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Capacitance-based stress self-sensing in cement paste without requiring any admixture

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ABSTRACT

This work reports capacitance-based stress self-sensing in cement paste without requiring any particular admixture (whatever type). The in-plane capacitance is measured between two coplanar electrodes (aluminum foil) adhered to the cement slab by double-sided adhesive tape. The capacitance decreases with increasing normal stress, whether the stress is purely compressive or flexural compressive, due to piezoelectricity. The capacitance decrease is completely reversible in the low-stress regime (normal stress up to 19 kPa), and partially reversible above this stress. The minimum normal stress change detected is 0.2 kPa, which, in case of flexure, corresponds to a flexural stress change of 8.5 kPa. The change in capacitance per unit normal stress change is up to 0.061 and 0.101 pF/kPa for purely compressive and flexural compressive loading, respectively; the value is higher in the low-stress regime, which gives superior linearity and reversibility. Low-stress sensing is relevant to pedestrian monitoring and room occupancy monitoring.

1. Introduction

Self-sensing refers to the ability of a structural material to sense its own condition without the need for embedded or attached sensors. In other words, a self-sensing structural material is multifunctional material that is capable of both structural and sensing functions. Such a material is also said to be intrinsically smart. Relevant attributes to be sensed include stress, strain and damage. The sensing is preferably fast enough (short enough in the response time) that it is suitable for real-time monitoring.

Compared to the use of attached or embedded sensors, the advantages of self-sensing include low cost, high durability, large sensing volume and absence of mechanical property loss. This is because structural materials are necessarily low in cost and high in durability. Attached sensors tend to be not durable, as they can be detached. Embedded sensors tend to degrade the mechanical properties of the structural material.

Self-sensing has been reported in continuous carbon fiber polymer-matrix structural composites [1,2] and short carbon fiber cement-matrix composites [3–5], as achieved by measuring the electrical resistance. The resistance relates to the stress, strain, damage and temperature, due to the electrical conductivity of the carbon fibers compared to the polymer or cement matrix and the effect of these parameters on the fiber arrangement in a microscopic level. These fibers are not the sensors, but the composites are. The phenomenon of the resistivity changing with strain is known as piezoresistivity, which is exhibited by both continuous carbon fiber polymer-matrix structural composites and short carbon fiber cement-matrix composites. The implementation of the self-sensing involves the application of electrical contacts, which are not sensors.

The sensing of stress is typically more subtle than that of damage, particularly when the stress is in the elastic regime. Applications of the stress self-sensing in cement-based materials include the monitoring of the stress in bridges, highways, nuclear reactors, underground spaces, oil and gas wells that involve cementing, and deep sub-surface storage of natural gas or carbon dioxide. In the implementation of the new self-sensing technology of this work, electrodes can be wrapped around a concrete pipe and positioned at various points along the length of the pipe, for example. By using an array of electrodes, the stress distribution can be obtained.

The new sensing method presented here involves capacitance measurement and does not require any particular admixture in the

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cement-based material. This is in contrast to piezoresistive cement-based materials, which require conductive admixtures such as carbon fibers. The fact that particular admixtures are not required greatly widen the applicability of the technique, as the technique can be used for both new and existing structures.

Capacitance measurement has been previously reported for cement-based materials for the purpose of determination of the electric permittivity [6,7]. It has also been previously reported that the permittivity (which relates to the capacitance) of cement paste without any admixture increases upon the application of compressive stress (2.8–6.0 MPa) in the direction of capacitance measurement [8]. However, the capacitance increase is essentially irreversible, thus limiting the sensing to the highest stress experienced so far, rather than sensing the instantaneous stress [8].

The objectives of this work are (i) to extend the prior work [8] from high stresses (MPa range) to low stresses (kPa range) for achieving reversible capacitance changes due to stress, so as to provide capacitance-based self-sensing of the instantaneous stress in a cement-based material, (ii) to evaluate the efficacy of the capacitance-based stress sensing for sensing small stresses, which are relevant to pedestrian monitoring and room occupancy monitoring. (iii) to extend the prior work [8] from through-thickness capacitance measurement using sandwiching electrodes to in-plane capacitance measurement using coplanar electrodes so as to provide a sensing technology that is more amenable to practical structural implementation, and (iv) to extend the prior work [8] from expensive silver paint electrodes to electrodes that are more suitable for practical structural implementation.

2. Methods

2.1. Materials

Portland cement (Type I, ASTM C150, from Lafarge Corp., Southfield, MI) is used. The density of the cement powder is 3.15 ± 0.02 g/cm^3. The cement-based material studied is cement paste; no aggregate is used. The water/cement ratio is 0.35.

A high-range water reducing agent (Glenium 3000NS, BASF Construction Chemicals) is used at 1.0% by mass of cement. The defoamer (Colloids Inc., Marietta, GA, 1010, USA) is used at 0.13% (% of specimen volume). No other admixture is used.

