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Case study

Development of Carbon Fiber-modified Electrically Conductive Concrete for Implementation in Des Moines International Airport

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A R T I C L E I N F O

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A B S T R A C T

This paper reports on the procedures of mix design preparation, production, placement, and performance evaluation of the first electrically conductive concrete (ECON) heated-pavement system (HPS) implemented at a U.S. airport. While ECON has drawn considerable attention as a paving material for multi-functional pavements, including HPS, the majority of ECON HPS applications and studies have been limited to laboratory scale or include materials/methods that do not conform to regulations enforced by airfield construction practices. Carbon fiber-reinforced ECON provides a promising prospective for application in airfield pavements. In this study, ECON mixtures were prepared in the laboratory using varying cementitious materials, aggregate systems, water-to-cementitious ratios, carbon fiber dosages, and admixtures. The results of tests on laboratory-prepared mixes were utilized to find the most suitable ECON mix design for application in an HPS test section at the Des Moines International Airport. The properties of the ECON produced at the concrete plant were measured and compared with equivalent laboratory-prepared samples. The final mix design exhibited electrical resistivity of 115 Ω-cm in the laboratory and 992 Ω-cm in the field, while completely meeting strength and workability requirements. Despite the higher ECON resistivity obtained in large-scale production, the fabricated HPS exhibited desirable performance with respect to deicing and anti-icing operations. The test section was able to generate a 300–350 W/m^2 power density and to effectively melt ice/snow with this level of energy.

1. Introduction

Surface conditions of paved areas during harsh winter weather conditions play a crucial role in airport operations. Bad weather conditions are responsible for about 29% of total airplane incidents and accidents, the majority of which occur during take-off and landing [1]. Ice/snow accumulation on paved surfaces of runways, aprons, and taxiways annually causes thousands of flight

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cancellations or delays [2]. Therefore, airlines and airports incur millions of dollars of expenditure to remove ice and snow from airport pavements. Traditional ice/snow removal methods are using deicing chemicals and mechanical removal that are associated with flight delays, large number of manpower, sophisticated machinery, environmentally harmful chemicals, and damage to pavement [3–8]. Furthermore, the common deicing methods have not shown effectiveness in extreme weather conditions. The machinery can face operational difficulty in freezing weather conditions. The effective temperature range for most deicing chemicals such as sodium chloride, calcium magnesium acetate, and urea does not fall below −10 °C (14 °F); only calcium chloride-based deicers −that cause chloride ingress risk for concrete pavements- are effective below −17 °C (1.4 °F) [9].

The shortcomings and drawbacks of current ice/snow removal practices have steered researchers toward seeking new methods. Factors such as geographical location, environmental conditions, material availability, and design specifications all influence selection of a deicing method, so no single solution for replacing current methods is available [10]. Many alternative methods have been proposed and tested for this purpose; among them are water-repellent coatings [2,11,12], heated pavements with embedded resistive heating elements [6], heated hydronic pavement systems [13,14], and self-heating electrically conductive concrete (ECON) [9,15–20]. Heated-pavement systems (HPS) combine two basic strategies of anti-icing and deicing for controlling snow and ice on pavement surfaces [10]. ECON-based HPS has proven to be an efficient approach in many locations [21]. The general constituents of ECON are cement, aggregates, water, electrically conductive additives (ECAs), and possibly admixtures, however, the primary source of electrical conductivity is the ECA phase that creates a continuous path for electrical conduction [3].

Carbon fibers can be used as an ECA in minor volume and weight dosages [22–26]. Previous studies have shown the ability of carbon fiber to render cementitious composites electrically conductive while improving the concrete properties such as freeze-thaw durability, compressive strength, tensile strength, fatigue cracking, shrinkage cracking potential, and expansion cracking susceptibility [3,27–30]. While carbon fiber has shown its effectiveness as an ECA in low volume dosages (0.4-1%Vol.), the optimum carbon fiber dosage in an electrically conductive cementitious composite is defined by multiple factors, the most important of which are so-called percolation phenomenon, the concrete workability requirements, and the economic considerations.

