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Time-Dependent Behavior of Saturated Cellulose Fiber Reinforced Cement (CFRC) Pipe

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Abstract: Cellulose fiber reinforced cement (CFRC) pipe has been gradually introduced in the pipe market as a replacement of previously popular asbestos cement pipes. Since CFRC pipe is still relatively unknown in the pipe market, there are great concerns for the design and application in practice related to the time-dependent behavior of CFRC under long-term sustained loading. This paper presents an experimental investigation of the time-dependent behavior of cellulose fiber reinforced cement (CFRC) pipe. A total of six CFRC pipes were tested under various loading levels, and their vertical deformation was recorded to understand the characteristics of the time-dependent behavior. Based on the test results, a factor of safety (FS) of 1.82 is proposed, and a regression factor (R) of 1.88 is estimated for the application of CFRC pipes in practice.

Keywords: cellulose fiber reinforced cement (CFRC) pipe, time-dependent deformation, creep, regression factor

1. Introduction

A pipe system is an important infrastructure used to convey water for irrigation, drainage, sewage and others. The materials used for the pipe system have been diversified during last 30 years. Steel reinforced concrete, corrugated steel, asbestos cement and aluminum corrugated pipes have long been used in the pipe systems because of their high strength, excellent load supporting capacity and widespread availability. Over the past few years, cellulose fiber reinforced cement (CFRC) pipes have been introduced in the pipe market as a replacement for the previously popular asbestos cement pipe.[1] CFRC pipes consist of cement, fine aggregate (sand) and cellulose fiber reinforcement. In general, CFRC pipes are designed with a service life of more than fifty years in their applications. Since CFRC pipe is still relatively unknown in the market, it has become very important to predict the time-dependent behavior of CFRC pipe because fiber reinforced pipe in a wet environment and under long-term sustained load will lose its strength and performance during its service life.[2] In addition, a complete understanding of time-dependent behavior may be very important for the design and applications of CFRC pipe. In general, the time-dependent behavior of any structural system can be explained by creep. Creep is defined as a test where a sample is subjected to a constant stress (load) and the strain (deformation) is monitored as a function of time.[3] Steel reinforced concrete pipes have a long success track record of service performance history. Meanwhile, a cellulose fiber reinforced cement pipe has a short-service performance history in the pipe industries.[4] With respect to this time-dependent investigation of pipe systems under long-term sustained loading, only a few investigations have been reported. The following discussions review the literature specifically focusing on the creep of pipes composed of various pipe materials.

MacDonald, Bullen, and Beal[4] reported on the performance of cellulose fiber reinforced concrete pipes subjected to various sustained loads. An experiment was carried out to establish the time to failure of the pipes at various sustained loads, and the overall plot was used to obtain creep parameters for the design process that is expressed in accordance with AS 4139 of Australia as shown below[2]:

$$P_m = 1.2\, C\, R\, T_c \qquad (1)$$

where, P_m= minimum allowable test load at failure, 1.2 = a specified safety factor, C = a test factor for the dry/wet strength relationship for the pipes, R = a regression factor, and T_c = the long-term design load. The authors found three distinctive phases in the creep curve with primary, secondary and tertiary phases as shown in other cementitious materials, they also found that the time frame of the tertiary creep phase may be relatively short. In addition, they concluded that the creep performance of CFRC pipes was predictable and could be incorporated in the design process by assigning appropriate creep load factors such as R value and factor of safety. Unfortunately, the authors did not mention the specific R value from the creep tests and level of failure load on long-term performance. In addition, the authors did not show any dimensions of the tested pipe specimens and test apparatus.

Al-Obaid[6] investigated the creep of 915 mm concrete pipes on six different roads in Kuwait and compared the experimental results with the results from finite element analysis. The researcher found that (1) the average deflection for six months and a year were 30% and 49% , respectively, smaller than that of the initial stage (2) the top strains of approximately 100 pipes increased by 10% and (3) the bottom strains remained unchanged. He also

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found that the analytical results from finite element analysis concurred fairly well with those obtained from the site monitoring.

