Sustainable Smart Self-Sensory Infrastructures for Leakage Detection

MEREL TANNOUS ABAYA and YISKA GOLDFELD

ABSTRACT

The study aims to develop sustainable smart self-sensory infrastructures with leakage detection capabilities. To answer this goal the study offers to combine two advanced technologies, namely: smart textile reinforcement (TR) and magnesium phosphate cement (MPC). The TR is produced with AR-glass and carbon yarns, in which the electrical conductivity of the carbon yarns enables them to be used also as smart self-sensory agents. The study presents the feasibility of the TR-MPC smart pipe concept by demonstrating its production possibilities, as well as its sensory capabilities to detect and distinguish between the magnitude of leakage events.

INTRODUCTION

The design and development of advanced, environmentally friendly, and sustainable infrastructures with integrated monitoring capabilities is one of the challenges of modern society. To face these challenges, the current study offers to develop smart and environmentally friendly infrastructure systems by combining two advanced technologies, namely: smart textile reinforcement (TR) and magnesium phosphate cement (MPC). Textile reinforcements are usually composed with Portland Cement (PC) matrices to construct thin-walled 2D and 3D textile reinforced concrete (TRC) structures (e.g. [1]). If the textiles are produced with electrically conductive yarns, such as carbon yarns, smart self-sensory systems can be developed [e.g., 2-5].

Recent study demonstrated that smart TRC pipes with integrated monitoring capabilities can be developed [6]. In such case, since the smart-sensory system is an integrated part of the reinforcement system, it can overcome some of the drawbacks of traditional sensory systems that are inherently separated from the structural system [e.g. 7-9]. Yet, the production processes of PC based matrices have a negative impact on the environment, and in case of aggressive environment, such as in cases of underground and buried pipe systems that convey aggressive liquid, PC based matrices are rapidly deteriorated. These are crucial aspects that must be considered in the development of a new age of pipe system.

Faculty of Civil and Environmental engineering, Technion City, 32000, Haifa, Israel

Magnesium phosphate cement (MPC) matrix offers green and durable alternative for PC. It is mainly related to the minimal carbon dioxide emission footprint associated with the production process of the matrix [10]. The advanced properties of the matrix include: high early age strength, fast setting and hardening time, low dry shrinkage, high bonding to various surfaces, high resistance to corrosion, and due to its excellent chemical resistance - long service life durability [e.g. 11, 12]. These properties are perfectly adjusted to the requirements of underground pipe systems.

The hypothesis of this study argues that by combining the two technologies, improved smart pipes with enhanced structural performance and monitoring capabilities can be developed. The study presents the idea based on an experimental investigation that considered the fabrication of the pipe, the monitoring system, the structural and the functional performances, and the mutual requirements of the above aspects. The study demonstrates that the integrated sensory system has the capability to detect leakage through cracked zones, and to estimate its severity.

SMART SENSORY CONCEPT

The sensory platform is based on textile that simultaneously serves as the main reinforcement system and as the sensory agent. The reinforcement materials consist of two types of yarns: yarns made of AR-glass fibers and yarns made of carbon fibers. The material properties are given in [13]. By taking advantage of the electrical conductivity of the carbon yarns, they serve as the smart-sensory agent. Accordingly, carbon yarns are positioned to answer both purposes. This means that in case of pipe systems, the carbon yarns are positioned along the circumferential direction [6].

The sensory concept assumes that infiltration of water occurs at cracked and damaged zones along the pipe. In such scenarios the carbon yarns are exposed to water which changes their electrical properties. It was reported that a consistent and clear electrical reading is obtained if two adjacent carbon yarns are electrically linked due to infiltration of water [14, 15]. A schematic layout of the chosen electrical setup is illustrated in Fig. 1, see also [6]. One end of each carbon yarn is connected to one of the terminals of the AC power source, in our case Wayne Kerr LCR meter 4300 (frequency range of 20Hz-1MHz). Due to wetting, the electrical characterization of the system is changed, from capacitance to resistance. As a result, pronounced and sensitive electrical readings are obtained. On the one hand, the single connection to the DAQ, simplifies the installation of the electrical connections, but, on the other hand, it limits the sensing capabilities to an integrative mode. It means that the system is able to identify the occurrence of wetting events in each pipe segment, but not its exact location within the segment.

