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Characterizing the pulse velocity and electrical resistivity changes in concrete with piezoresisitive smart cement binder using Vipulanandan models

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HIGHLIGHTS

- New concrete with smart cement binder is a piezoresistive bulk sensor.
- Electrical resistivity is the monitoring parameter.
- Resistivity changes during curing were higher than the pulse velocity changes.
- Vipulanandan composite, curing and piezoresistive models predicted the behavior.

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ABSTRACT

In this study the behavior of concrete made using piezoresisitive smart cement as the binder was investigated to test and model the concrete as a bulk sensing material. The coarse aggregate content in the concrete was varied up to 75% (by volume). The concrete property changes during curing were tested using the ultrasonic pulse velocity and compared it to the electrical resistivity, since it can be easily adopted for real-time monitoring. The initial (immediately after mixing) compressive pulse velocity for the piezoresistive smart cement (binder only) was 1050 m/s and it increased to 1490 m/s with the addition of 75%, a 42% increase in the initial pulse velocity. After 28 days of curing, the pulse velocity of smart cement increased from 3520 m/s to 4750 m/s with the addition of 75% aggregate, a 35% increase in the pulse velocity. Also the addition of coarse aggregates increased the initial electrical resistivity of the smart cement composite as well as the long term electrical resistivity. The initial electrical resistivity of smart cement was 1.02 Ω·m which increased nonlinearly to 3.74 Ω·m. with the addition of 75% aggregate, a 267% increase in the initial electrical resistivity. After 28 days of curing, the electrical resistivity of smart cement was 14.14 Ω·m and with 75% aggregate it increased to 61.24 Ω·m, a 333% increase in the electrical resistivity. Applicability of the mixture theory to predict the resistivity of the concrete from the constituents was verified and a new composite resistivity model was developed. Also Vipulanandan p-q curing model was used to predict the resistivity changes in the concrete with the curing time. The piezoresistivity of the smart cement without and with 75% aggregate after 28 days of curing were 204% and 101% at the peak compressive stresses of 21.7 MPa and 12.4 MPa respectively. The reduction in the piezoresistivity at peak compressive stress was due to not only the reduction of smart cement content in the composite but also the strength. Compared to the compressive failure strain of 0.3%, the resistivity change for the concrete with 75% gravel after 28 days of curing was over 336 times (33,600%) higher making the concrete with the smart cement binder a highly sensing bulk material. The composite behaviors (with curing time and applied stress) were modeled using the Vipulanandan pulse velocity, concrete resistivity and piezoresistivity models and compared with the current models used in the literature. Based on the coefficient of determination (R^2) and root mean square error (RMSE), Vipulanandan models predicted the experimental results very well.

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1. Introduction

Cement composites are one of the durable construction materials mainly composed of cement, aggregates, water and additives based on the applications. Concrete with high aggregate content in the cement composite can be used in the construction of different structures such as roads, houses, bridges, pipes, dams, canals, storage, missile silos and nuclear waste containment. To attain the required levels of safety and durability of such structures, mixing proportions and especially aggregate content must be adjusted according to application in order to achieve mechanical requirements which will significantly affect the performance during its life time [1]. In preparing the concrete and cement slurries, the water-to-cement ratios have been varied from 0.38 to 0.6 based on the mixing method, constituents of the concrete mix and applications [2–5]. There are many different testing techniques such as ultrasound, fiber optic, electronic microscopy, X-ray diffraction, thermography and vibro-thermography have been used to study the aging of cement composites and for damage detection [6]. Sayers and Grenfell [7] used the ultrasonic method to characterize the early age hydration of the cement and evaluated the Poisson's ratio of the slurries which decreased from the initial value of 0.5 for the fluid to values characteristic of a porous solid which was in the range of 0.25. Studies showed that using ultrasonic method with longitudinal wave, the location and size of the delamination in the slab can be evaluated [8]. Zeng et al. [9] used this method to characterize the development of bond slip in the concrete-encased composite. However, this method is difficult to adopt in some field conditions where accessibility becomes an issue in deep foundations, wells, dams, canals and pipes.

