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Effects of coarse aggregates on the electrical resistivity of Portland cement concrete

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HIGHLIGHTS

- Concrete resistivity was observed to be sensitive to the inclusion of CA.
- A strong relationship between concrete resistivity and CA content was observed.
- Variations in CA size/type exhibited no noticeable effects on concrete resistivity.
- Concrete resistivity was increased by the electrical obstacle effects of CA.
- Porosities and voids were not significantly influenced by the inclusion of CA.

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ABSTRACT

Electrical resistivity of concrete is an inherent material parameter associated with the composition, condition, and deterioration of concrete. Over the past few decades, studies have focused on the applicability of employing concrete resistivity as a self-monitoring indicator. This study attempted to investigate the effects of coarse aggregates (CAs) on the electrical resistivity of Portland cement concrete. Concrete mixtures with variations in CA content, size, and type were designed under identical water to cement ratios and curing conditions, and tested at 28 days. Bulk resistivity (BR) was measured using two-probe methods under saturated surface dry (SSD) conditions. Backscattered electron images (BEI) obtained using scanning electron microscopes (SEM) and X-ray computed tomography (CT) image analysis were also employed to study the capillary porosities and mesoscale voids that might affect BR. A mesoscale current conduction model was also employed for interpretation. The experimental results suggested that concrete resistivity is sensitive to the inclusion of CAs. Instead of altering the cement hydration, CAs were observed to serve as direct electrical obstacles that resulted in the enhancement of BR. Higher CA content increased the existence of obstacles, thereby increasing BR. Variations in CA size and type were observed to exert no effects on BR, which further validated the adopted mesoscale current conduction model, and further indicated that interfacial transition zones do not exert a substantial influence on concrete resistivity. It was also observed that capillary porosities and mesoscale voids were not influenced by CA content, indicating that cement pastes had similar quality among all concrete mixtures.

1. Introduction

Concrete is a composite material mainly composed of cement, cement substitutes, aggregates (fine and coarse), water, and functional admixtures. In most construction practices, concrete mixtures are subject to variations, not only in quantity, but also in quality. To achieve desired levels of safety and durability of concrete structures, mixing proportions must be adjusted according to application and environment during construction. To attain economic and mechanical requirements, aggregates generally account for 60–70% of the total volume of a concrete batch. The resulting mechanical properties significantly affect the performance levels of fresh and hardened concrete, and impact the cost effectiveness of concrete construction [1].

Concrete strength and durability are governed by the characteristics of the cement pastes, the physical and chemical properties of the aggregates, and the associated interfaces such as interfacial transition zones (ITZs) [2–5]. Concrete produced with coarse aggregates (CAs) of different types, shapes, textures, and mineralogy may exhibit variations in compressive strengths, even with identical mortars [6–8]. For example, the compressive strength of granite

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is 1.5 times higher than that of marble, and therefore would engender a 20% higher level of compressive strength in the end product [8]. The sizes of CAs also affect concrete properties [7,9–11]. It has previously been reported that the compressive strength of concrete increases with a decreasing aggregate size provided by a fixed water to cement (w/c) ratio [11]. Alongside the established knowledge that the mechanical properties of concrete vary with the addition of aggregates, researchers have also observed that concrete strength and aggregate volume fraction exhibit close relationships with the electrical properties of concrete [12,13].

Cement paste, mortar, and concrete are electrically conductive mediums, rated from sub-insulator to semi-conductor [14]. Electrical resistivity of concrete varies with its composition, conditions, and maturity [14–25]. Supplementary cementing materials (SCMs) such as fly ash, silica fume, and ground granulated blast furnace slag (GGBFS) can substantially reduce the pore size of cement paste, restrict electrical conduction through pore solutions, and produce a concrete with high resistivity [15,17,26]. Aside from SCMs, the addition of rice husk ash (RHA) was also observed to enhance concrete resistivity [18]. Because of cement hydration, water evaporation, surface carbonation, and possible chloride penetration, concrete resistivity evolves with age, and furthermore, these electrical evolutions are also environmentally subjective [16,22,23]. Unlike material compositions and maturity levels that cause microstructural differences, moisture content and temperature also affect concrete resistivity by influencing ion mobility, as well as ion-ion and ion–solid interactions [19,22,23].

Based on these observations, researchers have proposed employing the electrical characteristics of concrete for various sensing applications [12,17,22,27–40]. Although diffusive mass transport may not be fully interpreted by ionic conduction, many previous studies have indicated that electrical resistivity measurement could serve as a fast and economic alternative for assessing concrete resistance to chloride penetration [12,17,28,38,39]. The benefits of using resistivity measurement over conventional chloride penetration tests are the non-destructive nature, rapid on-site deployment, and substantially lower requirements of labor and time. Concrete resistivity has also been proposed for practical predictions of compressive strength [32,33,35], predictions of elastic modulus [29], and monitoring the progress of cement hydration [27,30,37], with the aim of achieving efficient on-site quality control. When loaded with mechanical externals, the piezoresistivity inherent enables concrete to function as a smart material for the self-sensing of strains and stresses without artificial sensors such as strain gauges [31,34,36,40].

