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Optimization of CF-GP Blended Electrically Conductive Concrete

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Abstract - The feasibility of blending carbon fiber (CF) with graphene powder (GP) to produce electrically conductive concrete has seen limited investigation. This study aims to optimize the mixture proportions of CF-GP blended electrically conductive concrete for superior durability and mechanical characteristics using the Taguchi optimization approach. The design of the experiments was carried out considering four factors, each having three levels. The resulting CF-GP blended electrically conductive concrete mixtures of the L9 orthogonal array were proportioned using different cement content, water-to-cement ratio, volume of ECM, and combination of ECM. Test methods included electrical conductivity and compressive strength. The two quality criteria were given equal weights to determine the optimal levels of factors. The method revealed that the optimum mix for electrical conductivity had a cement content of 400 kg/m^3, w/c of 0.55, ECM volume of 6%, and ECM combination of 40/60, whereas for compressive strength it had a cement content of 300 kg/m^3, w/c of 0.50, ECM volume of 2%, and ECM combination of 30/70. Experimental findings endorse the utilization of CF and GP in concrete as a means of improving the electrical performance of concrete.

***Keywords*:** Carbon fiber, graphene powder, Optimization, Electrical Conductivity, Concrete

1. Introduction

Recent innovative approaches are directed at improving the performance and functionality of concrete, the primary building construction material worldwide [1]. Nowadays, multifunctional smart concrete can be crucial to a more sustainable and environmentally friendly construction industry as it possesses one or more useful functional properties including excellent electrical conductivity [1-3]. Therefore, extensive efforts are focusing on developing electrically conductive concrete (ECC) which has higher conductivity than conventional concrete. Carbon black, carbon fiber (CF), steel fiber, and graphene powder (GP) have been proven to be efficient functional electrically conductive materials (ECM) in improving the electrical performance of concrete. These materials create electrically conductive networks inside the cementitious matrix that can significantly reduce the electrical resistivity by several orders of magnitude [4-5].

CF is defined as a fiber that contains a carbon content above 92%, by weight [4]. It can be used as an ECM in small volume and weight dosages. Past studies have shown the ability of CF to improve the electrical conductivity of cementitious composites while improving the concrete properties including compressive strength, tensile strength, and shrinkage cracking potential [6-7]. The electrical properties and high aspect ratio (length to diameter) of CF led to an increase in the conductivity of cement-based composites incorporating CF [4]. Chung reported that the incorporation of short CF into cement-matrix composites led to a reduction in the electrical resistivity, hence an increase in the electrical conductivity [8]. Wang et al. found that the cement-based composites integrated 0.6% CF, by cement mass, exhibited an increase in the compressive strength by 20% compared to that without CF. However, the strength does not always increase as it depends on the CF dispersion and its content [9]. Garce´s et al. also demonstrated that the addition of 0.5% CF, by cement mass, led to a considerable increase in the compressive strength (16%) relative to the CF-free mortars [10]. Chuanga et al. showed the dual effect of the well-dispersed CF in cement-based composites. The electrical conductivity and compressive strength are intended to increase with the increase of CF content by up to 0.6%, by cement mass, as the fibers can contact or overlap each other to form a conductive network [11].

GP is utilized in cementitious composites due to its remarkable electrical properties, and mechanical strength [12-13]. Previous studies have demonstrated the ability of GP to improve the electrical conductivity and compressive strength of cementitious composites. Sun et al. found that incorporating graphene in cementitious composites led to an increase in the electrical conductivity and compressive strength [14]. Dimov et al. showed that adding graphene to concrete composites improve mechanical properties offering up new possibilities for building materials [1]. Sedaghat et al. highlighted the significant effect of graphene on enhancing the electrical conductivity of cement composites [15]. Bai et al. also reported that the addition of graphene into cement matrix can further improve the electrical conductivity of the composite [16]. Based on the aforementioned, achieving optimal performance in electrically conductive concrete is a challenging task involving extensive experimental studies. Hence, many scientists have shifted their interest toward adapting systematic optimization methods before conducting the experimental program [17-18].

Anwar et al. adopted the Taguchi method to develop pervious geopolymer concrete mixtures with different variables including binder content, dune sand addition, alkali activated solution-to-binder ratio, and sodium hydroxide molarity. The corresponding signal-to-noise ratios (S/N) results showed that the optimum mix for a balanced performance scenario included 400 kg/m^3 of binder content, 10% of dune sand addition, 0.60 of alkaline-activator solution-to-binder ratio, and 12 M of sodium hydroxide molarity [19]. Similarly, Teimortashlu et al. employed the Taguchi method for a tertiary blended self-compacting mortar to optimize its compressive strength at the age of 28 days, considering three factors each at four different levels [20].

