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Influence of mix design variables on engineering properties of carbon fiber-modified electrically conductive concrete

Alireza Sassani [a,*], Halil Ceylan [b], Sunghwan Kim [c], Kasthurirangan Gopalakrishnan [d], Ali Arabzadeh [a], Peter C. Taylor [e]

[a] Department of Civil, Construction, and Environmental Engineering, Iowa State University, 176 Town Engineering Building, Ames, IA 50011, USA
[b] Program for Sustainable Pavement Engineering and Research (PROSPER), Department of Civil, Construction, and Environmental Engineering, Iowa State University, 406 Town Engineering Building, Ames, IA 50011-3232, USA
[c] Department of Civil, Construction, and Environmental Engineering, Iowa State University, 24 Town Engineering Building, Ames, IA 50011-3232, USA
[d] Department of Civil, Construction, and Environmental Engineering, Iowa State University, 354 Town Engineering Building, Ames, IA 50011-3232, USA
[e] National Concrete Pavement Technology Center, Iowa State University, 2711 South Loop Drive, Suite 4700, Ames, IA 50011-8664, USA

HIGHLIGHTS

- Electrically conductive concrete (ECON) was produced with different mix proportions.
- Carbon fiber was used as electrically conductive additive in Portland cement concrete mixtures.
- Calcium nitrite-based admixture was used as electrical conductivity-enhancing agent.
- Five easy-to-change mix design variables were studied by statistical analysis.
- Main effect of variables and two-way variable interactions were evaluated.

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ABSTRACT

This research was inspired by the need to optimize the mix design of electrically conductive concrete (ECON) for field implementation. Carbon fiber was used for producing ECON with different mixing proportions and constituents. Calcium nitrite-based corrosion inhibitor admixture and methylcellulose were used as conductivity-enhancing agent (CEA) and fiber-dispersive agent (FDA) respectively. Five easy-to-change mix design variables were evaluated for their effects on electrical conductivity and strength of ECON: carbon fiber dosage, fiber length, coarse-to-fine aggregate volume ratio (C/F), CEA dosage, and FDA dosage. The results approved the effectiveness of the applied CEA in improving electrical conductivity while positively influencing strength. Conductivity was significantly influenced by: fiber content, C/F, fiber length, and CEA dosage. The dosages of Fiber, CEA, and FDA exerted significant influence on compressive strength. C/F and FDA dosage were significant variables influencing flexural strength.

1. Introduction

Electrically conductive concrete (ECON) is a versatile type of concrete with potential benefits in different applications such as: self-sensing construction material for structural health monitoring practices [1–3], electromagnetic radiation reflector for electromagnetic interference (EMI) shielding [4–6], and resistance heating material in self-heating pavement systems [7–10]. Recent attention to ECON is mainly related to self-heating pavement systems [8,11,12] because of the inadequacy of common ice and snow removal methods [12–17].

The basic mixture components of ECON are cementitious materials, coarse and fine aggregates, water, electrically conductive additive (ECA), and possibly chemical admixtures [11]. Air-dried normal Portland cement concrete (PCC) has an electrical resistivity in a range between 6.54×10^5 and 11.4×10^5 Ω-cm [18], while,

Abbreviations: PC, Portland cement; PCC, Portland cement concrete; ECON, electrically conductive concrete; ECA, electrically conductive additive; CEA, conductivity-enhancing agent; FDA, fiber-dispersive agent; DOE, design of experiments; C/F, coarse-to-fine aggregate volume ratio.

* Corresponding author.
E-mail addresses: asassani@iastate.edu (A. Sassani), hceylan@iastate.edu (H. Ceylan), sunghwan@iastate.edu (S. Kim), rangan@iastate.edu (K. Gopalakrishnan), arab@iastate.edu (A. Arabzadeh), ptaylor@iastate.edu (P.C. Taylor).

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electrical resistivity of ECON is orders of magnitude lower (30 Ω-cm–1.00 × 10^4 Ω-cm) [4,12,19–22]. The primary source of electrical conductivity that renders ECON considerably more conductive than normal concrete is the ECA component that creates a continuous path for electricity conduction. ECA portion of ECON may consist of a single material or a mixture of two or more different materials all possessing high electrical conductivity. Forming a continuous network in concrete matrix by the ECA materials is referred to as percolation phenomenon and the volume content of ECA enabling the percolation is called the percolation threshold [23–25].

Since 1965, when the first patent related to ECON was issued [20], numerous mix designs have been proposed for production of electrically conductive cement paste, mortar, or concrete [4,24,26]. Carbon fiber is a material that has been used and tested as an ECA in production of electrically conductive cementitious composites for different purposes [7,27,28]. Moreover, previous research have postulated [29–31] that carbon fiber-reinforced concrete provides better characteristics in terms of freeze-thaw durability, tensile strength, fatigue cracking, shrinkage cracking potential, and expansion cracking susceptibility. Wu et al. [12] produced carbon fiber-modified ECON with 4000 Ω-cm resistivity using 0.8% (Vol.) carbon fiber dosage. While, Kraus and Naik [32] achieved 127 Ω-cm electrical resistivity with only 0.5% (Vol.) carbon fiber and Galao et al. [33] produced ECON with 40 Ω-cm resistivity using <0.2% (Vol.) carbon fiber in the concrete mix. This shows that the electrical resistivity of carbon fiber-modified ECON is dependent on multiple factors and not only the carbon fiber dosage. Speaking of carbon fiber-related factors, in addition to carbon fiber dosage [12], the properties of the fibers such as fiber length [23,24], material origin (e.g. pitch-based or polyacrylonitrile-based) [24,34], and the surface chemistry of carbon fiber strands [34,35] influence the effectiveness of fibers in modifying the properties of concrete. Percolation of fibers in concrete depends on dispersion level, that is, controlled by fiber properties, mixture constituents, mix proportions, and mixing procedure [23,30,36,37]. Improved fiber dispersion leads to improved fiber-cement paste bond, higher ductility, and reduced electrical resistivity [35]. A variety of chemicals can be used for facilitating the dispersion of fibers in concrete mixture; methylcellulose is a fiber dispersive material that is effective in minor dosages [30,38].

