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Factorial Study on Electrically Conductive Concrete Mix Design for Heated Pavement Systems

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Abstract

Application of heated pavement systems is a safer and faster alternative to currently predominant 46 methods of removing ice and snow from paved surfaces. Heated pavements not only can remove 47 ice/snow from pavement surfaces, but are also capable of preventing their 48 formation/accumulation in the first place. Electrically conductive concrete (ECON) provides an 49 effective and powerful means of producing self-heating pavements. The electrical conductivity 50 of ECON is dependent on numerous factors such as type and dosage of electrically conductive 51 materials (ECMs), mix proportions, aggregate type, ECM dispersion, and ionic environment of 52 concrete. Admixtures can be used for manipulating the internal environment of concrete and/or 53 improve the performance of ECMs. An optimized ECON mix design should account for all 54 influencing factors. The objective of this research was to investigate the influence of a variety of 55 factors on electrical and mechanical characteristics of ECON. To this end, a factorial 56 experimental plan was prepared with five factors, all varying in two levels. The test results were 57 analyzed through regression analysis to quantitatively evaluate the significance of the effects of 58 each factor. The results showed that the dosage and type of ECM, mix proportions of concrete, 59 and admixtures exert a significant effect on electrical properties of ECON while also affecting its 60 mechanical characteristics.

Disciplines

Civil and Environmental Engineering | Mechanics of Materials | Transportation Engineering

Comments

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ABSTRACT

Application of heated pavement systems is a safer and faster alternative to currently predominant methods of removing ice and snow from paved surfaces. Heated pavements not only can remove ice/snow from pavement surfaces, but are also capable of preventing their formation/accumulation in the first place. Electrically conductive concrete (ECON) provides an effective and powerful means of producing self-heating pavements. The electrical conductivity of ECON is dependent on numerous factors such as type and dosage of electrically conductive materials (ECMs), mix proportions, aggregate type, ECM dispersion, and ionic environment of concrete. Admixtures can be used for manipulating the internal environment of concrete and/or improve the performance of ECMs. An optimized ECON mix design should account for all influencing factors. The objective of this research was to investigate the influence of a variety of factors on electrical and mechanical characteristics of ECON. To this end, a factorial experimental plan was prepared with five factors, all varying in two levels. The test results were analyzed through regression analysis to quantitatively evaluate the significance of the effects of each factor. The results showed that the dosage and type of ECM, mix proportions of concrete, and admixtures exert a significant effect on electrical properties of ECON while also affecting its mechanical characteristics.

INTRODUCTION

Ice and snow accumulation on pavement surface in roads, highways, and airports is an important source of safety risks and huge costs are imposed on the transportation sector to deal with it. The common methods that are currently adopted to remove ice and snow include application of deicer chemicals, mechanical ice/snow removal, natural melting, and melting by traffic movement; however, these approaches are associated with serious implementation and environmental problems (*1*). Therefore, there is an imperative need to develop new technologies that can more effectively and efficiently remove or prevent the formation of ice and snow on paved surfaces. Some of the newly emerged or emerging techniques for this purpose involve the application of superhydrophobic coating on pavement surface to prevent ice formation (*2*, *3*), embedding electrically heating sheet/grille elements inside the pavement (*4*, *5*), and application of self-heating electrically conductive concrete (ECON) (*6*–*8*). ECON is an avant-garde technology attracting great attention from researchers, transportation authorities, and industry experts (*6*). The general constituents of ECON are cement, coarse and fine aggregates, water, electrically conductive materials (ECMs), and possibly admixtures (*6*); however, the primary source of electrical conductivity is the ECM phase by creating a continuous path for electricity conduction. Creation of a continuous network of ECMs in concrete matrix is referred to as percolation phenomenon and the volume content of ECMs enabling the percolation is called the percolation threshold (*9*–*11*).