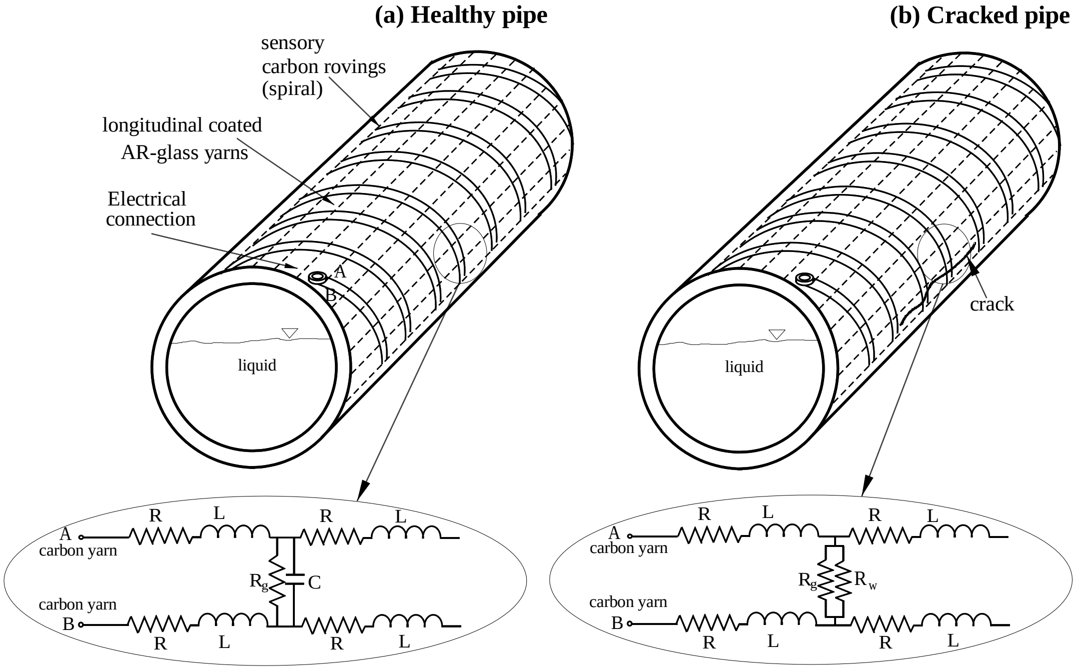

Figure 1. Schematic layout of the pipe and the sensory concept: (a) Healthy state; (b) damage state; (c) electrical circuit. Following Ref. [6]

This concept has been demonstrated in the case of TRC structural elements [6]. The hypothesis of this study argues that due to the advanced electrical properties of the MPC matrix, that is characterized by a high electrical resistivity compared to PC matrix [5], the electrical readings are enhanced which ultimately affect the sensory capabilities.

FABRICATION OF SMART TR-MPC PIPE SYSTEM

The study adopts the fabrication process developed in [16] for TRC pipe system. It is demonstrated that the same process can be used to MPC based matrix. Moreover, since MPC matrix is characterized by fast setting time, the demolding process was conducted only few hours after the casting process. This is an advantage in the construction industry that enables fast production process of TR-MPC pipes.

A single reinforcement cage was used and positioned in the middle of the pipe cross-section. The cage was manufactured by a filament winding process. First, AR-glass yarns were positioned in the longitudinal direction and then a pair of carbon yarns were continuously winded above the AR-glass yarns in the circumferential direction. Both yarns were slightly pre-tensioned during the winding process. The mesh opening between longitudinal AR-glass yarns and circular carbon yarns is specified as 10 mm. After the winding process, a pre-treatment procedure in terms of coating by styrene-butadiene rubber (SBR) was applied, see Fig. 2a and further details in [16].

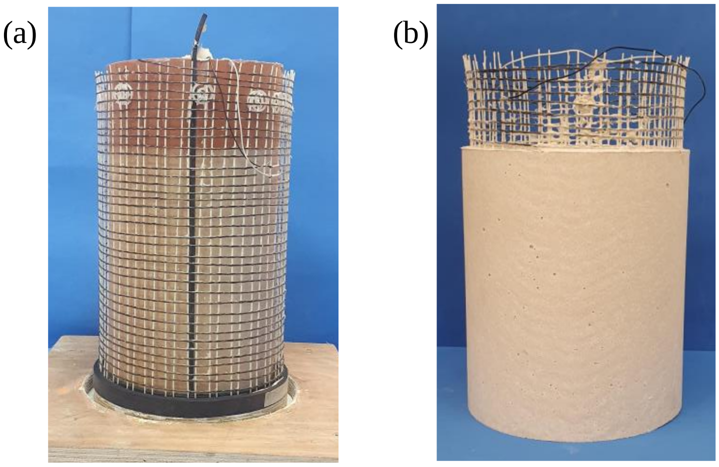

Figure 2. (a) The textile cage within the mold before casting, following Ref. [16]; (b) The TR-MPC pipe.