In both normal concrete and ECON, the mix design variables such as cement content, aggregate-to-cement volume ratio, and coarse-to-fine aggregate volume ratio (C/F) exert a significant influence on the electrical conductivity of the concrete [39–41]. In addition to the conventional applications of chemical admixtures - such as improvement of workability, air entrainment, etc.-, they can be used for engineering the internal environment of concrete to boost electricity conduction; for instance, calcium nitrite-based corrosion inhibitor admixtures can change the electrical conductivity of concrete [42,43]. While, sodium-based corrosion inhibitors tend to decrease the compressive strength of concrete, calcium compounds do not exert any reducing effect on concrete strength properties; in fact, calcium nitrite, which is an anodic corrosion inhibitor, has been found to increase the 28-day compressive strength of concrete [44]. Due to the presence of different ionic entities within the pore solution, it acts as the primary medium for ion/charge transfer within the concrete. The principal ions in the pore solution that enable the flow of electricity are Ca^{2+}, K^+, Na^+, SO_4^{2-}, and HO^- [18]. Hence, the ionic composition of pore solution and the ion concentration in the pore solution play an important role in electricity conduction by concrete [45]. It was reported, that when calcium nitrite is added to the mix water of concrete, the concentration of nitrite in the pore solution is comparable to the mix water, i.e. the majority of the nitrite is diffused in the pore solution. Furthermore, at high calcium nitrite contents, hydroxyl ions concentration in the pore solution is increased due to competitive adsorption of nitrite ions on the surface of cement hydration products [46,47]. Therefore, calcium nitrite admixture tends to enhance electricity conduction by increasing the ion concentration in the pore solution of concrete and thus improving the electrolytic conduction of electricity in the cementitious composites.

Different materials have been proposed in the literature to improve the dispersion of synthetic and/or natural fibers. Examples are Acrylic with or without Silica fume, Styrene acrylic [30], Latex with or without Silica fume [48,49], and methylcellulose [22]. Effective fiber dispersion by using Acrylic, Styrene Acrylic, and Latex is associated with high dosages of fiber dispersive agent (FDA) – in the range of 10–20% by weight of cementitious - [23,30,36]. On the contrary, the dosage of methylcellulose as a FDA in carbon fiber-modified concrete/mortar can be as low as 0.4% by weight of cementitious materials [22,38].

Developing an ECON mix design with desirable multifunctional behavior calls for adjusting all variables/constituents to achieve required electrical resistivity [41]. Furthermore, the final product should possess desirable mechanical properties. The majority of studies on electrically conductive cementitious composites have followed a trial–error approach using trial mix batches [12]. Regarding the heterogeneity of concrete and the uncertainty it adds to the evaluation of different variables' effects on concrete properties [50], generalizing the results of such trial-and-error studies is not an efficient and reliable way for development of a mix design; on the other hand, the heterogeneity of concrete continuum is more significant in fiber-containing concrete [51]. There are limited studies investigating the electrical conductivity of ECON in light of the ratio of mixture constituents. Wen and Chung [40] studied the double percolation of carbon fibers and cement paste in mortar. Baeza et al. [41] investigated the double and triple percolation of carbon fibers, cement paste, and mortar within a concrete mixture. Another example is the study by Shi [39] that investigated the effect of cement composition, aggregate content, and mineral admixtures on electrical resistivity of plain concrete.

Application of ECON in a real project calls for developing a project-specific mix design or using a previously proposed mix design. However, most ECON products presented in the existing literature suffer from disadvantages such as inadequate strength, high cost, low workability, and poor functionality [52]. On the other hand, developing a mix design in a timely manner requires knowledge about the effect of each component on the final product's characteristics. The dynamic of modern markets being profit-driven [53], necessitates thorough investigation of any new technology–such as ECON- before it gains wide acceptance by the industries. Therefore, the needs have arisen to investigate the role of each component of ECON in order to enable the producers to tailor the final product to their needs.

The use of statistical design of experiments (DOE) and regression analysis of the results is a powerful means of evaluating the influence of different variables on concrete characteristics [54]. By this method, the main effects of single variables and the interactions can be quantitatively evaluated with a certain confidence level [55]. ECON mix designs based on such pre-defined, structured DOE will be more rational and universal than those based on trial–error approach.

The primary objective of this study is to identify the effects of easy-to-change mix design variables on electrical conductivity and mechanical properties of ECON. The findings of this paper can provide a basis for developing an optimized ECON mix design that satisfies both electrical conductivity and strength requirements for a given project with efficient amount of ECA materials and admixtures. Therefore, it is worth mentioning that producing