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Multifunctional electrically conductive concrete using different fillers

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ABSTRACT

This study presents an experimental investigation on the effect of using different conductive fillers; steel shavings, carbon powder and graphite powder as partial replacement of fine aggregate (1%, 3%, 5% and 7% by volume) on the electrical, physical, mechanical and durability properties of structural concrete. The effect of including different conductive fillers on the properties of fresh and hardened concrete was evaluated (i.e. slump, air content, unit weight, compressive strength, splitting tensile strength and water absorption). Results showed that structural concrete with good electrical conductivity could be produced for various applications by incorporating appropriate conductive filler type and content. The produced electrically conductive concrete (ECC) showed different performance characteristics and could be used as a multifunctional material for different structural applications. A performance index (*PI*) approach was used to evaluate and select the most suitable concrete mixture of required performance(s) criteria for multifunctional structural applications.

1. Introduction

Resistivity for saturated and dry concrete ranges between 10^6 Ω cm and 10^9 Ω cm, respectively [1]. Concrete electrical resistivity lies at the border between insulators and poor semiconductors. It is theoretically feasible to improve the conductivity of concrete matrix by the addition of well dispersed electrically conductive components inside the concrete matrix to attain stable and good electrical conductivity [1–8]. However, the content of the conductive component should be within certain limits to avoid degradation of other related physical and mechanical properties of the concrete mixture [3].

Concrete conductivity received considerable attention [9]. Conductive concrete was investigated using different types of conductive fillers or phases in the form of particles or fibers which were included into the cement matrix. Examples of the conductive fillers or phases used are graphite and carbon fibers and microfibers [1,6,9,10–23], steel fibers and micro fibers [5,6,10,18,24–29], steel shavings [4,5,25,26,28], graphite powder [3,18,21,29–32], steel wool [27,32], carbon black powder and carbon black nanoparticles [19,33–35] and carbon nano-fibers and nanotubes [36–40]. The main conclusions from the different investigations were that the size and dispersion of the filler are more important than its conductivity and that the volume or quantity of the filler affected the concrete conductivity. Also, it was concluded that the concrete conductivity could be enhanced even by using fillers in low volume fraction. A minimum filler content of 0.8% of concrete volume was needed in order to attain good conductivity [14]. Also, it was emphasized that the properties of the produced concrete are significantly influenced by the inclusion of conductive fillers and the effect on the concrete properties mainly depends on the type and content of the filler used.

Several investigations found that the electrical resistivity of concrete was greatly affected by its constituent's mainly type and content of aggregate, w/c ratio and sand to cement ratio [9,12,14,18,25,41–46]. The main conclusion was the significant effect of aggregate content on concrete conductivity especially the sand content volume fraction. A sand content volume of 24% or less is needed to attain high conductivity [14]. Also, it was concluded that the concrete air voids adversely affected its conductivity [18,20]. The effect of filler type, size, content and distribution on the conductivity of concrete was also studied [10,11,18,27]. It was concluded that conductivity of concrete was affected not only by the type and content of fillers but also depends on the dispersion uniformity. The dispersion of fillers was found to be affected by mix proportions, filler content, mixing and efficiency of mixing [10,18].

Conductive concrete was proposed for several applications such as; overlay snow melting system of highway bridge decks, parking garages,

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Notations

A	Specimen's cross sectional area
AC	Alternating current
C.O.V	Coefficient of variation
Ci	Weight ranking
CP	Cathodic protection
EAFS	Electric arc furnace slag
ECC	Electrically conductive concrete
ITZ	Interfacial transition zone
L	Specimen's thickness
n	Number of required performance(s) criteria
NaCL	Sodium chloride
PI	Performance index
R^2	Coefficient of correlation
Rc	Electric resistance of concrete specimen
Ri	Numeric index
Ro	Electric resistance of setup with specimen
Rs	Electric resistance of setup
S_n	Mixture score based on (n) performance criteria
S_{nmax}	Highest mixture score based on (n) performance criteria
X	X-axis direction
Y	Y-axis direction
Z	Z-axis direction
ρ	Electrical resistivity
б	Electrical conductivity

