportunity to increase the protective cover thickness of concrete over steel reinforcement [15–17]. This can be accomplished in different ways; steel reinforcement may simply be moved towards the interior of concrete pipe thickness, relying on synthetic fibers [15] to compensate for the structural implications of this shift of steel position. Synthetic fiber reinforcement may also allow for reduction of steel ratio (and thus the number of steel reinforcement layers) in concrete pipes. Finally, the introduction of synthetic fibers into concrete pipes could enhance the resistance of unreinforced concrete pipes to damage during shipment and installation, which would enable use of plain concrete pipes. The preliminary studies conducted in the project identified polyvinyl alcohol (PVA) fibers as those offering the best promise for use in concrete exposed to sanitary sewer environment. PVA fibers are distinguished by their high acid resistance, and desired bond strength to concrete [18]. A comprehensive experimental program was conducted to: (i) further assess the benefits of PVA fibers of different geometric attributes and volume fractions to the mechanical performance of concrete; and (ii) determine the contribution of PVA fibers to the structural performance of concrete pipes. The gains in flexural strength and toughness of concrete with synthetic fiber reinforcement promise benefits to the structural performance of concrete pipes. These benefits can be used to design concrete pipes with increased protective concrete cover thickness over steel reinforcement. In this study, an experimental program was conducted to evaluate the structural efficiency of different fibers (PVA, aramid, AR-glass, and carbon) in concrete. Range 0.5–1.9 vol.% was selected to evaluate the reinforcement efficiency of different fibers. Cost considerations as well as the potential for fiber clustering (balling) in the lean concrete mixes were limitations for upper limit of fibers volume fraction in production of dry-cast concrete pipes which practically limit the volume fraction of fibers to 1.0%.

This comparative laboratory investigation leads to the selecting PVA fibers which offer a greater problem for enhancing the structural efficiency of concrete pipes. A comprehensive experimental program, involving industrial-scale production and structural testing of concrete pipes, was undertaken to verify the benefits of PVA fiber reinforcement to the structural performance of concrete pipes. Theoretical models were also developed for predicting the flexural strength and load-carrying capacity of concrete pipes. Experimental results were used to validate the theoretical models.

2. Materials and methods

2.1. Reinforcing fiber

An experimental program was conducted for identifying a fiber type with desired reinforcing effect toward enhancement of concrete structural qualities. The fibers considered in this experimental program included polyvinyl alcohol (PVA), alkali-resistant glass (AR-glass), carbon, and aramid.

Table 1
Selected fibers mechanical properties.

Fiber type	Elastic modulus (GPa)	Length (mm)	Aspect ratio	Strength (MPa)
PVA	45	12	100	1200
Aramid	125	7	100	3400
AR-Glass	70	18	100	275
Carbon	240	5.5	100	4000

Table 2
Concrete mix formulations.

Materials common to all the mix formulation	Proportion[a]
Aggregate (all natural stone)	2.21
Sand (2NS)	2.42
Plasticizer	6.83
Retarder	6.16
Fly ash	0.26
Water	0.44
Cement	0.74

[a] Proportions are per unit weight of cementitous materials (cement + fly ash), except for additives (plasticizer and retarder), which are in milliliter per kilogram of cementitous materials.

The contribution of fibers to concrete mechanical properties depends upon the elastic modulus, aspect (length-to-diameter) ratio, bond strength, and volume fraction of fibers. Fiber elastic modulus, in particular, plays a significant role; for example, the cracking strength (σ_c) of fiber reinforced concrete can be expressed as follows [19]:

$$\sigma_c = \sigma_m + \eta_l \cdot \eta_\theta \cdot E_f \cdot \varepsilon_m \cdot V_f \quad (1)$$

where σ_m and ε_m are the cracking stress and strain of plain concrete (matrix), E_f and V_f are the fiber elastic modulus and volume fraction, and η_l and η_θ are the fiber length and orientation factors (with length factor depending on fiber aspect ratio and bond strength, and orientation factor of 0.5 for random 3D fiber orientation). Given the significant effect of fiber elastic modulus, this investigation deviated from prevalent practice of using low-modulus synthetic (polypropylene or nylon) fibers in concrete at low volume fraction. Table 1 provides mechanical properties of the fibers used in this investigation to identify appropriate synthetic fiber for further investigation on structural performance of industrial-scale concrete pipe.

2.2. Concrete material

The mechanical properties of the dry-cast concrete which is known as no-slump mixes were evaluated. Concrete w/c is 0.32 with zero slump, and the forms can be stripped as soon as the concrete has been consolidated. Concrete mixes include 0.2, 0.4, 0.6, 0.8, and 1.0 vol.% of concrete by addition of PVA, AR-glass, aramid and carbon fiber. The materials used in concrete mixture were: 19 mm maximum size natural stone, natural sand, Portland cement (Type I), fly ash (ASTM Class F), plasticizer (Catexol 1000 NP) and set-retarding admixture (Catexol 1000 R). The concrete mix design considered in this investigation which is commonly used in dry-mixed concrete pipe production is shown in Table 2. Concrete materials were mixed following ASTM C192 [20] recommendations; steam curing was used in lieu of moist curing in these series of tests.

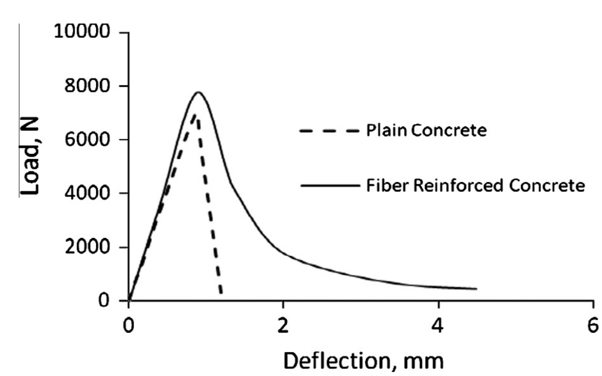

Fig. 1. Flexural load–deflection behavior of plain concrete vs. fiber reinforced concrete which reinforced with 1.0 vol.% of PVA fiber.