Forming a continuous network within the cementitious composite by the ECA materials is referred to as percolation phenomenon and the volume content of ECA enabling the percolation is called the percolation threshold [30–32]. With respect to percolative behavior, the effective carbon fiber dosage for producing electrically conductive cementitious composites is between 0.5% and 1% (Vol.) [27,30,33–42] which depends on the type of composite (paste, mortar, or concrete), fiber aspect ratio, and fiber length [25]. In short carbon fibers (represented by approximately 7–15 μm nominal diameter and 1–10 mm length), increasing fiber length decreases percolation threshold [25], but increasing the fiber length results in fiber dispersion difficulty [26], and loss of concrete workability [30]. Excessive carbon fiber content reduces the workability of the mixture and, since carbon fiber is the most expensive component of ECON, is not economically justified. So the carbon fiber dosage should be maintained in the vicinity of percolation threshold, such that sufficient electrical conductivity is achieved with minimum negative effects on workability and cost.

Polyacrylonitrile (PAN)-based carbon fibers [33] with diameters between 7 and 15 μm and nominal lengths of 3–6 mm provided superior effectiveness in improving mechanical properties of concrete and imparting high electrical conductivity to cementitious composites [24,25]. In this paper, carbon fiber and carbon microfiber are used interchangeably to refer to carbon fibers with μm-scale diameter and mm-scale length. Shown by previous studies [8,18,19,22,24,33,43], the carbon microfiber is the most effective carbon product for improving electrical conductivity. For example, carbon nano- fibers (CNF) are less effective than carbon microfibers which have length ranges between 3 and 15 mm [25]. Likewise, powder materials such as graphite powder or coke powder exert less effect on electrical resistivity improvement [25]. On the other hand, the most effective carbonaceous fibers for structural enhancement of concrete are carbon microfibers and microfibers work better than macro- and nano-fibers for structural reinforcement [26]. However, the smaller the fiber diameter, the more difficult is its dispersion in a concrete mixture and, given the same fiber material and diameter, shorter fibers are easier to disperse [26]. For volume dosages below 1%, and approximately 7 μm diameter, carbon fibers with aspect ratios of about 860 provided performance superior to either longer or shorter fiber types in improving electrical conductivity of concrete, but high aspect ratio fibers are more difficult to disperse in concrete and adversely affect the workability of the mixture [26]. Shorter length and lower aspect ratio carbon fibers are easier to disperse, and they contribute a smaller effect on workability, so, despite being otherwise inferior to the 860-aspect ratio-fibers, carbon fibers with an aspect ratio of about 430 have been found to exhibit good performance in improving electrical conductivity of ECON [41].

Wen and Chung [36,38] reported electrical resistivity values between 1.50×10^4 Ω-cm and 1.92×10^4 Ω-cm in cement pastes doped with carbon microfibers in dosages of 0.4-0.5% Vol.; they reached electrical resistivity as low as 8.30×10^2 Ω-cm in cement pastes when the carbon fiber dosage in cement paste was increased to 0.95% Vol. of the mixture [37]. Wen and chung [38] also suggested that electrically conductive cement paste behaves as a thermistor, i.e. its electrical resistivity decreases with increasing temperature. Baeza et al. [42] produced electrically conductive cement paste by adding carbon fiber to cement paste in dosages of 0.22-0.95% Vol. and reported the lowest resistivity of 6.04×10^5 Ω-cm achieved with 0.95% Vol. carbon fiber dosage. Hambach et al. [41] used cement paste modified with 1% Vol. carbon fiber and electrical resistivity as low as 3.6×10^1 Ω-cm for resistive heating of a small laboratory-scale slab. Having fine aggregates (sand) included in the carbon fiber-modified cementitious composites, electrically conductive mortar were produced. However, electrical resistivity of 5.41×10^2 Ω-cm was achieved only when carbon fiber dosage was increased up to 1.16% Vol. [27,39].

While mortar tests showed less success than cement paste, it was found that carbon fiber-modified concrete which essentially consists of cementitious materials, fine aggregate, coarse aggregate, water, carbon fiber, and admixtures, provides a promising perspective to attain low electrical resistivity with relatively low dosages of ECA [22,33–35,40]. Wu et al. [33] and Chang et al. [35] reported 4.00×10^3 Ω-cm and 2.00×10^4 Ω-cm resistivities in ECON with 0.8%Vol. and 0.75%Vol. carbon fiber dosages respectively. While, using 0.73% Vol. carbon fiber content in ECON, Hou et al. [34] achieved 3.8×10^1 Ω-cm resistivity. Also, Kraus and