Since the issuance of the earliest ECON patent (*12*), numerous ECON recipes have been developed (*10*, *13*, *14*) all including the same aforementioned components. Carbon fiber has been proved as a very efficient ECM that can be safely applied in ECON pavements (*4*, *5*, *15*). Carbon fiber dosage plays a very significant role in electrical, mechanical, and workability properties of ECON (*1*). Ability of fibers to achieve percolation is controlled by dispersion level of fibers (*16*). Improved fiber dispersion leads to improved fiber-cement paste bond, higher ductility, and reduced electrical resistivity (*17*). There is a variety of chemicals that can be used for enhancing fiber dispersion; methyl cellulose is a fiber dispersive material that unlike other dispersive agents is effective in minor dosages (*18*, *19*). In addition to type, dosage, and dispersion of fibers there are other important factors such as mix proportions and chemical admixtures that affect ECON's electrical conductivity (*20*). Cement content, aggregate-to-cement volume ratio, and coarse-to-fine aggregate volume ratio (C/F) significantly influence electrical properties (*20*). Also, it has been suggested that corrosion inhibitor admixtures can improve electrical conductivity of concrete (*21*, *22*). Developing an ECON mix design with desirable heating performance calls for adjusting all aforementioned factors/constituents to achieve as low electrical resistivity as possible (*1*). Furthermore, for pavement application the final product should possess desirable workability and mechanical properties.

A trial–error approach using trial mix batches has been employed for many ECON mix designs developed up to date because the heterogeneity of concrete introduces too much uncertainty in the evaluation of different factors' effects on concrete properties. However, application of statistical methods in design of experiments (DOE) and regression analysis of the measurement results provides a powerful tool to evaluate factor effects on characteristics of concrete (*23*). New ECON mix design based on such pre-defined, structured DOE will be more rational and universal than previous ECON mix designs based on trial–error approach.

It should be mentioned that the present research does not aim to produce highly conductive ECON samples, rather, the primary objective of this study is to identify the effect of easy-to-change mix design factors on electrical and mechanical properties of ECON in order to provide a basis for developing an optimized ECON mix design that can be applied in heated pavement systems. For this purpose, a statistical DOE was used to develop an experimental plan using five mix design variables and three responses. The tests results were analyzed by regression analysis to evaluate factor effects on responses. Carbon fiber in different size classes was used as electrically conductive constituent of ECON. The coarse-to-fine aggregate volume ratio (C/F) was used as a mix proportion variable according to which the whole mix design was adjusted. Methyl cellulose and corrosion inhibitor admixtures were used as fiber dispersive agent (FDA) and conductivity-enhancing agent (CEA) respectively. The analysis provided a quantitative evaluation of different factors' effects; this can be used as a concrete basis for optimizing the ECON mix design for heated pavement applications.

METHODOLOGY AND MATERIALS

Description of Statistical Experimental Plan

A factorial DOE was carried out to obtain a mathematical model for the influence of five variables. Selected variables/factors were carbon fiber content, carbon fiber length, C/F, FDA dosage, and CEA dosage (Table 1). A screening experimental design was used for evaluating the effect of each variable at two levels. Screening DOE -AKA 2^k design (k=number of factors) enables the number of experiments for each factor to be minimized (*24*). Also, a fractional factorial DOE was implemented so as to further reduce the number of experiments. Three replicate center points were incorporated in DOE to keep record of the error level in the modelled responses. The responses of the statistical model were electrical resistivity, compressive strength, and flexural strength. The DOE and analysis of results were performed using a commercial software (JMP®). Nineteen ECON types with different combinations of the variables were generated. The variable combinations for each mix design are given in Table 2.

TABLE 1 Variable Description in the Factorial Screening DOE

Variable	Unit	Levels		Variable type
Carbon fiber content	% of total mix volume (% Vol.)	0.1	1.0	Continuous
Carbon fiber length	mm	6.0	12.0	Categorical
C/F	N.A.	0.7	1.2	Continuous
FDA dosage	% of the cement weight	0.0	0.4	Continuous
CEA dosage	kg/m^3	0.0	15.0	Continuous

Note: N.A-Does not apply.