Research studies on the electrical resistivity of the cement composites over the past two decades have shown that out of all the different methods of characterizing the cement composites, electrical resistivity is one of the highly sensitive and economical nondestructive method to monitor the serviceability of the cement composites throughout the entire service life [10]. Several studies have proved the sensibility of this method on monitoring any chemical or physical changes in concrete during its life time (Table 1). Ramezanianpour et al. [11] suggested surface resistivity as an indicator of concrete chloride penetration resistance for a wide range of concrete compositions. Azhari and Banthia [12] worked on conductive cement-based materials which are also piezoresistive and proved that the electrical resistivity responses of such cement-based sensors with applied load are nonlinear and rate-dependent. Vipulanandan et al. [13] characterized modified cementitious and polymer composites using electrical resistivity measurements. Also newly developed smart cement studies have shown up to 400% increase in piezoresistivity which is defined as the changes in the electrical resistivity of the materials at peak stress [3–5,14]. Electrical resistivity can be a sensitive method for characterization of the concrete which can be affected by the curing conditions, concrete composition and cement type [15–19]. Chu and Chen [20] provided a correlation between real-time damage and resistivity of concrete under the condition of a static load (Table 1). They also showed the exponential growth of concrete resistivity and residual damage under the condition of a cyclic load. As previously mentioned, aggregates play a vital role in concrete strength, and the effects on electrical resistivity should be considered while employing concrete resistivity for various monitoring purposes. Aggregate content and size and type of aggregates are parameters which have been documented to affect the electrical resistivity of the concrete [21,22]. Hou et al. [1] studied the effect of up to 30% Coarse aggregates based on the total weight on electrical resistivity of the concrete using AC measurements of 1 Hz frequency (Table 1). These studies have shown that adding coarse aggregates increased the bulk resistivity.

2. Objective

The overall objective of this study was to compare the changes in compressive pulse velocity and electrical resistivity with curing time and the piezoresistive behavior of concrete with up to 75% aggregate (by volume) and smart cement binder. The specific objectives are as follows:

1) Effect of adding aggregates on the initial and long-term pulse velocity, electrical resistivity and compressive strength of smart cement composites.
2) Investigate the effect of adding up to 75% gravel (based on the total volume of cement composite) on the smart cement composite curing and piezoresistive behavior up to 28 days.
3) Modeling the behavior of concrete with smart cement binder.

3. Materials and methods

3.1. Sample preparation

In this study table top blenders were used to prepare the cement and concrete specimens. Cement (Portland cement Type 1 (ASTM C 150)) specimens were prepared using smart cement with water-cement ratio of 0.38 to minimize the bleeding and blended for at least 10 min [3]. Concrete specimens were prepared using 25%, 50% and 75% coarse aggregates based on the total volume of cement composite. Sieve analysis (ASTM C136) was done to determine the gradation of aggregate and the gradation is shown in Fig. 1. The median diameter [27], which also represents d_{50} (ASTM) the size of 50% of the particles less than 4.2 mm [28]. After mixing, the cement and concrete were placed in 100 mm height and 50 mm diameter cylindrical molds with two conductive flexible wires 1 mm in diameter (representing the probes) were placed 50 mm apart vertically to measure the electrical resistance. The specimens were cured up to 28 days under relative humidity of 90%. At least three specimens were test under each condition and the average values are presented in the figures, tables and discussion.

3.2. Density

In order to determine the density of smart cement and concrete composites with different percentages of aggregate contents mass and volume were measured immediately after placing the mixers in the molds. The dimensions of the specimen were measured using a Vernier Caliper.

3.3. Pulse velocity (ASTM C597)

The ultrasonic pulse velocity measurements were made by longitudinal waves using 150 kHz transducers. Smart cement composite mix was place in a cylindrical mold and the ultrasonic compression pulse produced by the transmitter was passed through the specimen and the arrived time was measured accurately up to 0.01 μs, using a commercial available device and a transducer as a receiver which was embedded on the other side of the mold.

3.4. Electrical resistivity

Two different devices were used to measure the changes in the electrical resistivity of the smart cement and concrete immediately after mixing up to the time they solidify.