Limited investigations have assessed the feasibility of blending CF with GP to produce electrically conductive concrete. Based on the literature, it is obvious that electrically conductive concrete mixtures containing CF and GP have not been optimized for superior durability and mechanical properties yet. Such a process is complex, as multiple factors must be considered simultaneously along with different performance criteria, which may require an extensive number of experiments. Accordingly, this work aims to find the optimum mixture proportions of CF-GP electrically conductive concrete using the Taguchi optimization method. Research findings provide evidence of the effective use of CF and GP in concrete as a means of improving its electrical performance.

2. Experimental Program

2.1. Materials

ASTM Type I ordinary Portland cement (OPC) was used as a binder in the concrete mixes [21]. Crushed dolomitic limestone and dessert dune sand were utilized as aggregates. Their specific gravity, specific surface area, and fineness modulus were 2.82/2.77, 2.49/142 cm^2/g, and 6.82/1.45, respectively. Tap water with a pH of 7.1 was used as the mixing water in the ECC mixes. Superplasticizer at a constant dosage of 2% of the binder mass was also used in the hybrid ECC mixtures to maintain their workability. CF and GP were used as ECMs. The CF exhibited specifications such as a 7 μm diameter, 6 mm length, 0.55 g/cm^3 bulk density, and a 3.5 GPa tensile strength. Meanwhile, GP served as an alternative conductive material, having a particle size of 100 μm and a specific gravity of 2.15.

2.2. Sample preparation and test methods

Electrically conductive concrete mixes were prepared by mixing cement, crushed dolomitic limestone and dune sand, using hand mixer, for three minutes. Water and superplasticizer were then gradually added to the dry components and further mixed for another two minutes. Subsequently, the ECMs were incorporated into the mix and mixed for an additional two minutes to ensure a homogenous and uniform mixture. The ambient temperature and relative humidity during mixing and sampling hovered around 25±2°C and 50±5%, respectively. The fresh ECC specimens were cast into cubic (50 mm), and cylindrical (100 × 200 mm) steel molds for strength and resistivity assessment. The samples were demolded after 24 hours, then cured in ambient air conditions until the testing age of 7 days. Furthermore, the mechanical properties were characterized by the compressive strength (f'_c), which was determined following ASTM C39 [22]. For the resistivity performance tests, the electrical conductivity was determined in accordance with ASTM C1876 [23]. For each property, triplicate samples per mix were tested to obtain an average.

2.3. Optimization methodology

A total of nine CF-GP blended electrically conductive concrete mixes were designed based on Taguchi's method to concurrently consider different factors (Table 1). Each factor was characterized by three levels, i.e., binder content (300, 350, and 400 kg/m^3), water-to-cement ratio (0.50, 0.55, and 0.60), volume of ECMs (2, 4, and 6%) and combination of ECMs (20/80, 30/70 and 40/60).

Two quality criteria, i.e., Q1-Q2, were allocated to electrical conductivity and f'_c. The quality criteria were given equal weights in the analysis. The signal-to-noise (S/N) ratio was used to analyze the experimental results. It was calculated using the target parameter (i.e., response) optimization characteristics, which are the nominal-the-better, the smaller-the-better, and the larger-the-better. In this study, the S/N ratio of "larger-the-better" was chosen for the electrical conductivity and compressive strength as they should be maximized.

Table 1: Mixture proportions of the ECC mixes for the L_9 Taguchi array.

Mix ID	Cement Content (kg/m^3)	w/c	Volume of ECM (%)	Combination of ECM (%)
L1	300	0.6	2	20/80
L2	300	0.55	4	30/70
L3	300	0.5	6	40/60
L4	350	0.6	4	40/60
L5	350	0.55	6	20/80
L6	350	0.5	2	30/70
L7	400	0.6	6	30/70
L8	400	0.55	2	40/60
L9	400	0.5	4	20/80

3. Results

The electrical conductivity and compressive strength of CF-GP blended electrically conductive concrete mixes are considered key hardened properties that assess the resistivity and mechanical performance (Fig. 1). Mix L7, comprising a cement content of 400 kg/m^3, ECM volume of 6%, and ECM combination of 30/70, exhibited the highest electrical conductivity response of 631 mS/m. Conversely, mix L1, with a cement content of 300 kg/m^3, ECM volume of 2%, and ECM combination of 20/80, yielded the lowest electrical conductivity of 77 mS/m. Such a finding is independent of the w/c or cement content, indicating the critical influence of ECM volume compared to these two factors.