TABLE 2 Combination of Variables for ECON Mix Designs

Mix design No.	Variable				
	Fiber length (mm)	Fiber content (% Vol.)	C/F	FDA dosage (% wt. cem.)	CEA dosage (kg/m^3)
1	6	0.10	1.20	0.4	15.0
2	12	0.10	0.70	0.4	15.0
3	12	0.10	1.20	0.4	0.0
4	6	0.10	1.20	0.0	0.0
5*	6	0.55	0.95	0.2	7.5
6	12	0.10	1.20	0.0	15.0
7*	6	0.55	0.95	0.2	7.5
8	12	1.00	0.70	0.4	0.0
9	6	1.00	0.70	0.0	0.0
10	6	0.10	0.70	0.4	0.0
11	6	1.00	0.70	0.4	15.0
12	12	0.10	0.70	0.0	0.0
13	6	1.00	1.20	0.4	0.0
14	12	1.00	1.20	0.0	0.0
15	6	0.10	0.70	0.0	15.0
16*	6	0.55	0.95	0.2	7.5
17	6	1.00	1.20	0.0	15.0
18	12	1.00	1.20	0.4	15.0
19	12	1.00	0.70	0.0	15.0

Note: * sign marks the center points

ECON Mix Proportions for Evaluation

Variation of C/F in a concrete mix requires adjustments to the entire mix proportions. In this study, C/F of the concrete mix design was a DOE variable with two levels and one additional level for center points. Therefore, to maintain the consistency among specimens, three basic normal Portland cement concrete (PCC) mixtures were designed as the basis upon which the ECON mix designs were developed by applying required changes to proportions and/or mixture components. According to the variable combination corresponding to each ECON type, the mix designs were made by replacing prescribed volume fraction of fine aggregate with carbon fiber. In addition to carbon fiber, each ECON mix design had specific admixture requirements. After incorporation of carbon fiber and admixtures into the mix design, required adjustments to the mix proportions were made according to specific gravity and water absorption capacity of the materials to maintain fixed values of water-to-cement and C/F ratios (Table 3). Water contents were not changed during mixing, i.e. the exact amount of water prescribed by the mix design was added to the batch and high range water reducer (MasterGlenium 7500) was used for achieving target slump of 75-100 mm. Mixture proportions of the three PCC mix design types are shown in Table 3.

All mixture proportions and materials conformed to Iowa DOT Materials I.M. 529 specification and FAA advisory circular 150-5370-10G. Coarse aggregate's nominal maximum size was 25 mm. Aggregates and cement conformed to ASTM C 33 (*25*) and ASTM C150 (*26*) specifications respectively. Methyl cellulose in fine powder form was used as FDA. The FDA was dissolved in the mix water before being added to the batch. CEA was 30% aqueous solution of calcium nitrite with 1.2 specific gravity; this material is commercially available as a corrosion inhibitor admixture by *WR Grace & Co.* under the trade name DCI. Mix designs accounted for the extra water added to the mix by DCI. Chopped carbon fiber used in this study was polyacrylonitrile-based with 7.2 µm diameter, 95% carbon content, and electrical resistivity of 1.55×10^{-3} Ω-cm. Two different length size classes of the same type carbon fiber with respectively 6 mm and 12 mm nominal length were used. Specific gravity and water absorption capacity of the carbon fiber were 1.81 and 7.35 (% wt.) respectively.

TABLE 3 Mix Proportions of the Basic PCC Mixtures

Component	**Properties**			**Mix design C/F ratio**		
				0.7	**0.95**	**1.2**
	Type	**Specific gravity**	**Absorption (% wt.)**	**Volume fraction**		
Cement	Type I/II	3.15	-	0.135	0.135	0.135
Coarse aggregate	Lime stone	2.67	1.4	0.290	0.334	0.378
Fine aggregate	River sand	2.49	1.7	0.395	0.351	0.307
Water	Tap water	1.00	-	0.180	0.18	0.180

Sample Preparation

The ECON mix designs prepared as explained above were used for making concrete samples. The batches were mixed using a 0.5 m^3-capacity rotating pan mixer. Three batches were made out of each mix design. From each batch three 100 × 200 mm cylinders, three 75×75×300 mm beams, and three 100×100×100 mm cubic specimens were prepared for compressive strength, flexural strength, and electrical resistivity measurements, respectively. All specimens were cured at 100% relative humidity and 23° C temperature during the entire study. All specimens were brought to saturated surface dry condition prior to conducting the measurements. Compressive and flexural strength tests were respectively performed according to ASTM C 39 (*27*) and ASTM C 78 (*28*). Copper mesh electrodes –Figure 1(a) - were embedded within the cubic specimens for measuring electrical resistance. Electrical resistance was measured by a LCR meter (BK Precision® 875B) using direct current and then electrical resistivity was calculated from resistance; the test setup is illustrated in Figure 1 (b). Electrical resistivity was measured at three ages (3, 7, and 28 days), while, compressive strength, and flexural strength were measured at 28-day age.

