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Capacitance-based nondestructive detection of aggregate proportion variation in a cement-based slab

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ABSTRACT

This paper reports unprecedentedly capacitance-based nondestructive detection of aggregate proportion variation in cement-based materials. It uses the fringing electric field of a capacitor comprising a cement-based slab and two relatively small copper electrodes. The aggregate volume fraction increases from cement paste to mortar and to concrete, thus causing the apparent permittivity (high due to the fringing field) to decrease in the same order. Each slab consists of two regions with different aggregate proportions. The through-thickness and in-plane capacitances are measured using sandwiching and coplanar electrodes, respectively. To locate the interface, the capacitance is innovatively measured using a series of electrodes.

1. Introduction

Aggregates are important in cement-based materials as reinforcement and drying shrinkage restrainer. Thus, the spatial variation in the aggregate proportion in a cement-based structure can result in undesirable spatial variation in the mechanical properties and drying shrinkage. In a cured cement-based material, a higher aggregate proportion corresponds to a lower cement paste proportion. Since the cement paste is the binder for the aggregates, its amount must be adequate.

Aggregate proportion variation can occur due to the separate pouring of the cement-based mix in different sections of a large structure. It can also occur due to the variation in aggregate size. Furthermore, it can occur in the repair of a concrete structure using new concrete that differs in mix design from the old concrete present in the structure.

Aggregate proportion variation does not necessarily result in defects (such as voids and cracks) at the interface between parts that involve different aggregate proportions. Thus, techniques (such as ultrasonic inspection) that focus on the detection of defects are not adequate for the detection of aggregate proportion variation. Moreover, aggregate proportion variation does not necessarily result in significant variation in the radio wave reflection/absorption behavior, so techniques involving radars are not adequate for the detection of aggregate proportion variation.

The true permittivity of cement-based materials does not vary over a wide range upon loading [1] or upon admixture addition [2], so the true permittivity is not sufficiently sensitive to the aggregate proportion or defects. However, we recently reported that, when the capacitance is unconventionally measured using electrodes (electrical contacts) that are smaller in area than the cement-based material being sandwiched by the electrodes, the fringing electric field is substantial and greatly increases the apparent (measured) relative permittivity of the cement-based material [3].

The apparent relative permittivity (2 kHz) increases with increasing thickness, due to the increasing fringing field with increasing thickness. For plain cement paste of various thicknesses, it ranges from 150 to 375. In contrast, when the electrodes conventionally cover the entire area of the cement-based material, the fringing field effect is much weaker, so that the apparent relative permittivity is much lower, ranging from 24 to 38 for plain cement paste of various thicknesses.

As a consequence of the high apparent permittivity, the fringing

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field allows the apparent permittivity and the associated capacitance to provide nondestructive detection of defects in a cement-based material [4]. In this paper, we investigate for the first time the use of this technique to detect a microstructural aspect that is more subtle than defects, namely the aggregate proportion variation in a cement-based slab.

The total aggregate proportion inversely relates to the proportion that is not in the form of aggregates, i.e., the proportion that is cement paste. The technique of this work is based on the detection of the proportion that is cement paste rather than detecting directly the proportion that is in the form of aggregates.

This work is not directed at detecting the aggregate or cement paste proportion, but is directed at detecting the variation in the proportion. In particular, this work concerns the determination of the location of the interface between regions that differ in the aggregate proportion. For the sake of demonstrating the feasibility of the concept, this work uses aggregate proportions that correspond to those of cement paste, mortar and concrete. The determination of the minimum detectable aggregate variation is beyond the scope of this work. Furthermore, the variation used in this work for the sake of feasibility demonstration is associated with the presence of contiguous regions in the same slab, such that the regions differ in the aggregate proportion.

The objectives of this work are (i) to demonstrate the feasibility of using capacitance measurement to detect aggregate proportion variation (i.e., cement paste proportion variation) in a cement-based slab, (ii) to provide a methodology for capacitance-based detection of aggregate proportion variation in a cement-based slab, and (iii) to investigate the effects of aggregate proportions on the apparent permittivity and capacitance of a cement-based material.

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 (measured in this work and the same as the previously reported value of 3.15 g/cm^3 [5,6]). The cement-based materials studied are cement paste, mortar and concrete. The water/cement ratio is 0.35, 0.55 and 0.42 for cement paste, mortar and concrete, respectively. The fine aggregate is sand with true density 2.55 g/cm^3 (measured in this work). The sand/cement mass ratio in the mortar is 3.0. The coarse aggregate is gravel with true density 2.59 g/cm^3 (measured in this work). The mass ratio of cement to fine aggregate to coarse aggregate in the concrete is 1: 1.3: 2.2.

