INTELLIGENT TEXTILE AND FIBER REINFORCED MPC COMPOSITES FOR SHM

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ABSTRACT

This study develops novel intelligent composite structural elements combining three advanced technologies: magnesium phosphate cement (MPC) matrix, smart-self sensory carbon-based textile reinforcement system, and additive short-dispersed fibers. In such system, the carbon rovings simultaneously serve as the main reinforcement system and the sensory agent. The material properties of the MPC matrix include minimization of environmental effects, high flexural strength and enhanced rheological properties which is an advantage in textile reinforcement system. From the sensory point of view, MPC is electrically insulated matrix which enhances the measured electrical signal from the carbon rovings.

Experimental investigation demonstrates the advanced capabilities of the new hybrid structures. The investigation compares between the structural and electrical responses of textile reinforced MPC elements and TRC elements under flexural loading. The structural-electrical correlation enables to further explore new composite configurations and to develop enhanced smart self-sensory systems. The study demonstrates that by merging MPC mixture with textile and fiber reinforcement systems, it is possible to design and construct thin-walled, elements with advanced structural and self-sensing capabilities.

KEYWORDS

Intelligent structures; Advanced structural response; Enhanced sensory capabilities; Textile and fiber reinforcement.

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INTRODUCTION

The technology of textile reinforced cementitious structures (TRC) is based on the synergy between the high compressive strength of the concrete and tensile strength of the textile. The technology enables to construct thin-walled structural elements with advanced structural performance, to reduce the amount of consumed building materials, with the benefit to integrate structural health monitoring (SHM) systems [8-9,12,14,16]. To further enhance the structural and sensory capabilities of the TRC technology, the current study investigates the use of magnesium phosphate cement (MPC) which is a perfect candidate for development of smart TRC structures.

MPC is an eco-friendly material that is characterized by a high early strength [15,18], high corrosion resistance and advanced bonding with existing concretes. These qualities were mainly used for development of rapid retrofitting existing concrete structures and roads [19]. Recent studies investigated the possibility to merge MPC mixture with textile for strengthening of reinforced concrete elements [22]. Furthermore, the improved rheological and electrical properties of the MPC is advantageous for textile reinforced composites from both structural [4] and sensory aspects [20]. The current study investigates the combination of MPC matrix with textile and fiber reinforcement systems for development of light, and optimal structural elements with integrated self-monitoring system.

Generally, textile reinforced cementitious structures are based on Portland cement (PC) matrix. The level of impregnation of the matrix into the roving cross-section affects the load transfer mechanism and govern the overall structural response [10-11,17]. It is affected by the properties of the matrix and the bundle of filaments that characterize rovings, and results in partial roving impregnation. Accordingly, the roving is usually divided into two sub rovings that called sleeve and core [21]. The load transfer mechanism of the sleeve filaments is based on adhesion with the concrete matrix, while the core filaments carry stress by cohesion with the neighboring filaments. The volume fraction of sleeve to core filaments significantly affects the overall structural response. Therefore, the research in this focus on exploring the bond mechanism and the parameters that governed it [3,13]. The resultant macrostructural response of TRC composites can be divided into four main states according to the ACK model. State I, is the healthy state; State II, in which distributed multiple microcracks are formed, is the design state of the element; State III, in which the existing cracks expand and propagate, is related to the damage state; and State IV, in which the rovings are pulled out from the matrix, leads to failure of the element [1].

PC based TRC structures were investigated for SHM purposes such as monitoring the load pattern [2], distinguishing between micro and macro-cracks [5] and detecting accumulated damage [7]. Further research investigated the effect of textile configuration, which change the textile-matrix bond mechanism, on the SHM capabilities [6]. The current study argues that the advanced rheological and electrical properties of MPC matrix enhance the bond mechanism, and accordingly will be reflected by advanced monitoring capabilities. The study investigates three types of composites: textile reinforced PC matrix (TRC), textile reinforced MPC (TR-MPC) and TR-MPC with additive short aramid fibers. The experimental investigation is based on monotonic flexural loading tests and focuses on the effect of the composite configuration on the structural and electrical responses, and the correlation between them.