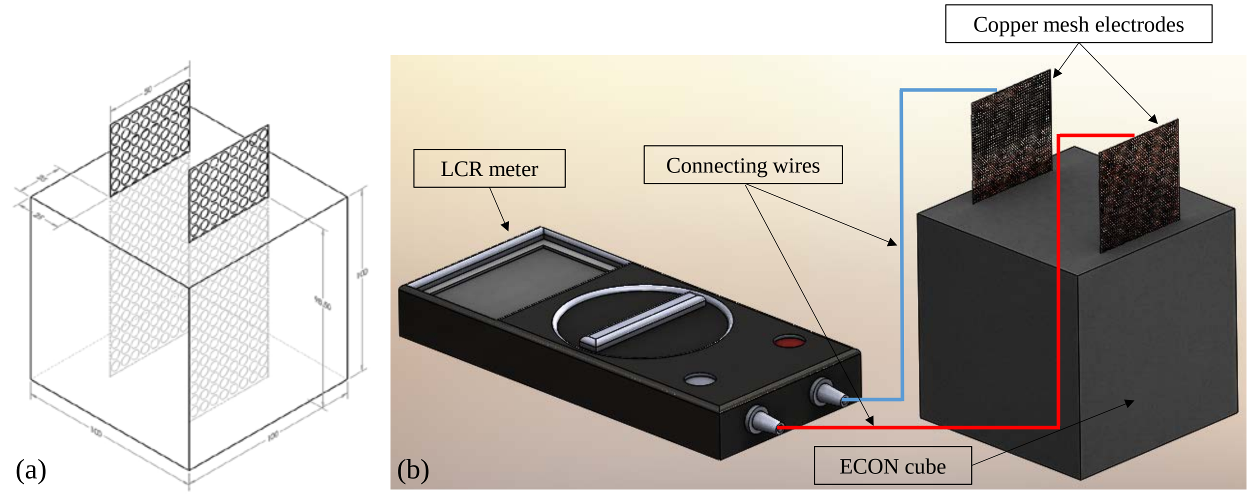

FIGURE 1 Measurement of electrical resistivity: (*a*) schematic of cubic ECON specimens with embedded electrodes and (b) test set up for measurement of electrical resistivity.

Data Analysis

Variable estimates were derived by standard least square regression analysis of the measured responses. This method applies a separate two-way analysis of variance (2-way ANOVA) on each response to generate a model for a particular response. The significance of each variable's effect on each response was indicated by the p-value (i.e. probability) parameter. The confidence interval (1-α) was selected as 0.95. A variable was considered to be significant if it took a p-value smaller than α; therefore, the effects corresponding to a p-value smaller than 0.05 would be significant. The smaller the p-value the higher would be the significance level. The estimates for a variable refer to the coefficients of the model built up by least square analysis (*23*). Herein, the model feature was used to simulate the effect of individual variables on the responses.

RESULTS AND DISCUSSION

The test results used to derive the factorial design models are presented in Table 4. Note that each value in the table is the average of nine measurements (three batches from each particular mix design and three specimens for each test from each batch). However, the raw results of the experiments do not provide a thorough understanding of factor influences and does not enable one to come up with recommendations for optimizing the ECON mix design. Therefore, the regression analysis results were used for interpretation of the test data.

TABLE 4 Averaged Measurement Results for Each Mix Proportion

Mix proportion No.	**HRWR (% wt. cem.)**	**Age (days)**		
		3	**7**	**28**
		Response		