From the mechanical performance perspective, for each group of the mixes with a constant cement content (300, 350, and 400 kg/m^3), those made with a w/c of 0.5 experienced the highest compressive strength, i.e., mixes L3, L6, and L9, respectively. Indeed, as the w/c increases, the free water occupies the pore voids of the concrete microstructure evaporates leaving air voids that led to a reduction in the strength [24-25].

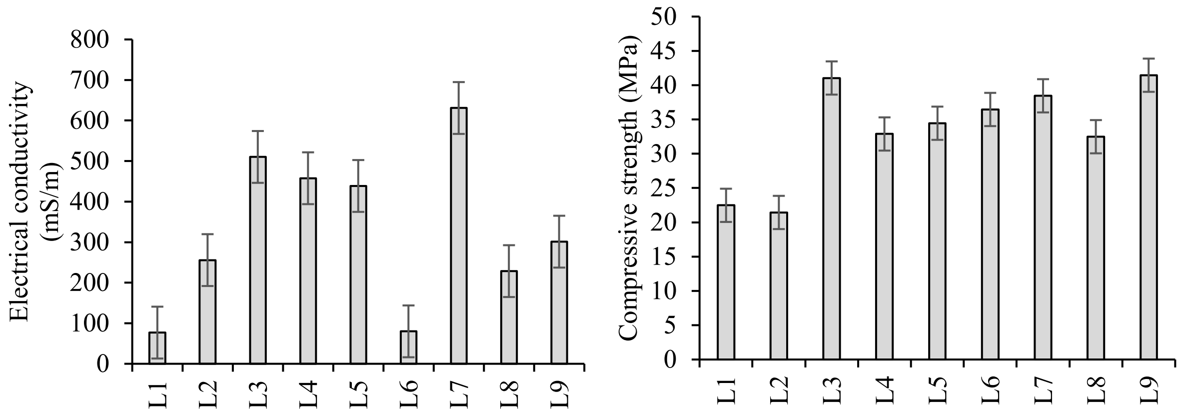
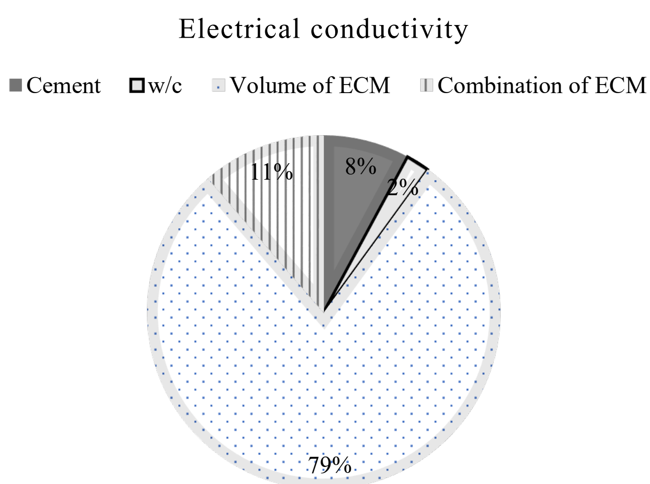


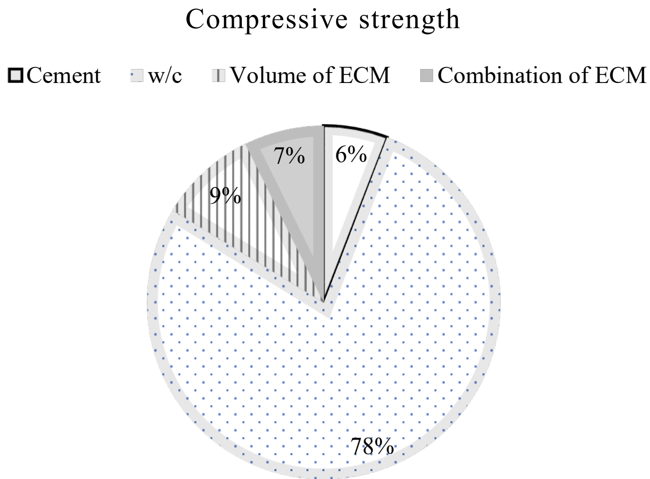
Fig. 1: Electrical conductivity and compressive strength of CF-GP concrete mixes.