In summary, despite some uncertainties presented in the study described above, we believe that these investigations are important in understanding the characteristics of time-dependent behaviors and the development of the design process and applications of CFRC pipes.

2. Experimental investigation

When it is not possible to cover the entire actual conditions, laboratory test may be used to predict or understand the behavior of the system under the study with respect to some aspects of interest. Particularly, the time-dependent deformation (creep) under long-term loading relies heavily on experimental test results because the time-dependent deformation varies significantly with the materials and environment of the structural systems. In addition, long-term creep tests are very difficult to perform accurately because of the difficulty in executing the loading system, support conditions, expense and extensive test time required.

2.1 Pipe specimen

The CFRC pipe specimen had an inside diameter of 450 mm (18 in.), a length of 610 mm (24 in.), and a wall thickness of 38 mm (1.5 in.). CFRC pipe is manufactured by the Mazza process from meticulously mixed aqueous slurry of Portland cement (80~85%) and a mixture of relatively long and medium grade cellulose fibers (15~20%). This mix is then spread into a thin continuous layer, which proceeds through a vacuum dehydration process before being laminated and compressed onto mandrels to form pipes of the desired dimensions. After an initial pre-steaming phase, the mandrels are removed and the pipes are cured at high temperature (110~150°C) and high pressure (820 kPa) in an autoclave. This manufacturing process results in a composite with unique interfacial characteristics and nature. The cross sectional configuration of the pipe specimen and water tank for the creep test is shown in Fig. 1.

2.2 Short-term pipe strength

A design criterion used by engineers is to specify the strength of reinforced concrete pipe (RCP) for its applications. The D-Load represents the maximum force that will bear down on the RCP once it has been put in place and backfilled. The load includes the dead and live loads. The D-Load represents the sum of the dead and live loads divided by the diameter of the pipe. The manufacturer produces the pipe to meet the specified loading criteria. To determine the average pipe strength (D-load strength), a short-term test was conducted on three wet CFRC pipes immersed in a water bath for 21 days. Each pipe for the short-term test had an inside diameter of 450 mm (18 in), a length of 610 mm (24 in.), and a wall thickness of 38 mm (1.5 in). The short-term experiment was carried out on a MTS machine using the longitudinal axes of the pipe section, and the bearers were parallel with one another. The line of the applied load lied in the symmetrical plane to the bearers. The load was applied at a rate of 130 N/sec. (30 lbs/sec), and the pipe usually failed in 4-5 minutes after the initial loading. Fig. 2 illustrates the short-term test set-up used in this study.

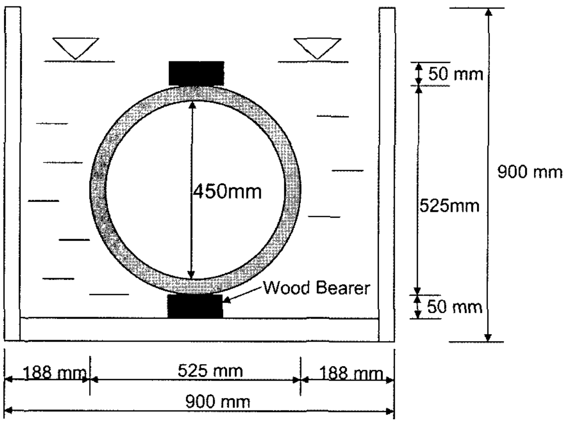

Fig. 1 Configuration of pipe specimen.

A typical load-vertical displacement diagram for the pipe under short-term loading is shown in Fig. 3. The ultimate pipe strength was obtained when the pipe failed with some longitudinal cracks in bottom. This curve shows a linear relationship up to a point known as the proportional limit, which essentially coincides with the first crack, and then the load suddenly dropped and picked up a little until pipe was broken down. Unlike the plain concrete and steel reinforced concrete pipes, this phenomenon comes from the effect of cellulose fibers. The addition of cellulose fibers in the pipe increased the ductility compared to the ductility of the pipe without fibers. This attests for the fact that the reinforcing fibers provided the roles to resist cracking and failure mode.