EXPERIMENTAL INVESTIGATOIN

Materials

The study aims to develop new textile reinforced composite elements, with enhanced structural and sensory capabilities. The investigation focuses on three different types of matrices: Portland cement (PC); plain MPC; and MPC with 0.5% of additive short aramid fibers. The PC matrix is classified as a fine-grained matrix. This study uses a commercial mixture (Sika grout 214). The MPC matrix is a commercial potassium-based mixture (K-MPC) called Phosment, produced by ICL LTD. The short aramid fibers (AF) are commercial product of Teijin Fournier LTD, called Technora and their typical length is 3mm. The material properties of the AF are given in Table 1. In case of TR-MPC with additive AF, the fibers were added to the water and then mixed with the dry MPC powder.

The PC and MPC mixtures were prepared with water to dry material ratios of 1:8 and 1:4, respectively. The flexural and compression strengths of the matrices were tested at age of 28 days by using 40/40/160 mm and 50/50/50 mm specimens. The mean compression and flexural strengths and standard deviation of PC, MPC, and MPC with short AF are: ($6.33 \pm 0.1, 67.99 \pm 0.14$), ($9.90 \pm 0.42, 69.35 \pm 1.5$), ($11.29 \pm 0.95, 72.75 \pm 2.64$).

The textile reinforcement is a generic glass-carbon bi-axial mesh with mesh size of 7-8 mm [4-7] The warp direction is composed of 6 AR-glass rovings and 2 carbon rovings, while in the weft direction only AR-glass rovings are positioned. The material properties of the textile and short fibers are given in Table 1.

The geometrical dimensions of the beam specimens are length 300mm, width 70mm, height 15 mm. Each beam is reinforced with a single textile layer, located 5 mm above the lower face of the beam. The textile layer is slightly pretensioned in the mold before casting, see Fig. 1.

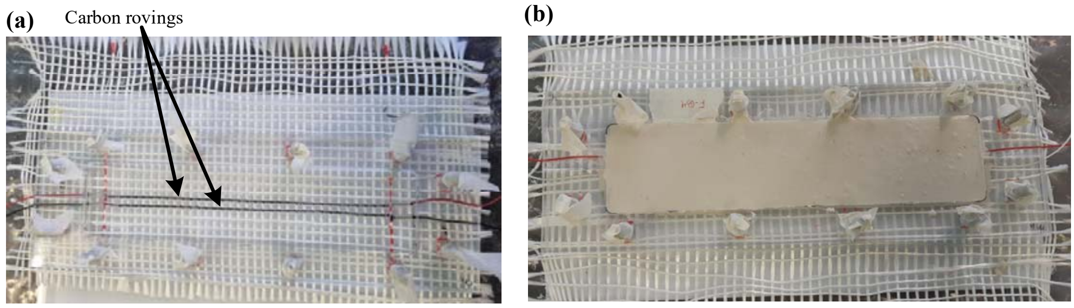


Figure 1. Beam specimen in the mold: (a) Before casting, (b) After casting.

Table 1. Material properties of the textile and short fibers [4,5].

	AR-Glass roving	**Carbon roving**	**Aramid fibers (3 mm length)**
Specific mass density [g/cm^3]	2.68	1.8	1.39
Modulus of elasticity [GPa]	72	270	65-85
Filament Tensile strength [GPa]	1.7 (elongation 2.4%)	5 (elongation 1.7%)	3.2-3.5 (elongation 3.9-4.5%)
Filament diameter	19 μm	7 μm	12 μm
Linear density [Tex]	2,400	1,600	-
Electrical resistance [W/m]	Infinity	13	Infinity

Methods

The study investigates three different cementitious composites: PC based TRC, textile reinforced MPC (TR-MPC) and TR-MPC with additive short fibers. The specimens were experimentally tested in monotonic flexural loading tests by using a four-points bending scheme [4-7,20]. The beams span length was 210 mm and the distance between the load points was 70 mm. The experiment is performed in a displacement control mode in loading rate of 0.1 mm/min by using an Instron loading machine (Model 5966), see Fig. 2(a). The specimens were loaded from the healthy state and up to the ultimate load capacity, the experiments were terminated at a drop of 15% of the ultimate load. The DIC method was used to monitor the displacement field at the front face of the beam, and to analyze the formation and propagation of cracks. The front face of each beam is photographed along the experiment for the DIC analysis (1 photo every 3 seconds).