The mold that was designed in case of TRC pipes [16] was used in this study. The mold consists of two main cylindrical parts (internal and external) that were cut along the longitudinal direction. Along the cut edge a thin rubber strip was attached to prevent leakage of the wet matrix. Spacers were used to position the reinforcement cage in the middle of the mold during the casting process.

The pipes were cast using MPC matrix. The study uses a mixture produced by ICL group LTD, its commercial name is Phosment. The matrix is characterized as potassium-based MPC (K-MPC) and it doesn't involve any ammonia in the chemical reaction. The MPC matrix was supplied as a dry material (powder) and was prepared with 1.5 kg of water per 6 kg of dry material. Additive short Aramid fibers (produced by Teijin company Ltd, the commercial name is Technora CF320) were added to enhance the ductility of the structure. The volume fraction of the fibers is 0.5%. The mean values ± standard deviations of the flexural and compression strengths were determined according to EN 196-1:2005 and were 12±1.1 MPa and 67±4.7 MPa, respectively. Fig. 2b presents the TR-MPC pipe after the casting procedure. The geometrical dimensions of the pipe: 272 mm length; 202 mm inner diameter; 18 mm thickness.

INVESTIGATING THE SENSORY CAPABILITIES

In order to investigate the sensory capabilities of the TR-MPC pipe, especially its monitoring capabilities to distinguish between the magnitude of the leakage associated with the severity of the cracks, three wetting tests were investigated. The tests are associated to: the healthy state - before any loading procedure; the design state – after the crushing test; and the damage state – after the monotonic loading.

The design state of concrete pipes is determined by their functional-structural performance, according to acceptable standards and codes. The performance is usually determined by crushing tests of three edge bearing test (TEBT) setups, see Fig. 3a. Ref. [16] adopted these concepts and adjusted them to TRC pipes. Following ref. [16], the current study estimated the proof load of MPC pipes from the minimum crushing load.

It is found that the minimum crushing load of the investigated MPC pipes is F_n=13.4 kN/m and, as a result, the proof load is F_c=0.67F_n=9 kN/m. Both values are higher by 33% compared to TRC pipes with the same geometrical configuration, which is associated with the advanced material properties of the MPC matrix.

Since it is assumed that the pipe gravitationally conveyed liquid, the study focuses on the invert crack, located at the inner lower part of the pipe. The three wetting tests were conducted with tap water (electrical conductivity of 1200 µSiemens and temperature of 23^{o}C) at an unloaded state, see Fig. 3b. The amount of water was specified as 100 ml and the water was sustained at the pipe invert for 1400 sec. In each structural state the pipes were tested on a dry surface.

Therefore, the sensory capabilities are investigated by the following procedures:

- Performing first wetting test at the healthy state, the light blue line in Fig. 4c.
- Performing crushing test that determines the design state of the pipe, see Fig. 4a. It is seen that the width of the invert crack, measured by the DIC technology, is smaller than 100 µm and is considered a micro-crack.
- Performing second wetting test at the design state, the red line in Fig. 4c.
- Performing monotonic loading test, see Fig. 4b, which aims to degrade the structural health. It is seen that the width of the invert cracks at the end of the loading is 550 µm, and the crack is classified as a damaged state.
- Performing third wetting test at the damage state, the black line in Fig. 4c.

Results from Fig. 4 reveal that the smart sensory system successfully detects the leakage immediately after the wetting event (at 100 sec) and after a relatively long term (after 1400 sec). Moreover, the sensory system has the capability to distinguish between the magnitude of the water infiltration, which is ultimately associated with the structural health. Higher changes in the impedance are correlated to the degradation of the structural state and, as a result, to extensive water leakage.