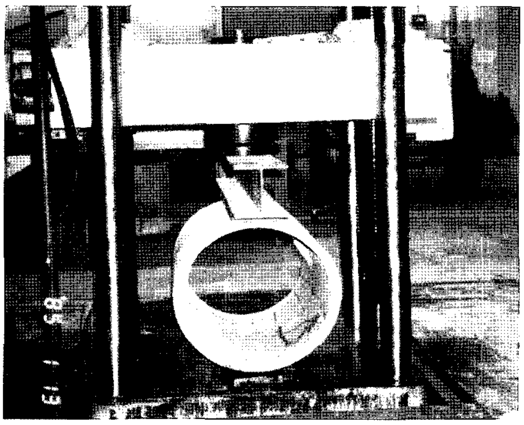

Fig. 2 Short-term CFRC pipe test set-up.

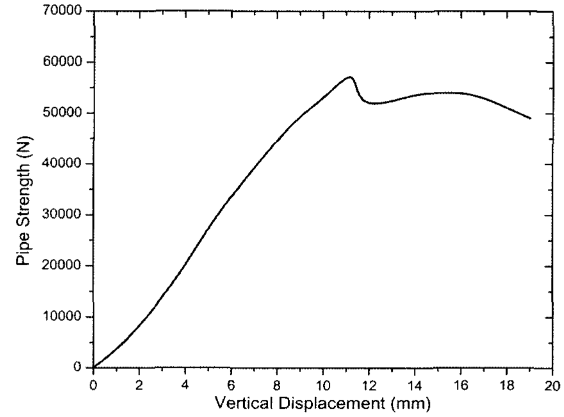

Fig. 3 A typical load-deformation of CFRC pipe.

The result of the short-term pipe tests for ultimate pipe strength and D-load strength is given in Table 1. The average ultimate pipe strength and D-load strength obtained in this study are 59.73 kN and 2.14 kN with standard deviation of 1.5 kN and 0.048 kN, respectively.

2.3 Creep test setup

The experimental works of creep study for the CFRC pipe were carried out in the laboratory kept at a constant temperature of 22°C ± 2°C (73°F ± 5°F) and relative humidity of 50% ± 0.5%. Prior to each creep test, each pipe specimen was immersed in a water bath for 21 days before it was transferred to a water tank. The loading apparatus used in the present work is a simple level-arm system, which has a length of 3,048 mm (10 ft) and 1,450 N (326 lbs) weight of two MC 9 × 25.4 steel beams fixed to a column with a pin connection by two channel sections. The loading sags are suspended at the end of the level-arm to apply the required sustained loading with steel bearing balls. The water tank had 914 × 914 × 1,829 mm (36 × 36 × 72 in.) dimension. The tank was built with steel plates and was coated with epoxy on both interior and exterior walls and base plate. Fig. 4 shows a schematic illustration of the level-arm loading test setup. Additionally, Fig. 5 shows the actual pipe creep setup for this study after loading. The loading sag at the end of the level-arm is gradually applied manually at a constant interval time.

A total of six loading levels, 19.71 kN, 25.68 kN, 28.07 kN, 32.85 kN, 35.84 kN and 41.82 kN, were investigated in this study. These values represent 33%, 43%, 47%, 55%, 60%, and 70% of the average ultimate pipe strength obtained from the short-term test, respectively. Table 2 summarizes the details of creep test with the applied loading levels.

In Table 2, the creep loading by different loading levels was applied to the pipe specimen using the loading sags at the end of the level-arm. The applied load at the end of the level-arm was calculated using the equilibrium equation for the moment about the pin point of level-arm. The free-body diagram of the level-arm system with applied load ($P_{applied}$), location of level-arm weight and creep load (P_{creep}) is shown in Fig. 6. The balancing for the location (1,603 mm) of the level-arm weight from the pin point was determined by trial and error method.

Table 1 Pipe strength from short-term test.