		Resistivity (Ω-cm)	Resistivity (Ω-cm)	Resistivity (Ω-cm)	Compressive strength (MPa)	Flexural strength (MPa)
1	1.0	2,543	3,370	4,313	55	6.5
2	1.0	2,263	2,953	3,730	59	5.5
3	1.0	3,193	4,023	5,293	44	7.0
4	1.0	4,197	4,873	5,890	46	6.0
5	1.0	2,583	2,837	3,177	50	8.0
6	1.0	2,963	3,560	3,943	65	8.5
7	1.0	2,457	2,670	2,910	52	6.0
8	3.0	897	1,087	1,163	37	6.5
9	3.0	988	1,107	1,563	22	5.5
10	3.0	2,673	3,567	4,093	45	7.0
11	2.0	1,350	1,520	1,753	53	7.5
12	1.0	3,953	4,593	5,373	52	6.0
13	2.5	1,997	2,273	2,643	39	7.0
14	3.0	600	647	800	20	6.5
15	1.0	2,697	2,727	3,297	66	6.0
16	1.0	2,080	2,323	2,750	53	7.0
17	2.5	1,950	2,337	2,653	31	6.5
18	2.5	1,463	1,737	1,983	60	9.0
19	3.0	780	870	1,110	24	5.5

Note: HRWR=high range water reducing admixture

Effect of Factors on ECON Electrical Resistivity

Table 5 presents p-values and standard error (SE) for the main effects of factors on electrical resistivity of ECON. As far as main effects are concerned, for the selected confidence interval ($1-\alpha = 0.95$) the four factors of fiber content, fiber length, C/F, and CEA dosage were found to be significant at all ages acquiring p-values smaller than 0.05. FDA dosage was significant only at 3-day age. This showed that factor effects are likely age-dependent. Variation of FDA effectiveness with cement hydration time can be attributed to the effect of excessive porosity at early ages when fibers are clustered/flocculated in absence of FDA; nevertheless, as the results showed, by evolution of cement hydration the effect of excessive porosity caused by fibers tends to become less significant. Therefore, 28-day measurement results would be more reliable than earlier ages because cement has undergone most of its hydration by this age.

Considering 28-day results analysis, fiber content and C/F ratio having infinitesimally small p-values were the most significant factors followed in importance by CEA dosage and fiber length. In addition to the significance level of factors, the way each factor individually affected the responses can be investigated through the predicted response values. Figure 2 shows predicted electrical resistivity values by variation of each factor. It can be seen in Figure 2 that electrical resistivity was decreased with increasing fiber content, fiber length, CEA dosage, and FDA dosage, while, higher C/F led to increased resistivity. Fiber length exerted a moderate effect on electrical resistivity and the effect of FDA dosage was negligible.

TABLE 5 Parameter Estimates of Main Effects of the Factors for Electrical Resistivity Response

Factors/variables	Age (days)					
	3		7		28	
	P-value	SE	P-value	SE	P-value	SE
Fiber content	0.00E+00	2.8	0.00E+00	3.1	0.00E+00	3.3
Fiber length	5.35E-07	2.6	5.27E-05	2.9	3.04E-06	3.3
C/F	4.00E-09	2.8	0.00E+00	3.1	0.00E+00	2.7
CEA dosage	1.51E-06	2.5	1.58E-07	3.1	1.20E-09	3.3
FDA dosage	3.03E-04	2.8	7.11E-01	3.0	5.16E-01	2.6