As previously mentioned, aggregates play a vital role in concrete strength, and the effects on electrical resistivity should be discussed and documented when employing concrete resistivity for various monitoring purposes. Princigallo et al. revealed that a strong and positive dependence on aggregate content exists in concrete resistivity [13]. Similarly, Sengul observed a proportional relationship between concrete resistivity and aggregate content when using crushed limestone or gravel [12]. Specifically, Sengul's work also concluded that crushed stone aggregates of large sizes engendered higher concrete resistivity. For recycled aggregates (RAs), Surya et al. observed that concretes made with RAs exhibited higher resistivity as well as lower chloride permeability than those made with natural aggregates (NAs) [41]. Arredondo-Rea et al. reported that the addition of fly ash can significantly improve the electrical resistivity of concrete made from RAs because of cement matrix densification and pore refinement [42]. In order to employ resistivity measurements (e.g., durability) as concrete quality indicators for practical use, investigation into the influences of CA content, size, and type on the electrical resistivity of Portland cement concrete is required. In comparison with the pozzolanic additions to concrete resistivity, the influence of CAs has seldom been directly discussed. Necessities for the research exploration is supported by the fact that the presence of aggregates result in three paths of electrical conduction (mesoscale conduction model): (1) through the aggregate and paste in series, (2) through the aggregate granules in contact with one another, and (3) through the paste itself (Fig. 1) [43,44]. Resistivity of aggregates is much higher, generally several orders of magnitude, than that of cement pastes [45].

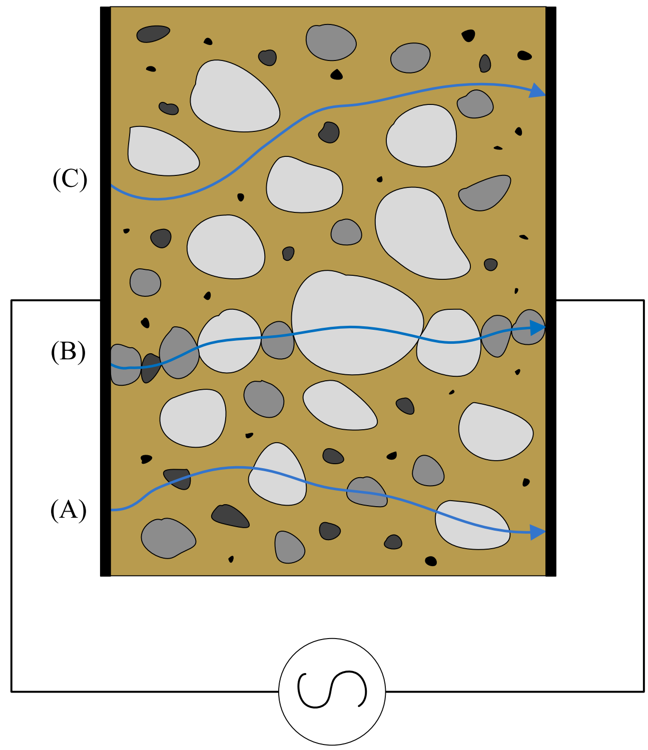

Fig. 1. Electrical conduction paths of concrete: (A) through the aggregate and paste in series, (B) through the aggregate granules in contact with each other, (C) through the paste itself (in accordance with [43,44]).

In this study, various types, contents, and sizes of CAs were employed to study the effects of CAs on the bulk resistivity (BR) of concrete. Backscattered electron images (BEIs) obtained using scanning electron microscopes (SEM) were analyzed to qualify and quantify the microstructural details of the cement pastes of each composition. Specifically, microscale porosities of the cement matrices were evaluated. BEI analysis was performed to clarify whether CAs affect concrete resistivity by simply contributing to the electrical obstacle, or in the more complex fashion of altering the capillary porosities of the cement matrices. In addition, mesoscale voids obtained through X-ray computed tomography (X-ray CT) were also provided to further validate the results of the resistivity measurements. Variations of porosity/void and the corresponding effects on concrete resistivity were also discussed. This study explored the extent of knowledge concerning concrete resistivity being sensitive to the presence of CAs; even the effects of the content were subtle. Details of the experimental preparation, resistivity measurements, BEI analysis, and X-ray CT scanning are provided below.

2. Experiments

2.1. Raw materials

Type I Portland cement (ASTM C150-16 [46]) was used for all compositions in this study. The specific gravity was 3.15, and the