MULTIFUNCTIONAL CEMENT-BASED MATERIALS

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ABSTRACT. Multifunctional cement-based materials provide both structural and non-structural functions in the absence of embedded or attached devices. The non-structural functions include sensing, with the attributes sensed including stress, strain, damage and temperature, as needed for structural health monitoring, structural vibration control, room occupancy monitoring for building facility management, and pedestrian/vehicle monitoring for transportation control. Other functions include electromagnetic interference (EMI) shielding (as needed for avoiding electronic malfunction), deicing, radiation heating, and vibration damping. The achieving of a non-structural function may or may not require admixtures. Not requiring admixtures is preferred, as the technology can be applied to existing structures without the admixtures. Sensing can be provided by measuring either the resistance or capacitance of the cement-based material. The resistance method (Chung, 1993) is based on the piezoresistivity of the cement-based material and requires the cement-based material to be rendered conductive by the addition of a conductive admixture, such as short carbon fiber, the dispersion of which requires the addition of silica fume. The capacitance method (Chung, 2018) is based on the piezoelectricity of the cement-based material and does not require any admixture or poling. EMI shielding, deicing, anti-icing and radiation heating are functions that require the addition of a conductive admixture. Vibration damping can be provided by using interfaces obtained by nanostructuring the cement-based materials and the interfacial friction mechanism of mechanical energy dissipation. The nanostructuring can be obtained by using silica fume and exfoliated graphite as admixtures.

Keywords: Cement, Concrete, Multifunctional, Sensing, EMI shielding, Vibration damping.

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INTRODUCTION

Multifunctional cement-based materials provide both structural and non-structural functions in the absence of embedded or attached devices. Compared to the use of embedded or attached devices, advantages include low cost, high durability, large functional volume and absence of mechanical property loss.

The non-structural functions include sensing, with the attributes sensed including stress, strain, damage and temperature, as needed for structural health monitoring, structural vibration control, room occupancy monitoring for building facility management, and pedestrian/vehicle monitoring for transportation control. Other functions include electromagnetic interference (EMI) shielding (as needed for both electronics and radiation sources), deicing (as for roads), anti-icing, radiation heating (as for floors), vibration damping (as for bridges and high-rise buildings) and sound absorption (as for railroad ties and bridges).

The achieving of a non-structural function may or may not require the use of admixtures. Not requiring admixtures is preferred, as the technology can then be applied to existing structures, which do not have the required admixtures. In contrast, the requirement of specific admixtures would limit the application to new structures.

SENSING

Sensing is the most basic function of a smart structure. It can be provided by measuring the resistance (which relates to the electrical conductivity), the capacitance (which relates to the electric permittivity) and the thermocouple voltage (which relates to the thermoelectric behavior) of the cement-based material. Although electrodes (electrical contacts) are used for measuring the resistance, capacitance or thermocouple voltage, they are not sensors. The thermocouple refers to a cement-based thermocouple.

In relation to stress/strain sensing, the resistance method (first reported by Chung in 1993 [1,2]) is based on the piezoresistivity (effect of the strain on the electrical resistivity) of the cement-based material and requires the cement-based material to be rendered sufficiently conductive by the addition of a conductive admixture, such as short carbon fiber of diameter of the order of 10 µm. Although percolation is not required, the sensing is superior when the fiber volume fraction is around the percolation threshold, which was first reported by Chung in 1995 [3]. The dispersion of the fiber requires the addition of silica fume, which is suitable due to its small particle size [4]. In the absence of a conductive admixture, the resistance method is less sensitive and less repeatable. Nevertheless, it can be used, as shown for in-situ monitoring of the damage evolution during freeze-thaw cycling [5]. In relation to damage sensing, the resistance method (first reported by Chung in 1993 [1,2]) is based on the effect of the damage on the electrical resistivity. In relation to temperature sensing, the resistance method (first reported by Chung in 1999 [6]) is based on the effect of temperature on the resistivity, i.e., the cement-based material functioning as a thermistor.

