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# Mechanical performances and evolution of stiffness of thin-walled strain hardening cement-based composites pipes during cyclic loading

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## HIGHLIGHTS

- RSHCCP had the highest load-carrying capacity and deflection ratio.
- The pipe stiffness of RSHCCP decreased continuously.
- RSHCCP satisfied the requirements for the installation flexural stiffness ratio of semi-rigid pipe.
- The deflection ratio of RSHCCP was greater than 3%.

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## ABSTRACT

Four series of pipes such as reinforced strain hardening cement-based composites (SHCC) pipe (RSHCCP), plain SHCC pipe (SHCCP), reinforced cement mortar pipe (RMP) and plain cement mortar pipe (MP) were investigated by means of Three-Edge Bearing Testing (TEBT) under monotonic and cyclic loading. Results show that RSHCCP had the highest load-carrying capacity and deflection ratio among them. The synergy reinforced effect of PVA fiber and reinforcing steel to improve load-carrying capacity and deflection ratio of pipe was validated. Under cyclic loading, the irreversible deflection at the crown of pipe increased gradually. The envelope of the load–deflection response of cyclically loading pipe was consistent with the load–deflection curve of monotonically loading pipe. The pipe stiffness of concrete pipe under TEBT was characterized using the ratio of load to the reversible deflection at the crown of pipe during cyclic loading. The pipe stiffness of RSHCCP decreased continuously after the applied load exceeded the elastic range while the pipe stiffness of SHCCP, RMP, and MP remained stable unless the imposed load was close to the ultimate load. The pipe stiffness of RSHCCP could satisfy the requirements for the installation flexural stiffness ratio of semi-rigid pipe as the applied load was more than 70% of its ultimate load. The deflection ratio of RSHCCP was greater than the minimum deflection ratio level (i.e. 3%) of semi-rigid pipe.



## 1. Introduction

Reinforced concrete pipe, metal pipe, and plastic pipe such as high density polyethylene pipe and glass fiber reinforced plastics mortar pipe (FRPM) have been widely used in water supply and drainage engineering [1,2]. Usually, they are classified into two categories: rigid pipe and flexible pipe. According to GB 50332-2002 (Structural design code for pipelines of water supply and waste water engineering) [3], buried circular pipe is judged whether it belongs to rigid pipe or flexible pipe in terms of the ratio of stiffness of pipe to stiffness of the surrounding soil. Then, corresponding analysis model is employed for structural calculation of pipe. Flexible pipe system has low stiffness of pipe versus the surrounding soil ratio so that it can deflect out into the soil to gain surrounding soil pressure acted upon the outer wall of pipe [4,5]. However, ordinary reinforced concrete pipe (RCP) is a type of rigid pipe. The inherent high pipe stiffness and low capacity of deflection (below 2% [6]) of RCP make it hard to develop passive lateral soil pressure when RCP is installed underneath the ground. Thus, the wall of RCP is often thicker than that of FRPM with the same inner diameter.

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Different from conventional rigid concrete pipe, a type of pipe referred to as semi-rigid concrete pipe has been developed and installed in the practical engineering. The basic characteristics of semi-rigid concrete pipe are defined in AS 4139-2003 (Fiber-reinforced concrete pipe and fitting) [7]. Semi-rigid concrete pipe possesses higher deflection to diameter ratio upon loading than rigid concrete pipe. Thus, it can also pick up the passive support from the surrounding soil, leading to compressive stress in the pipe wall and enhancement of load-bearing capacity [8]. Park et al. [6] have developed a type of semi-rigid concrete pipe by utilizing thinner walls and embossed polypropylene fibers to improve the deflection to diameter ratio and decrease the stiffness of pipe. Bar-wrapped concrete cylinder pipe (BCCP) regarded as a semi-rigid pipe consists of a steel cylinder lined with concrete or cement mortar, then helically wrapped with a steel bar and coated with dense cement mortar [9,10]. BCCP is fabricated in accordance with AWWA C303 standard [11].

Here semi-rigid concrete pipe is fabricated with PVA (Poyvinyl Alcohol) fiber reinforced concrete. Until now, studies on semi-rigid PVA fiber reinforced concrete pipe have seldom been seen in the literature. PVA fiber, cementitious matrix and fiber/matrix interface are tailored comprehensively so that PVA fiber reinforced cement-based composite has ultra-high tensile ductility (ultimate tensile strain reaches more than 3%) [12–14]. It exhibits strain hardening behavior and multiply cracking upon direct tension. So, this kind of cementitious composite is also called as strain hardening cement-based composites (SHCC). It has been applied into full-size civil engineering structures, such as the deck of bridge and high-rising buildings. Recently, some attempts have been performed to develop various SHCC pipes. An et al. [15] have tested a kind of sandwich pipe consisting of the outer steel pipe (200 mm in diameter), SHCC filling material and the inner steel pipe (150 mm in diameter). The buckling of the outer steel pipe under external hydrostatic pressure was analyzed. However, the influence of SHCC filling material on load-carrying capacity and deformation of the sandwich pipe has not been studied. Authors [16] have first studied reinforced SHCC pipe (RSHCCP) with an inner diameter of 375 mm and the wall thickness of 25 mm. Three-Edge Bearing Testing (TEBT) has been performed to investigate the load-bearing capacity, deflections at the crown, the invert and the springline and crack patterns. The load-bearing capacity and deflection of RSHCCP improved greatly in comparison with reinforced cement mortar pipe. Multiple fine cracks were observed within the circumferential zones of the pipe wall which were subjected to tensile stress.