No. of specimen	Ultimate pipe strength (kN)	D-load strength (kN/cm/cm)	Visual results
1	58.88	2.112	Longitudinal cracks observed at bottom, and more ductile failure mode observed
2	60.77	2.180	
3	59.55	2.136	
Average	59.73	2.143	

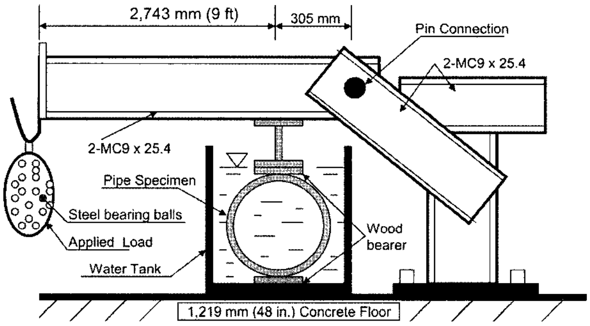

Fig. 4 Schematic test setup for the creep of a CFRC pipe.

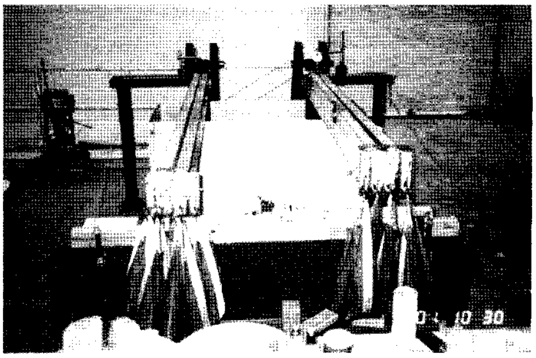

Fig. 5 Actual creep test of a CFRC pipe.

Using the equation of equilibrium about the pin point, the applied load at the end of level-arm can be calculated as follows:

$$P_{Applied} = \frac{(P_{creep} \times 305) - (1,450 \times 1,603)}{3,048} \qquad (2)$$

From Eq. (2), the applied load is calculated and is shown in table 2. A dial gauge was installed in each pipe specimen to measure the vertical displacement under creep loading. The displacement readings were recorded at the following time intervals;

Step 1: Once each 10 minutes for the first hour,

Step 2: Once each 1 hour for the next 23 hours following Step 1,

Step 3: Twice each day for the next one month following Step 2,

Step 4: Once each day until the end of the experiment.

The creep tests on CFRC pipes under six different loading levels continued until the vertical displacement of the pipe was stabilized, or the pipe failed.

3. Experimental results and discussion

Fig. 7 shows the experimental creep strain obtained for each of the six loading levels. As shown in Fig. 7, the creep strains of the pipe specimens subjected to loading levels less than 50% of their ultimate pipe strength were stabilized for approximately

Table 2 Creep test matrices and applied loading level.

Loading level (%)	Creep loading (kN)	Applied load at the end of level- arm(kN)
33	19.710	1.208
43	25.684	1.806
47	28.073	2.045
55	32.852	2.523
60	35.838	2.821
70	41.811	3.418

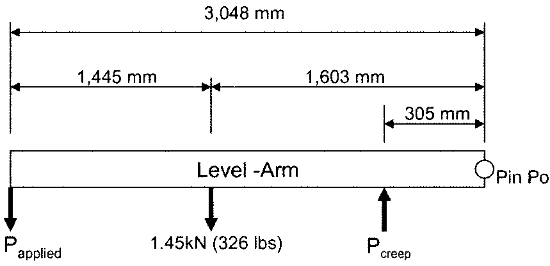

Fig. 6 Free-body diagram of level-arm system.

900 hours, and the pipe specimens did not fail. The creep strains of the pipe specimens subjected to loading levels of 55%, 60% and 70% of their ultimate pipe strength gradually increased until the specimens failed. The pipe specimen subjected to the loading level of 55% failed the last in this study after approximately 950 hours, and the pipes subjected to loading levels of 60% and 70% failed after approximately 350 and 7 hours, respectively. The creep strain curves shown in Fig. 7 exhibited a typical creep curve having primary, secondary and tertiary phases and manifested a relatively short time frame of the tertiary phase in cases of failed pipes. A similar result was reported in reference 4 (MacDonald, Bullen, and Beal).