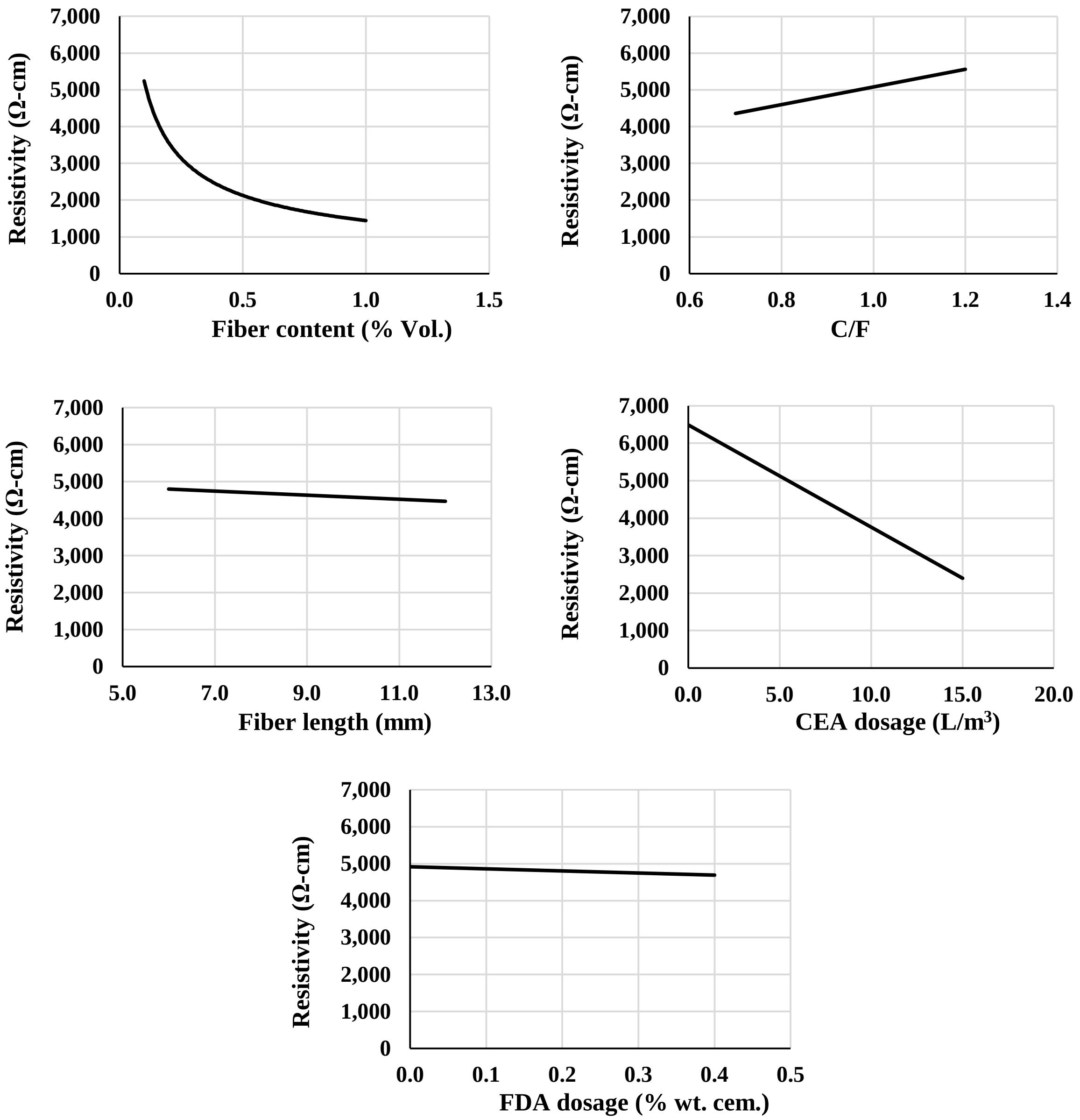

FIGURE 2 Predicted main effects of individual factors on electrical resistivity.

Effect of Factors on ECON Strength Properties

Factor effects on strength properties are shown in Table 6. Figure 3 provides predicted variations of the strength responses with each factor derived from regression analysis model. Regarding p-values of main effects, three factors of fiber content, CEA dosage, and FDA dosage were significant with respect to compressive strength, while, only C/F ratio and FDA dosage were significant factors influencing flexural strength. It is revealed in Figure 3 that fibers positively affected compressive strength only to a certain fiber content (ca. 0.55%). Unlike compressive strength, flexural strength kept a constantly increasing trend with increasing fiber content.

Both compressive and flexural strengths were increased with increasing CEA dosage or using longer fiber. Higher C/F or higher FDA dosage resulted in lower compressive and flexural strengths. Note that the effects of fiber length and C/F factors on compressive strength as well as the effects of fiber content, fiber length, and CEA dosage on flexural strength were non-significant.

TABLE 6 Parameter Estimates of Main Effects of the Factors for Strength Responses.