sidewalks, driveways and airport runways [2,4,5,18,23,26,47–49], cathodic protection (CP) systems of steel reinforcement in concrete structures [11,16,17,21,50–53], structural health monitoring systems and self-sensing for smart structures [6,12,13,19,30,33,35–39,54–58], antistatic flooring and electromagnetic pulse shielding [1,2,14]. Also, electrically conductive concrete (ECC) has good potentials to be used in grounding systems [14,29,59]. Grounding is crucial in structures especially those which require good grounding such as central offices, electrical power stations, residential buildings, etc. Conventional grounding systems could be in some cases ineffective and could cause great deal of damage. Besides, traditional grounding systems are prone to damage due to natural processes and human behavior (i.e. cutting or theft). Using ECC to replace or enhance foundations and buried ground grid systems will allow for integral above and below grade ground connections that are efficient, low maintenance, easy to test and resilient to damage. Recently, conductive concrete was proposed to be used in electrochemical extraction of chloride from reinforced concrete structures [60] and in the developing battery in the form of cement-matrix composite [34].

The application of ECC has been limited because the earlier conductive concrete mixtures did not meet structural requirements, i.e. mainly strength, and/or were too expensive to produce [2]. Vipulanandan and Garas [61] highlighted that previous studies have focused on getting the percolation thresholds and the critical percolation exponents for the different composites and to assess the nature of conductivity, while the correlations between the electrical properties and the physical and mechanical properties of cement-based materials have received little attention. It was found that some studies [2,4,17–19,21,25,29,35,62] included the measurement of some mechanical properties of produced conductive concrete such as compressive, tensile and flexural strengths and modulus of elasticity. Almost no study reported the effect and correlation of using different conductive fillers on fresh concrete properties and durability characteristics. Fresh concrete properties are important during the construction of structural concrete. While durability characteristics are important for producing structural concrete with desired service life.

2. Objective of the invesigation

This study investigates the effect of different conductive fillers on the fresh concrete properties, compressive and splitting tensile strengths and durability performance of electrically conductive concrete (ECC) for structural applications. The main objective of the study is to improve the electrical conductivity of structural concrete and to produce electrically conductive concrete (ECC) with good structural properties and durability characteristics for multifunctional applications. Different conductive fillers such as steel shavings, carbon powder and graphite powder were used as partial replacement by volume of the fine aggregate (1%, 3%, 5% and 7% by volume). Electrical conductivity was measured using AC (50 Hz) voltages. Fresh concrete properties (i.e. slump, air content and fresh density) and hardened concrete properties (i.e. compressive, splitting tensile and bond strengths, abrasion resistance and water absorption) of the produced mixtures were measured to evaluate the performance of produced ECC. A performance index (*PI*) approach is used to evaluate and select the most suitable mixture that satisfies required performance(s) criteria for multifunctional structural applications.

3. Experimental work

3.1. Materials and mixture proportion

Ordinary Portland cement which conforms to (ASTM Type I) and (BS EN 197 CEM I) was used in the study. Natural crushed stone of nominal size 20 mm (3/4 in.), specific gravity of 2.6, and absorption percentage of 1.1% was used as coarse aggregate. Fine aggregate used was natural siliceous sand with a fineness modulus of 2.56 and specific gravity of 2. Table 1 shows the grading of used fine and coarse aggregates. Concrete mixture proportions are given in Table 2. The mixture was designed to have a slump ranging between 80 and 100 mm and 28 days compressive strength of 30 MPa which represents a typical structural concrete grade. As per the findings of Wen and Chung [14], the sand content was maintained at 23% by volume. Steel shavings, carbon powder and graphite powder were included in the mixtures as partial replacement of the fine aggregate by volume (1%, 3%, 5% and 7% replacement levels), which corresponds to 0.23%, 0.68%, 1.13% and 1.58% of the total concrete volume. The fine aggregate content of the mixtures including various conductive fillers with different volumes were adjusted accordingly. Table 3 shows the matrix of different concrete mixtures and mixtures' identifications. The cement, coarse aggregate and water contents were kept constant to study the effect of including different conductive fillers on the properties of the fresh and hardened concrete.

Measured characteristics of the used conductive fillers are given in Table 4. Steel shavings size ranged between 0.2 mm up to 2 mm in size. Carbon powder and the graphite powder size were in the range of few microns. The texture of the steel shavings particles was rough and includes surface pores while that of carbon and graphite powder was smooth. It should be noted that the specific gravity of carbon and graphite powder is similar and is lower than the fine aggregate, while that of steel shavings is much higher than carbon and graphite powders and fine aggregate. The specific surface area of the steel shavings was

Table 1
Concrete mixture proportions. (kg/m^3).

Cement	350
Water content (water/cement ratio)	200 (0.57)
Fine aggregate	597
Coarse aggregate	1194