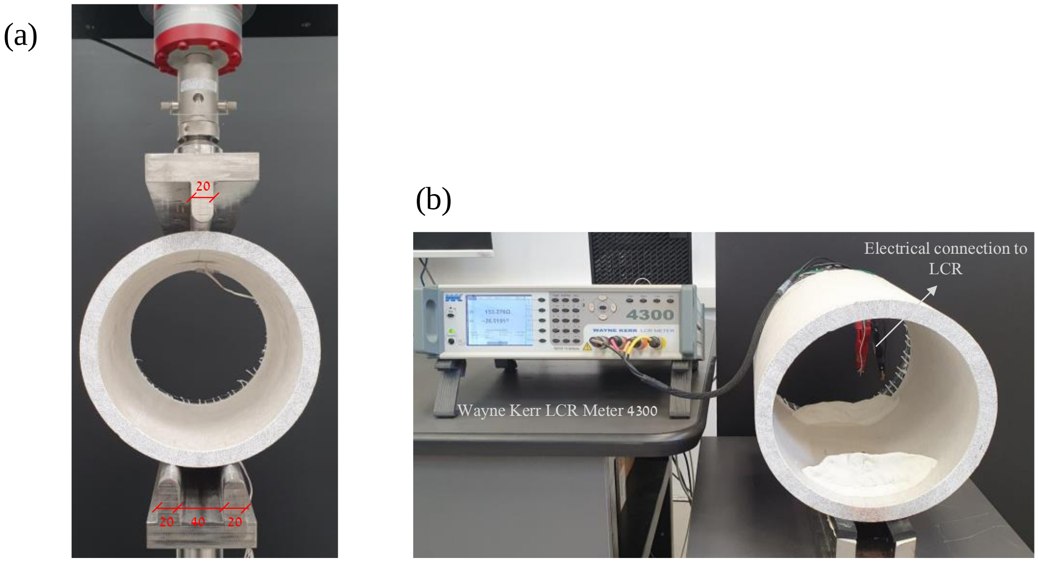

Figure 3. (a) The three edges bearing test setup, following Ref. [16]; (b) The wetting test setup, following Ref. [6]

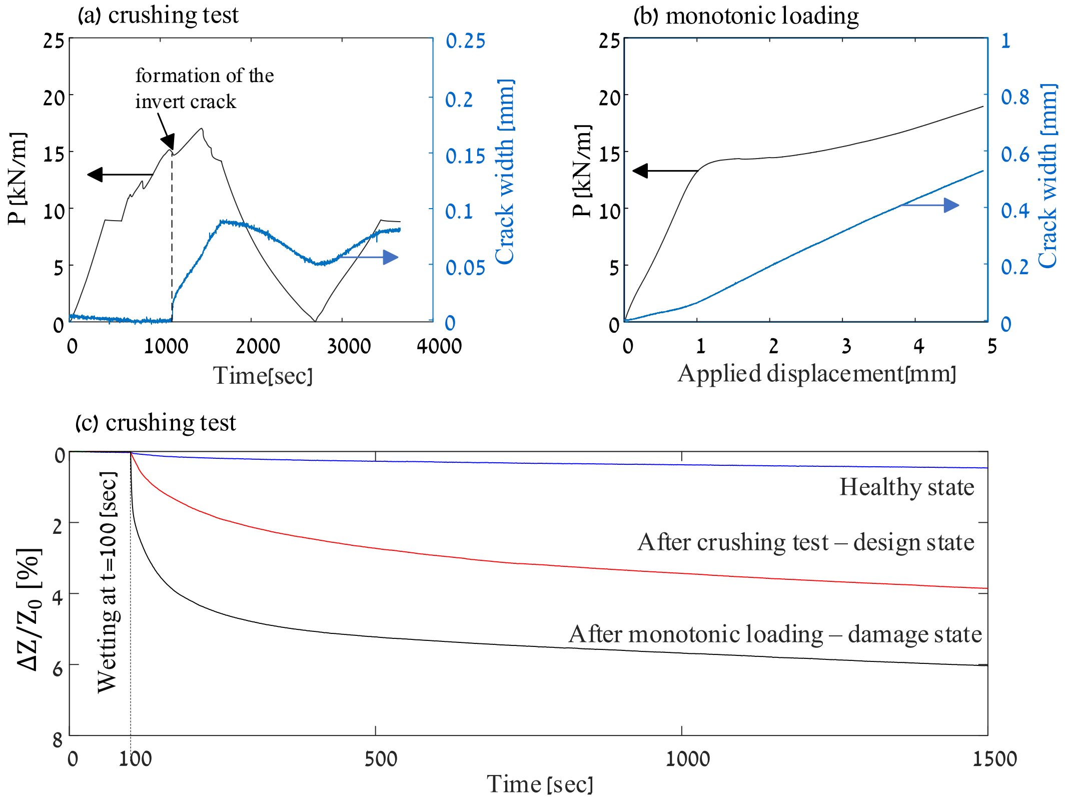

Figure 4. (a) Results from the crushing test (load and crack's width versus time); (b) Results from the monotonic test (load and crack's width versus applied displacement); (c) results from the three wetting events.

SUMMARY

The study demonstrated that the synergy between carbon-based textile and MPC matrix yields advanced and sustainable smart self-sensory pipe system. The experimental investigation, as well as the production process, were conducted with respect to structural, functional and sensory responses. Results demonstrated the efficiency of the hybrid monitoring system to detect and distinguish between the magnitude of the leakage associated with the structural health. The degradation of the structural health and the extension of the crack, affect the magnitude of the leakage, and is reflected by the electrical signals.

The study presented the advanced capabilities of smart TR-MPC pipes, and, accordingly, took a major step toward the realization of smart and sustainable infrastructures with self-monitoring capabilities.

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