Factors/variables	Response			
	Compressive strength		Flexural strength	
	P-value	SE	P-value	SE
Fiber content	0.00E+00	0.5	5.79E-01	0.1
Fiber length	5.82E-01	0.5	3.35E-01	0.1
C/F	5.41E-01	0.4	2.79E-04	0.1
CEA dosage	0.00E+00	0.5	1.36E-01	0.1
FDA dosage	0.00E+00	0.5	1.18E-02	0.2

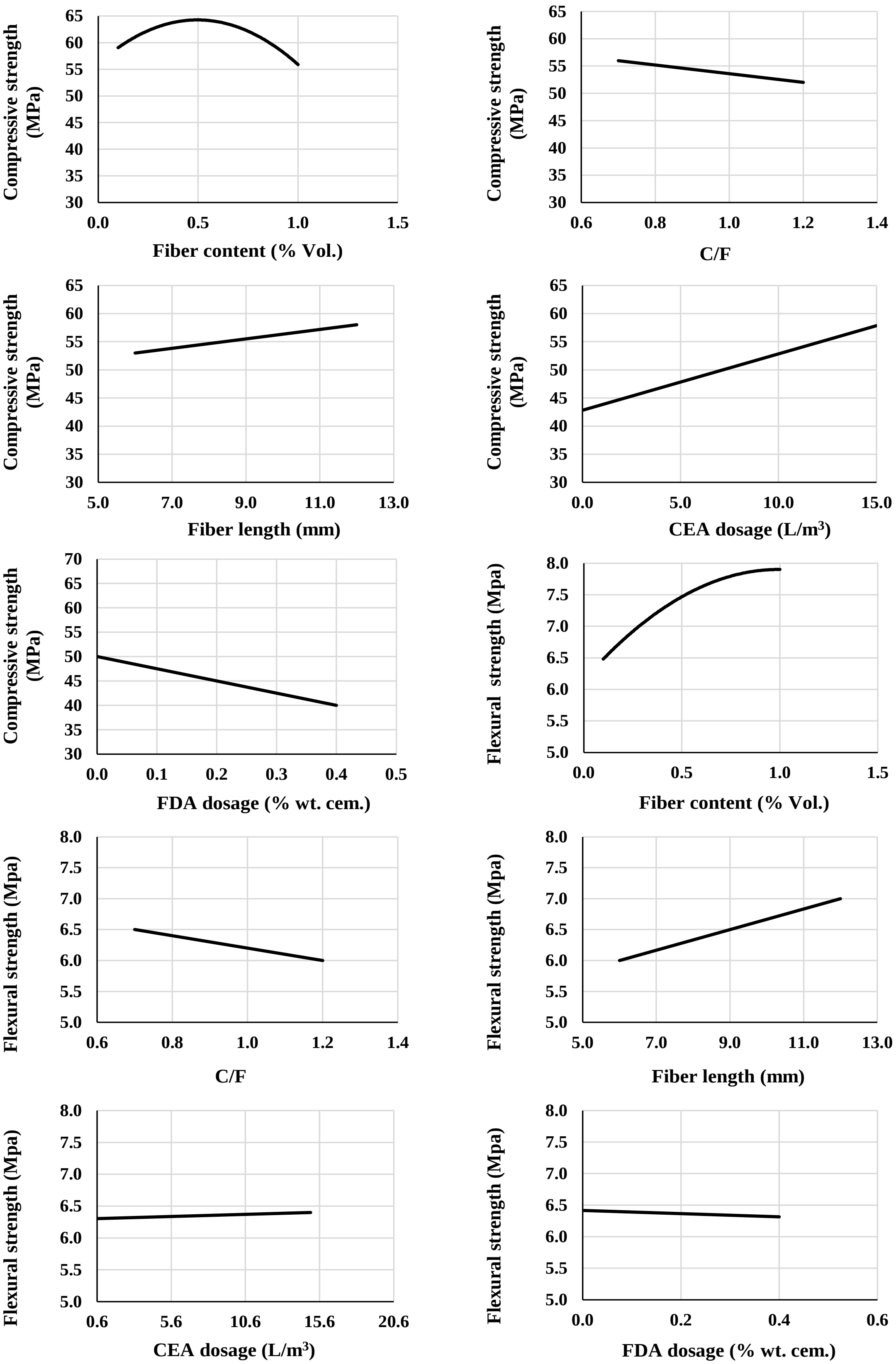

FIGURE 3 Predicted main effects of individual factors on strength properties.