When evaluating the results of a creep test, we can specify allowable load values and then calculate the factor of safety for design. An appropriate factor of safety is chosen by several considerations such as the accuracy of load and the consequences of failure. A factor of safety (FS) applied for CFRC pipes under long-term loading can be calculated as follows;

$$FS = \frac{\text{Ultimate pipe strength(\%)}}{\text{Initial pipe failure strength(\%)}} = \frac{100}{55} \qquad (3)$$

From Eq. (3), a factor of safety of 1.82 is proposed for the allowable load in the design of a CFRC pipe. The time-to-failure and the creep loading level of the pipes were established to obtain the regression factor (*R*). The regression factor (*R*) can be substituted in Eq. (1) described earlier. A plot of these data in logarithmic scale is shown in Fig. 8 with log-load on the ordinate and log-time on the abscissa. The log-loads are the failure loading levels from the creep loading levels of 55%, 60% and 70% of the ultimate pipe strength. By regressing this log-load and log-time relation linearly, the regression factor (*R*) is calculated. The regression factor is the regression ratio that describes the relationship between the initial strength of pipe and the estimated strength of pipe at 50 years in a saturated condition. A regression factor of 1.88 was estimated in this study. This regression factor of this study may be compared to that of Concrete Pipe Association of Australasia.[2] It was approximately the same as that determined by Concrete Pipe Association of Australasia. This result is depicted in Fig. 8 with the regression equation.

4. Conclusions

This paper has presented a comprehensive experimental study on time-dependent behaviors of saturated cellulose fiber reinforced cement pipe under long-term sustained loading. Based on the experimental results and data analysis, the following conclusions are drawn;

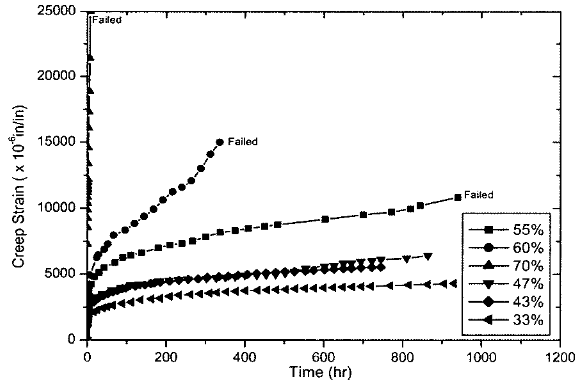

Fig. 7 Creep strain of CFRC pipes.

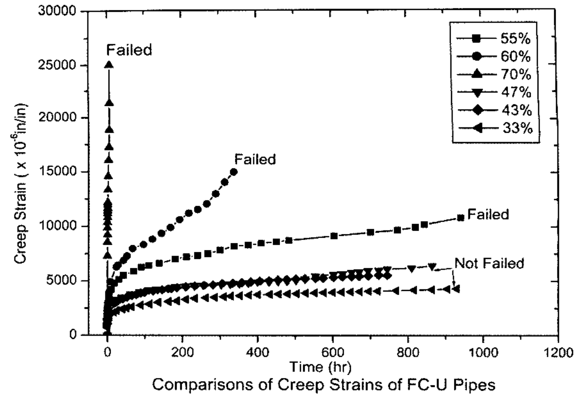

Fig. 8 Log-load and log-time relation.

1) For load levels higher than 50% of the ultimate pipe strength, the maximum creep strain of CFRC pipes increased 25-50% for every 5% increase in the loading level. The obtained creep strain curves were of a typical creep curve having primary, secondary and tertiary phases and exhibited a relatively short time frame of the tertiary phase in cases of failed pipes.

2) A factor of safety FS of 1.82 is proposed for the design of a CFRC pipe under long-term loading based on the test results of loading level and failure of the pipe.

3) A regression factor of 1.88 is estimated from the regression analysis for the service life of the CFRC pipe in saturated condition.

4) More reliable test data and analytical model should be developed in the future for better understanding of the time-dependent behavior of a CFRC pipe system.

Acknowledgments

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