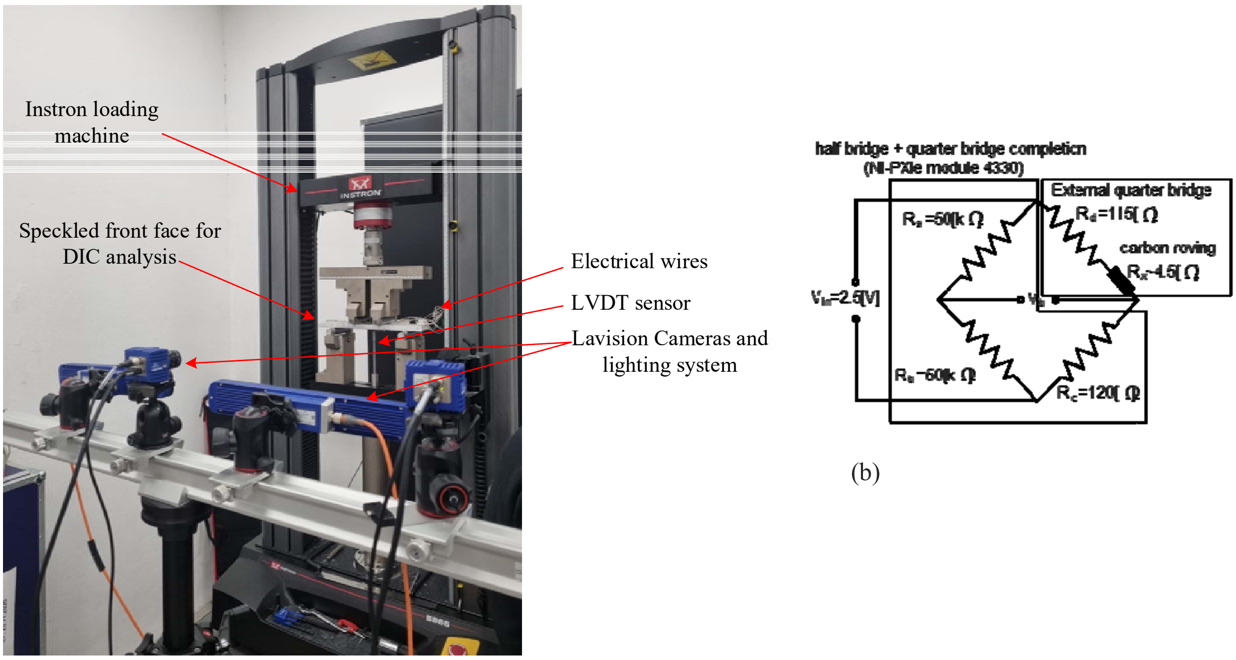
The study utilizes the piezoresistive capabilities of the carbon rovings. The sensory concept is adopted from [6] and is based on DC measurements by using a Wheatstone bridge electrical circuit. Each carbon roving functions as electrical resistor that is connected to an individual bridge. The measured voltage changes across the bridge is used to evaluate the integrative electrical resistance change (ERC) of the carbon roving, by using the following equation, see also Fig. 2(b):

$$R_x = V_{in}\frac{R_c}{V_b + \left(\frac{R_b}{R_a + R_b}\right)V_{in}} - R_c - R_d \tag{1}$$

Where R_x is the rovings integrative resistance, V_{in} is the excitation voltage, R_a, R_b, R_c, R_d are known resistors, and V_b is the measured voltage change across the bridge. The ERC is measured relative to the electrical resistance at the beginning of the experiment, which represents the healthy state. The study also adopts the compensation procedure of environmental parameters such as temperature and moisture by using a non-loaded reference beam [6]. Accordingly, the ERC which is solely related to structural-mechanical change is calculated as follows:

$$\Delta R = R_x - R_0 - \Delta R_{reference} \tag{2}$$

The study explores the structural performance and the structural-electrical correlation for each of the composite beams. The structural electrical correlation is based on two integrative values. The first is the ERC, which is measured over the length of roving, and the second is the strain at the front face of the beam, that is correspondingly calculated over the length of the roving. It means that according to this sensory concept, only an integrative measure of the structural health is obtained, which limit the possibility to identify the exact location of a crack. Yet, it was demonstrated that the integrative measurements yield sufficient information that can be used for SHM purposes [4-7].



(a)

Figure 2. (a) Experimental test setup: Specimen, loading machine and DIC system, (b) DC measurement by Wheatstone's bridge scheme [6].