The foregoing discussions suggest that application of fiber in a volume fraction that lies within the percolation threshold -0.4 to 0.8% Vol. (*1*, *10*)- was desirable with respect to all three responses. Therefore, it is not recommended to exploit carbon fiber contents higher than required amounts for achieving percolation. It was revealed that longer fiber resulted in lower resistivity and higher strength values; but note that the effects of fiber length on the reponses were either moderate or non-significant. On the other hand, application of 12-mm fiber was associated with significant drawbacks in terms of mixing practice and fresh properties. The mixtures containing 12-mm fiber suffered from low workability and were prone to excessive bleeding and segregation especially when high C/F prevailed; even using low amounts of HRWR could not eliminate the bleeding problem. Consequently, it can be suggested that 6-mm fibers appeared to be more appropriate for application in ECON. Using 6-mm fiber rendered the mixture very sensitive to variation of C/F as electrical resistivity dramatically increased by increasing C/F. Furthermore, mixtures with low (0.7) or moderate (0.95) C/F values exhibited considerably better workability and cohesiveness. Hence, practical considerations and C/F effect on all responses suggest in favor of reducing C/F as much as allowed by the relevant specifications and/or application-induced requirements. The effect of FDA on electrical resistivity was found to be non-significant. However, for fiber contents in the percolation threshold range, minor dosages of FDA can result in improvement of both compressive and flexural strengths. A FDA dosage of 0.2 (by weight of cement) did not exert adverse effects on fresh mix rpoperties. CEA exerted a significant reducing effect on electrical resistivity as long as fiber content did not exceed percolation threshold. Moreover, CEA helped improving compressive strength and slightly the flexural strength.

CONCLUSIONS AND RECOMMENDATIONS

A factorial design of experiments (DOE) was used for developing an experimental plan to investigate the main effects of five factors in two levels on the electrical and mechanical properties of electrically conductive concrete (ECON). The responses were electrical resistivity, compressive strength, and flexural strength. Regression analysis model provided the significance levels of each factor in terms of p-value and predicted response simulations. The results can be summarized in the following statements:

- Significance of factors varied by hydration time (age) becoming almost steady after 7 days. It is recommended to use 28-day or later age measurement results for analyses.
- Four significant factors affecting electrical resistivity arranged from most to least significant were fiber content, coarse-to-fine aggregate volume ratio (C/F), fiber length, and conductivity-enhancing agent (CEA) dosage.
- Compressive strength was significantly influenced by fiber content, CEA dosage, and fiber-dispersive agent (FDA) dosage.
- Two factors showed significant effect on flexural strength, namely, C/F and FDA dosage.
- In addition to main effects of factors, practical and implementation considerations should be taken into account when the results are being used for optimization of the ECON mix design.
- In the boundaries of the carbon fiber percolation threshold range (0.4%-0.8% of total mix volume) increasing the fiber content tends to improve electrical conductivity,

compressive strength, and flexural strength. Also, using minor amounts of FDA can help enhancing the ECON properties. The observations during mix preparation showed that using 0.2% (by weight of cement) FDA does not adversely affect fresh properties of ECON.

- Although using 12-mm fiber exerted positive effect on the responses, the effect was moderate in case of electrical resistivity and non-significant on strength properties. Therefore, considering the adverse effect of 12-mm fiber on fresh properties of concrete it is recommended that 6-mm fiber be used in production of ECON.
- Increasing the C/F from 0.7 to 1.2 turned out to have a significant adverse effect on electrical conductivity and flexural strength.
- CEA application considerably improved electrical conductivity and compressive strength especially at low fiber contents. Although CEA improved flexural strength, its effect was not significant.
- Optimization of ECON mix design can include applying 0.4-0.8 % (Vol.) of 6-mm carbon fiber with calcium nitrite solution as CEA -15 l/m^3 of calcium nitrite 30% aqueous solution was used in this study- and a minor amount (e.g., 0.2 % wt. of cement) of methyl cellulose additive. It is desirable to adjust the mix proportions such that a low C/F is attained.

The results of this research are being used for producing ECON specimens with higher functionality, higher constructability, and lower production cost. Future studies on this topic can use the results of this study to develop an extensive experimental plan for investigating the discussed effects with more levels of the significant variables. A full factorial DOE can be used to obtain more accurate predictive models. There are a variety of admixtures and electrically conductive materials that still need to be evaluated for improvement of electrical conductivity of ECON. Developing three-phase electrically conductive composites (*1*) is a viable method that can be integrated with the methods proposed in this study to expand the functionality of ECON beyond the levels achieved so far.

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