The capacitance method (first reported by Chung in 2002 [7-9]) is based on the piezoelectricity of the cement-based material and does not require any admixture or poling. In contrast, conventional piezoelectric materials, such as the piezoceramics, require poling. Poling is not desirable, because of depoling that occurs after the poling and the consequent need for repoling. Furthermore, poling requires a high electric field and subjecting a large structure to a high electric field is not feasible. The capacitance method is also advantageous over the resistance method in that the electrodes do not need to be in intimate contact with the cement-based material.

The Seebeck effect in cement-based materials was first reported by Sun et al. in 1998 [10] and elucidated by Chung in 1999 [11]. A cement-based thermocouple, which involves two dissimilar cement-based materials (with one material being n-type and the other material being p-type) that are in electrical contact, was first reported by Chung in 2001 [12].

EMI SHIELDING AND LATERAL GUIDANCE

EMI shielding (radio wave or microwave regime), deicing, anti-icing and radiation heating are functions that require the addition of a conductive admixture. Without a conductive admixture, the cement-based material does not adequately absorb or reflect radio wave or microwave. Cement-based materials rendered effective for EMI shielding were first reported by Chung in 1989 [13]. Steel fiber of diameter in the micrometer range is particularly effective for improving the shielding ability of cement-based materials [14].

The improved reflection ability makes the cement-based material also useful for the lateral guidance of vehicles in automatic highways [15]. The lateral guidance requires a part of a highway lane (say, the middle part) to be paved with the reflective concrete, so that this part would reflect the radiation emitted by the vehicle. Based on the amount of reflected radiation received by the radiation receiver in the vehicle, whether the vehicle has deviated from its correct path can be assessed.

DEICING, ANTI-ICING AND RADIATION HEATING

Deicing, anti-icing and radiation heating are functions that also require the addition of a conductive admixture. Without a conductive admixture, the resistivity of the cement-based material is much too high for a meaningful current to pass though the material. The heating involved in deicing, anti-icing and radiation heating involves Joule heating (resistive heating). If the resistance is too high, the voltage needed to provide a meaningfully high current would be impractically high. The use of the cement-based material as a heating element is in contrast to the embedding of heating elements (such as heating wires or hot water pipes) in a cement-based structure.

The use of a cement-based material for Joule heating was first reported by Yehia et al. in 2000 [16]. In order to use the cement-based material effectively for Joule heating, the electrodes used to pass the current must be associated with sufficiently small values of the contact resistance [17]. If the contact resistance is large compared to the volume resistance of the cement-based material, the electrodes rather than the cement-based material are the components that get hot due to the Joule heating. In this case, the cement-based material is heated because of the conduction of heat from the electrodes and the heating of the cement-based material becomes non-uniform.

VIBRATION DAMPING AND SOUND ABSORPTION

Vibration damping and sound absorption can be provided by using interfaces obtained by nanostructuring the cement-based materials and the interfacial friction mechanism of mechanical energy dissipation [18]. This mechanism of vibration damping was first reported in a cement-based material by Chung in 1996 [19]. This mechanism of sound absorption by a cement-based material for first reported by Chung in 2013 [20]. The interfacial mechanism is attractive for the feasibility of increasing both the stiffness and the viscous character [21]. The stiffness is valuable for the structural performance as well as the mechanical energy dissipation. In contrast, the conventional viscous mechanism involving bulk viscoelastic deformation (as exhibited by rubber) tends to result in the increase of the viscous character at the expense of the stiffness.
The nanostructuring can be obtained by using nanoscale admixtures such as silica fume [22] and exfoliated graphite [21-24].

Polymer admixtures such as latex particle dispersion and dissolved methylcellulose are also effective for enhancing the vibration damping, due to the bulk viscoelastic deformation provided by the polymer admixtures [19]. However, the proportion of polymer admixture required for providing appreciable damping tends to be high and the polymer admixtures are expensive compared to silica fume.

CONCLUDING REMARKS

Multifunctionality has been achieved in cement-based materials for numerous functions, including sensing, EMI shielding, lateral guidance, deicing, anti-icing, radiation heating, vibration damping, and sound absorption. The associated science relates to piezoresistivity, piezoelectricity, thermoelectricity, radio wave absorption, radio wave reflection, Joule heating, and the interfacial friction mechanism of viscoelasticity. Admixtures are typically used for rendering the functions, but they are not required in some cases, as in the case of capacitance-based sensing.

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