RESULTS AND DISCUSSION

Fig. 3(a-c) presents the structural and electrical response of the three composite beams. The figure also presents the formation and propagation of cracks along the experiment, see Fig. 3 (d-f). The structural-electrical correlation is presented in Fig.4 by the measured relative ERC versus the integrative strain along the roving. The results highlight several observations:

First, from Fig. 3 it is seen the structural response of the three composites can be divided into the four main structural states that characterized textile reinforced cement beams. Yet, each beam is characterized by a different structural response. The differences between the beams are explained by the matrix properties and especially by the different bond-mechanism between the textile-fiber reinforcement and the matrix. In state I, the differences in the first cracking loads are associated with the higher flexural strength of the MPC matrix (0.92-1.3 KN for TR-MPC and 0.33 KN for the TRC). In state II, the differences are observed by the number and severity of the cracks. While in case of TRC multiple micro-cracks (up to 150 mm) are formed, in the TR-MPC the matrix is relatively brittle which result in formation of only two macro-cracks, see Fig. 3(d-e). This behavior is improved by adding short AF to the MPC matrix Fig. 3(c,f). The contribution of the short AF in this state is reflected by higher ductility and by adding new cross links with the matrix that result in multiple microcracks and wider range of State II. In state III, the improved bond mechanism of MPC composites is expressed by enhanced strain hardening behavior and higher ultimate loads that are carried by the improved composite elements (1.21-1.91 KN for TR-MPC and 1.13 KN for the TRC).

Second, it is observed that there is a consistent increase in the ERC signal of the three specimens. Yet differences between the trend and intensity of the signals are also observed. In case of MPC based specimens (Fig. 3(b,c)) the intensity of the ERC signal is higher along the entire structural-electrical response (0.26-0.31% for TR-MPC and 0.19% for the TRC at the ultimate load). Furthermore, while in TRC specimen (Fig. 3a) the trend of the ERC is dependent on the structural state, in the TR-MPC the trend is relatively linear. These differences are associated with the structural states and the microstructural mechanism of each composite configuration. In case of TRC the mechanism is changing from sleeve controlled in state II, to core controlled in state III, while in TR-MPC the contribution of the sleeve filaments remains consistent along the entire response, see Fig. 3(b-c).