Cement powder and water are mixed for 5 min using a rotary mixer with a flat beater. The cement mix is poured to an oiled plastic mold. After filling the mold, an external vibrator is used to facilitate compaction and diminish the air bubbles. The specimens are demolded after 24 h and then cured at a relative humidity of nearly 100% for 28 days. The demolded specimens are ground and burnished to ensure that the surfaces are smooth before capacitance measurement. During subsequent testing conducted at room humidity, the specimens do not change their water content or their functional performance. The cement-based material specimens are in the form of square slabs of size 48 mm × 48 mm x 4.39 mm.

2.2. Testing method

For measuring the in-plane capacitance, two coplanar electrodes on the surface of the cement specimen, with their proximate edges separated by a distance of 25 mm, are used (Fig. 1). Aluminum foil is used as the electrode. Commercial double-sticky adhesive tape (79 µm thick) is positioned between the aluminum foil (48 mm × 11.5 mm) and the specimen in order to adhere the specimen to the electrode. The tape also serves as a dielectric film, which is used due to the fact that an LCR meter is not designed for measuring the capacitance of a conductor. Although the cement-based material is not conductive enough to require the dielectric film, the film is used. No pressure is applied to the electrodes.

In the stress sensing investigation, force in the direction perpendicular to the plane of the specimen is applied to the 48 mm × 25 mm region between the two electrodes. The force is provided by using known weights positioned above this region. Two testing configurations are used. In configuration I, the specimen has no support, so that the applied normal stress is purely compressive. In configuration II, the specimen has two supports (48 mm × 3 mm each) that are positioned along the two opposite edges of the specimen, so that this configuration is not purely compressive, but involves flexure under three-point bending. In both configurations, the baseline (minimum) normal stress is 3.4 kPa (arbitrarily chosen).

The normal stress is progressively increased, with the specific values of the stress in the progression being arbitrarily chosen. The highest compressive stress of 283.4 kPa (arbitrarily chosen) is within the elastic regime of the specimen. The compressive elastic modulus is 2.92 GPa and the compressive strength is 57.9 MPa, as previously measured and reported by the research group of the present paper using materials of the same composition [9].

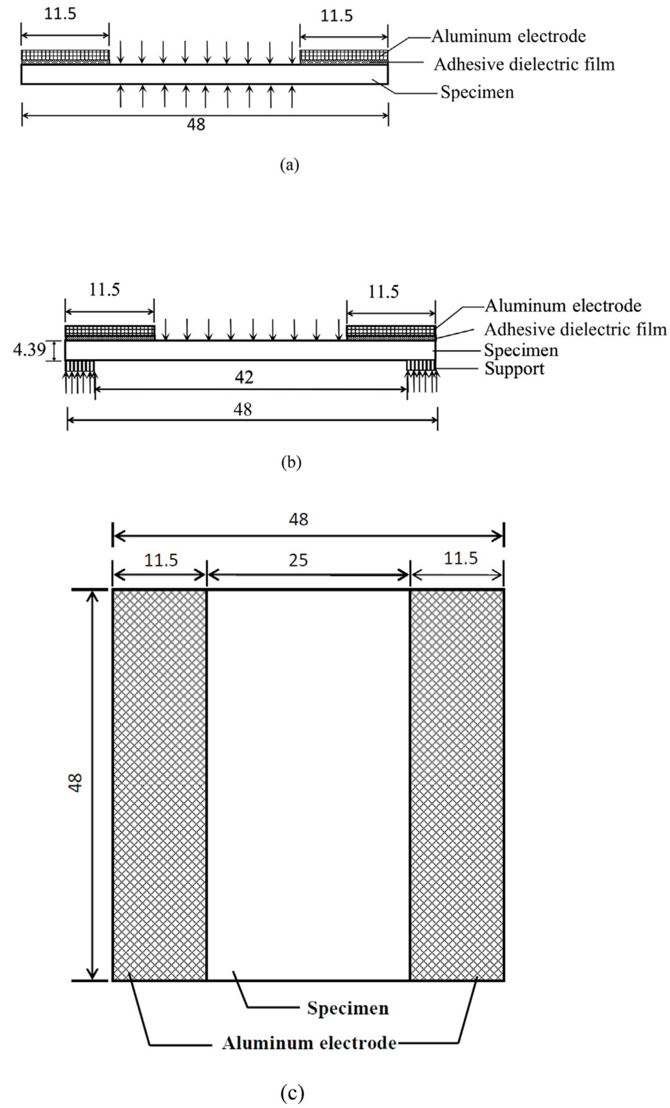

Fig. 1. Testing configurations. (a) Side view of testing configuration I (without supports, with the applied stress being normal compressive). (b) Side view of testing configuration II (with two parallel supports along two opposite edges of the specimen and the applied normal stress providing flexure). (c) Top view of either testing configuration. A normal force is applied to the entirety of the area between the electrodes. A dielectric film (double-sided adhesive tape) is positioned between each aluminum electrode and the specimen. All dimensions are in mm.