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Thin-walled flexible concrete pipes with synthetic fibers and reduced traditional steel cage

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A B S T R A C T

Structural classification of buried pipes depends on their inherent response to external loading and interaction between the pipes and the surrounding soil. There are mainly two classified types of pipes, rigid pipes and flexible pipes. This study focused on performance evaluations of a proposed new class of concrete pipes, semi-rigid pipes, which are flexible concrete pipes that are reinforced with synthetic fibers and have thinner walls relative to standard concrete pipes. The innovative flexible concrete pipe system has the advantages of simplified structural design, thinner pipe walls, lighter weight, improved durability due to the use of non-corrosive reinforcement (synthetic fibers), and potentially lower production cost due to reduction of steel reinforcement and wall thickness. Based on the three-edge bearing test in accordance with ASTM standard C497, 44 thin walled concrete pipes (flexible concrete pipes) with diameters from 760 mm (30 in.) to 3050 mm (120 in.) were tested with different fiber dosages (ranges of 1.2–14.3 kg/m^3) and reduced steel reinforcement (ranges of 35–50% reduction).

Test results show that discrete synthetic fibers increase the shear capacity of the thin walled concrete pipes and delay the shear failure mode, significantly enhancing the load carrying capacity with the reduced steel reinforcement. Moreover, thin walled concrete pipes with 50% reduction of steel reinforcement and the addition of synthetic fibers maintained bending stiffness up to 5% deflection of the inside diameter for small diameter pipes [760 mm (30 in.), 910 mm (36 in.) and 1370 mm (54 in.)], and bending stiffness up to 3% deflection for large diameter pipes [1830 mm (72 in.), 2130 mm (84 in.) and 3050 mm (120 in.)].

1. Introduction

Sewer systems account for approximately half of the infrastructure investment in the United States [1]. One of the key items in a reliable infrastructure is the buried pipe system used for sewers and water supply networks. Sewer pipelines are important structures which should be designed and installed to specific engineering requirements. These requirements vary markedly with (i) the rigidity or stiffness of the selected pipe material, (ii) the ability of the pipe to interact with the embedment materials, and (iii) the dimensions and shape of the embedment. Buried pipe systems rely on soil–structure interaction, whereby the soil surrounding the pipe not only induces load on the pipe, but also serves to assist the pipe in developing its full structural capability [2]. In the design of buried pipe systems, there are two general methods of evaluating the pipe–soil structure interaction; that is, evaluating the pipe as a rigid pipe, or evaluating it as a flexible pipe. Rigid and flexible pipes are distinguished by the deflection ratio or by the relative stiffness of the pipe versus the surrounding soil. Rigid pipe systems only rely on active soil pressure, and primarily resist the loads on the pipe by carrying moment and shear in the pipe wall. They show signs of structural distress before being vertically deflected to 2% of the inside diameter [2,3].

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In the storm sewer market in the United States, there are three predominant pipe materials: concrete, metal, and plastic. Flexible pipe systems such as corrugated metal pipe (CMP), polyethylene pipe (PE) and high density polyethylene (HDPE) pipe carry load by deflecting out into the soil to pick up additional passive soil pressure, which then results primarily in compressive forces in the pipe wall. Due to their different structural behavior characteristics, rigid and flexible pipes have different design criteria and installation methods [4]. Reinforced concrete pipe (RCP) is a rigid pipe which upon loading has a deflection level that is too small to develop passive lateral soil pressure. The benefit of relying primarily on the pipe strength, which is assured since the pipe is produced under controlled conditions (precast), is promoted by the concrete pipe industry. Metal and plastic pipes are flexible pipes. These pipes may sometimes have lower cost but rely much more heavily on the contractor's ability to perform a quality installation in the field, which often does not have the same quality control as the plant environment in which concrete pipes are produced [5,6]. The performance of the pipe product is in part determined by strength in the case of rigid pipes, and by normal stiffness in the case of flexible pipes which require different installation standards for bedding and backfill.

This study was conducted to evaluate the potential of developing a semi-rigid or flexible concrete pipe. This pipe would utilize thinner walls and synthetic fibers to reduce the cost of pipe material, yet still allow the pipe to take more advantage of the surrounding soil without greatly increasing its sensitivity to installation practices. Compared to traditional flexible plastic or metal pipes, the development of the flexible concrete pipe system has the advantages of simplified structural design with a higher stiffness than flexible pipes, light weight, less sensitivity to backfill compaction and lower cost for construction.