Following authors' previous work, this study is performed to characterize structural performances of thin-walled RSHCCP, SHCCP (plain SHCC pipe without steel reinforcement cage), RMP (cement mortar pipe with steel reinforcement cage), and MP (plain cement mortar pipe without steel reinforcement cage and fiber). It is more advantageous to clarify the roles paid by reinforcing materials (steel reinforcement and PVA fiber) to improve the load-bearing capacity and the deflection of pipe under TEBT than authors' previous work. Pipe stiffness is an important index for judging whether SHCC pipes can be classified as semi-rigid pipe or not, and determining the deformation of SHCC pipes buried underneath the ground. Further, more fine cracks (the width is less than 0.1 mm [17]) will generate in the tensile areas of SHCC pipe with an increase of the applied load under TEBT, which will induce the decrease of pipe stiffness gradually. But, the evolution of pipe stiffness of SHCC pipe with increasing load has not been addressed yet.

In accordance with Appendix D of AS 4139, the pipe stiffness of fiber reinforced concrete pipe is defined as Eq. (1), which is the same as that defined in GB/T 5352-2005 (Fiber-reinforced thermosetting plastic composites pipe—determination for external loading properties by parallel-plate loading) [18]. That is,

$$S = \frac{EI}{(D+t)^3} \tag{1}$$

where E is bending modulus of elasticity, I is moment of inertia of pipe per meter, $D$ is the inner diameter of pipe, $t$ is the wall thickness. And based on the theory of elasticity Eq. (1) can be expressed by using the applied load per meter at the crown of the pipe (P) and the deflection at the crown of pipe ($\Delta$). That is,

$$S = 0.0186\frac{P}{\Delta} \tag{2}$$

where the unit of P is kN/m, and the unit of $\Delta$ is m. Eq. (2) can also be derived using Eq. (J8) in AS 4139. While in ASTM D2412-11 (Standard test method for determination of external loading characteristics of plastic pipe by parallel-plate loading), the pipe stiffness (secant stiffness) is gained by dividing P by $\Delta$ directly [19]. Since the bottom of pipe has experienced a relatively concentrated reaction in both cases of TEBT and the parallel plate test [6], the pipe stiffness can be calculated using almost the same formula (i.e. Eq. (2)) in both cases of TEBT and the parallel plate test.

Eq. (2) stems from the elastic or near elastic load–deflection relation. However, because of strain hardening behavior of SHCC the load–deflection curve of SHCC pipe is nonlinear under TEBT [16], so large errors will be produce if Eq. (2) is adopted directly. In this paper, cyclic loading is conducted on pipes under TEBT so as to gain the irreversible deflection and reversible deflection at the crown of pipe. Then only the reversible deflection is adopted to analyze the variation of pipe stiffness with increasing load. Finally, the possibility of SHCC pipe classified as a semi-rigid pipe is discussed in accordance with related criterions specified in AS 4139.

## 2. Experimental program

### 2.1. Specimens and materials

Four series of pipes were fabricated using different reinforcing materials (see Table 1) but the same cementitious matrix. Pipe 1, Pipe 2, Pipe 3, and Pipe 4 in Table 1 belongs to RSHCCP (with steel reinforcement cage and fiber), SHCCP (with fiber), RMP (with steel reinforcement cage) and MP (without reinforcing materials), respectively. The inner diameter (D) of pipe specimen was 375 mm, the wall thickness (t) was 25 mm and the length of pipe was 320 mm. The physical and mechanical properties of PVA fiber[1] are shown in Table 2. The volume fraction of fiber was 2.0% (i.e. equivalent to 26 kg/m$^3$). The yield strength of ribbed steel rebar was 600 MPa. Circular reinforcement cage was welded using ribbed steel rebar. The diameters of stirrup and longitudinal rebar were 4 mm and 5 mm, respectively. The mean diameter of the reinforcement cage was 395 mm (that is, the reinforcement cage was located at 2/5 of the pipe wall from the inner surface of the pipe). The stirrup spacing was 50 mm. Other raw materials included P.O. 42.5 cement[2], Class I fly ash[3], fine silica sand (particle diameter less than 0.3 mm), water, superplasticizer (SP)[4] and viscosity modifier agent (VMA)[5].

### 2.2. Preparation of specimens

The mix proportion of raw materials is given in Table 3. Firstly, cement, sand and fly ash were mixed for 1 min using a 30 L concrete mixer. Then water and 80% of SP were added and mixed for 2 min. Afterwards, PVA fiber (if applicable) was added slowly and mixed with cement mortar. In the process of adding fiber, VMA and the rest of SP were added to adjust the flowability of fresh mixture. The suitable flowability of fresh mixture was beneficial to disperse PVA fiber into cement mortar uniformly. The reinforcement cage (if applicable) was fixed inside the mould, then the fresh mixture was poured into the mould as shown in Fig. 1. The filling mould was vibrated on the vibration platform for 2 min. It was demoulded after 48 h. Specimens were cured at room temperature and 95% RH for 28 days. Two specimens of each pipe were prepared and tested.

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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.