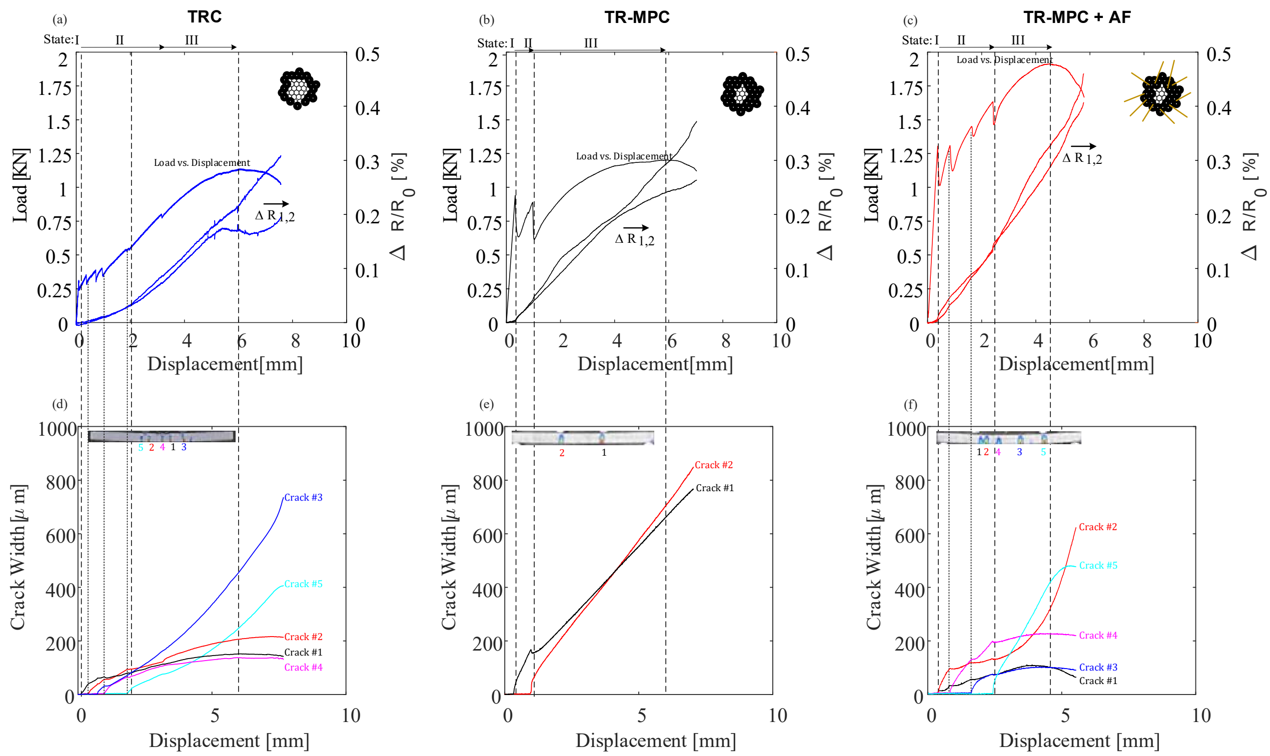


Figure 3. Structural and electrical response of TRC, TR-MPC and TR-MPC +AF: (a-c) load vs. displacement and ERC of the carbon rovings, (d-f) crack formation and propagation analysis.

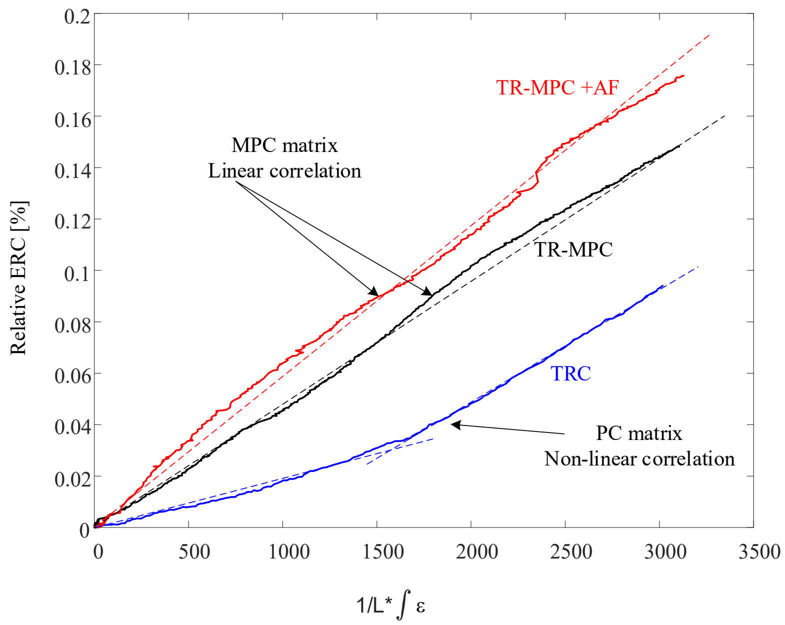


Figure 4. Comparison of the composites structural-electrical correlation: Linear correlation of MPC matrices and nonlinear correlation PC matrix

Third, the different composite configurations yield different structural-electrical correlations. It is associated with the bond mechanism of each composite, and especially the active sub rovings in each state, see Fig. 4. In case of TRC, the active sub-roving changes from sleeve to core (State II - State III). As a result, the structural-electrical correlation yields a non-linear correlation function [7]. In case of TR-MPC, the improved rheology is expressed by relatively high-volume fraction of sleeve filaments that are active along the response. It leads to a linear structural-electrical correlation, see Fig. 4. Furthermore, the contribution of the short AF leads to enhanced textile-matrix bond and higher ERC, which is expressed by higher trend of the structural-electrical correlation.

The above results show the advantage of MPC based composites from both the structural and sensory points of view. The improved rheological and electrical properties of the MPC matrix [4,20] result in enhanced structural response and sensing capabilities. The structural-electrical correlation reflects the unique bond mechanism of each composite.

CONCLUSIONS

This study investigated the structural and sensory capabilities of intelligent MPC based composite elements that were made of three types of matrices: PC, MPC and MPC with short additive fibers, reinforced with glass-carbon textile. The structural and electrical behaviors of the composites were investigated in flexural tests from a healthy state and up to the ultimate load. It is seen that the enhanced material properties of the MPC matrix resulted in advanced performance of the thin-walled element compared to the PC based TRC. The MPC based composites exhibited higher cracking loads and ultimate carrying loads. The contribution of the short fibers to the TR-MPC was expressed in enhanced cracking pattern and higher ultimate loads which indicated on the improved textile-matrix bond mechanism. Accordingly, the TR-MPC elements were characterized by enhanced sensory capabilities. It was expressed by higher ERC signal along the entire structural response, linear electrical trend, and higher SNR values. The differences in mechanical and sensory capabilities of the composites are associated with the matrix properties and the contribution of the dominant sub-roving to the structural-electrical correlation in each composite.

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