2. Classification of buried pipes and research objectives

Metal and plastic are the most popular pipe materials of choice for flexible pipe systems in the world [6]. In order to keep their cost to a minimum, the producers of pipes made from these materials have used corrugated wall structures to enhance the pipe stiffness to reduce the volume of material used. A side effect of this is that these pipes tend to have less wall area than the solid wall pipe more commonly utilized in the water distribution system. Additionally, even with the corrugated walls, these pipe materials have very low pipe stiffness. The stiffness can be as low as 104 kPa (15 psi) for a 1524 mm (60 in.) diameter plastic pipe [7,8]. Most flexible pipe standards allow up to 5% deflection. The deflection is limited to 2% if the flexible pipe has a rigid lining and coating, and 3% for a rigid lining and flexible coating [9]. Specifiers call these pipes "flexible." These pipes are truly "very flexible", and engineers and contractors have to accept the installation risks that come with such high flexibility. As noted previously, flexible pipe deflects into the surrounding soil and develops primarily compressive stresses. Utilizing corrugated (or profile walls) allows plastic and metal pipe producers to reduce their wall area. However, the thin profile sections are susceptible to local buckling within their profile as well as global buckling of the wall while under compression.

Concrete pipe represents the predominant pipe material used for rigid pipe systems in the storm sewer market in the US [5]. Concrete pipe is very durable, and utilizes design methods that have been in place for decades to design a pipe product that provides a large portion of the soil-structure on its own. However, concrete pipe is brittle in comparison to metal and plastic pipes, and can experience only minute deformation in the field before it cracks. American standards (ASTM C76) limit the allowable crack width in a buried concrete pipe to 0.3 mm (0.01 in.) for the service load condition [3].

Flexible pipe is considered a pipe that can deflect under load without structural damage. It is widely accepted that any pipe that can deflect 2% or more without structural damage is flexible [9,25]. Some standards, such as Australian Standard AS4139-2003 [24], Fiber-Reinforced Concrete Pipe and Fittings, contain a requirement for the ratio of pipe stiffness to soil stiffness, as well as a minimum acceptable deflection of 2%. The pipe must have sufficient ductility to deflect out into the soil and develop soil pressures beyond the at-rest earth pressure that might otherwise exist for a rigid pipe. Maintaining a minimum deflection level of 3% in thin wall concrete pipe ensures that it performs as a non-rigid pipe when installed.

This study is focused on the development of thin walled flexible concrete pipes (TW pipes) with synthetic fibers that would be lighter, cheaper, and more durable than the concrete pipes currently in use, while still providing a pipe product much less dependent upon installation conditions than the very flexible metal and plastic pipes used in underground infrastructures. One of the benefits of using synthetic fibers is the effect they have on the cracking properties of the concrete. By incorporating synthetic fibers in the concrete mix that are dispersed throughout the concrete pipe wall in a random fashion, the effective area of concrete around each fiber is much smaller than when a standard circumferential steel reinforcing cage is used. Inclusion of fibers in conjunction with standard reinforcing steel would result in several much smaller cracks as opposed to the few larger cracks that occur with standard steel wire reinforcement. If the concrete material in the pipe can be made flexible enough to allow for some deflection of the pipe, then any potential loss of strength through thinning the wall can be regained in the soil–structure interaction through the additional passive soil support. Thus, unlike above grade structures, a more flexible concrete matrix with thinner wall thicknesses could be of maximum benefit for circular buried structures. The deflection of the pipe to produce passive pressure from the surrounding soil relieves the pipe of the burden of carrying the soil load through the moment and the shear in the pipe wall, as occurs in the case of standard reinforced concrete pipe, and allows the flexible pipe to perform primarily under compressive stress in the pipe wall. Concrete performs most suitably in compression and, unlike existing plastic/metal pipes with the corrugated/profile wall, there are no elements susceptible to local buckling. Hence, some of the most significant concerns with flexible metal and plastic storm drain pipes are eliminated if a suitable ductile concrete pipe can be developed.

The design and utilization of circumferential reinforcing in large diameter concrete pipe is a complicated procedure. Small diameter pipe utilizes circumferential steel to resist the ultimate flexural load on the pipe. As pipe diameters get larger, a wider array of design considerations come into play such as crack control, shear, and radial tension. While the use of circumferential reinforcement is very efficient in terms of assisting the concrete to resist ultimate flexural loads, it becomes less efficient as the pipe sizes become larger, pipe strengths increase, and other failure modes come into play. Fig. 1 is taken from ASCE 15-98, Standard Practice for Direct Design of Precast Concrete Pipe Using Standard Installations (SIDD) [10]. As the applied load increases, the serviceability requirements become more important, and additional steel area in the pipe should be considered to account for crack control, and eventually shear failure. Shear force in a concrete pipe is also known as "diagonal tension". This is because the tensile stresses resulting from shear do not run perpendicular to the applied force, but rather in a diagonal direction. Circumferential reinforcement runs parallel to the wall of the pipe, and is thus relatively efficient when addressing normal (flexural) forces. However, its orientation does not allow it to be fully utilized in addressing diagonal tension forces. The use of synthetic fibers in the concrete mix results in a random orientation of the fibers. Thus, there is a large amount of