Silica fume (Elkem Materials Inc., Pittsburgh, PA, microsilica, EMS 965, USA) is used at 15% by mass of cement, as in prior work [7]; it has particle size ranging from 0.03 to 0.5 μm, with average size 0.2 μm; its true density is 2.2 g/cm^3; it contains >93 wt% SiO_2, <0.7 wt% Al_2O_3, <0.7 wt% CaO, <0.7 wt% MgO, <0.5 wt% Fe_2O_3, <0.4 wt% Na_2O, <0.9 wt% K_2O, and <6 wt% loss on ignition. The silica fume has been subjected to silane treatment in order to improve its dispersion in the cement mix [8,9]. The silane coupling agent is a 1:1 (by mass) mixture of Z-6020 ($H_2NCH_2CH_2NHCH_2CH_2CH_2Si(OCH_3)_3$) and Z-6040 ($OCH_2$-$CHCH_2OCH_2CH_2CH_2Si(OCH_3)_3$) from Dow Corning Corp. (Midland, MI). The amine group in Z-6020 serves as a catalyst for the curing of the epoxy and consequently allows the Z-6020 molecule to attach to the epoxy end of the Z-6040 molecule. The trimethylsiloxy ends of the Z-6020 and Z-6040 molecules then connect to the −OH functional group on the surface of the silica fume. The silane is dissolved in ethylacetate to form a solution with 2.0 wt% silane. Surface treatment of the silica fume is performed by immersion in the silane solution, heating to 75 °C while stirring, and then holding at 75 °C for 1.0 h, followed by filtration and drying. Subsequently, the silica fume is heated at 110 °C for 12 h [8,9].

The silane treatment increases the density of the 28-day cured silica-fume cement paste from 1.72 to 1.73 g/cm^3 [10]. Hence, the effect of the silane treatment on the density is small.

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).

Cement powder and silica fume are dry mixed by using a rotary mixer with a flat beater without water addition for about 3 min. Then water is gradually added to the mixture while mixing continues for an additional period of 5 min. After this, the fine aggregate is added in case of the preparation of mortar, whereas both fine and coarse aggregates are added in case of the preparation of concrete.

The cement-based material specimens are in the form of rectangular slabs of size 300 mm × 150 mm x 19.5 mm. Cement-based mixes with different aggregate proportions are poured to the two halves of the oiled plastic mold, using a thin cardboard partition to separate the two halves during pouring. The size of each half is 150 × 150 mm (Fig. 1). For all specimens, 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.

2.2. Methodology

2.2.1. Permittivity measurement

The measurement of the relative permittivity typically involves a parallel-plate capacitor configuration, with the specimen under investigation being sandwiched by electrodes [2]. There is an electrically insulating plastic film positioned between the specimen and each electrode, as necessitated by the fact that the RLC meter used for the capacitance measurement, as typical for RLC meters, is not designed for measuring the capacitance of a conductive material. Although cement in the absence of a conductive admixture is only slightly conductive, the use of an insulating (dielectric) film is recommended and is used in this work. The electrodes are in the form of copper foils. The electrode, plastic sheet and cement-based specimen in the form of a stack are held together by adhesion.

The relative permittivity κ in the direction perpendicular to the plane of the sandwich is given by the equation

$$C_v = \varepsilon_o \, \kappa \, A_s / l, \quad (1)$$

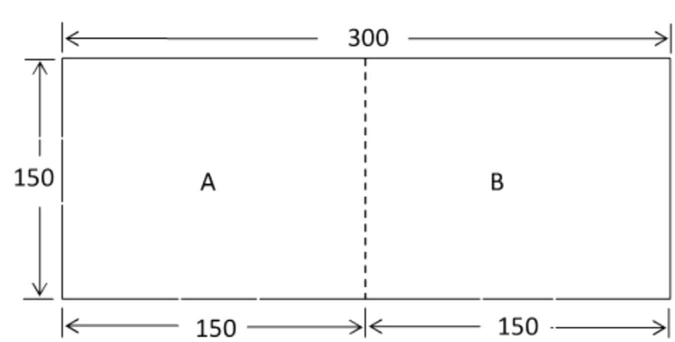

Fig. 1. Specimen configuration. A single rectangular specimen (300 mm × 150 mm) consists of two regions (A and B) of equal size (each 150 mm × 150 mm) but different aggregate proportions. All dimensions are in mm.