ANOVA was carried out to assess the contribution of each factor toward the electrical conductivity and compressive strength responses, as shown in Fig. 2. The volume of ECM had the highest contribution toward the electrical conductivity with a value of 79%, while the w/c had the least contribution of 2%. These results were well aligned with the conductivity outcomes in Fig.1, whereby the highest electrically conductive CF-GP concrete could be produced with ECM volume of 6% regardless of the w/c. These findings show that the volume of ECM predominantly controlled the durability properties of CF-GP concrete.

On the other hand, the w/c was the most significant factor influencing the compressive strength of CF-GP concrete mixes with a respective contribution of 78%. However, the cement content had the least significant impact on the strength with the lowest contribution of 6%.



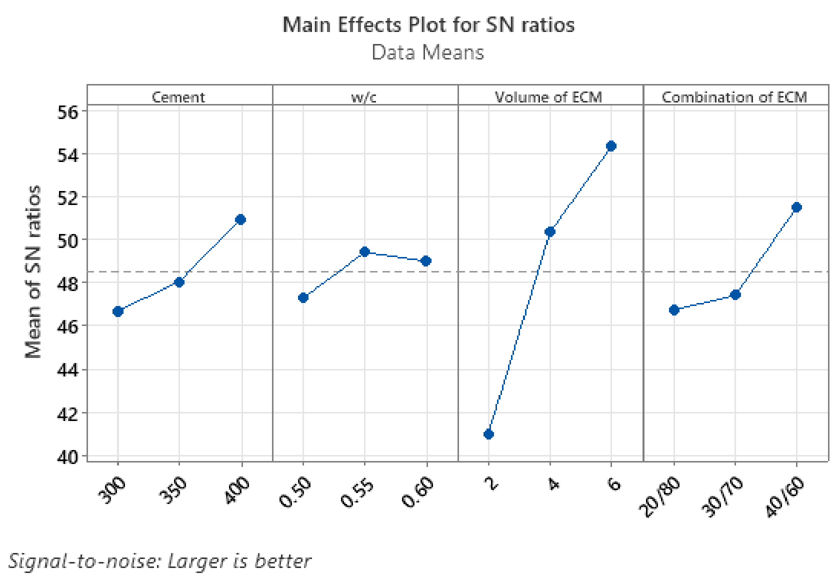
(a)



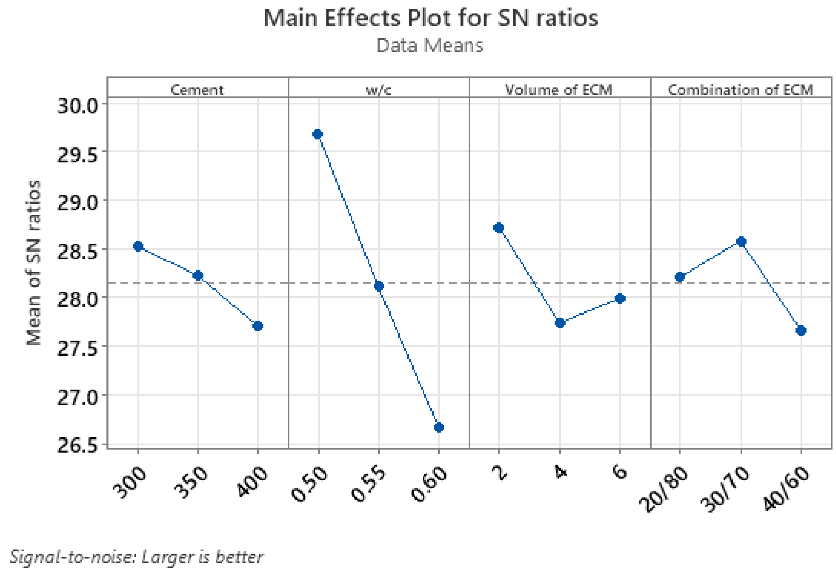
(b)

Fig. 2: ANOVA contribution factors for (a) electrical conductivity and (b) compressive strength.

The signal-to-noise (S/N) ratio was used to obtain the optimum mixture proportions for each of the two quality criteria, including electrical conductivity, and compressive strength as illustrated in Fig.3. The target response for CF-GP blended concrete mixes using the Taguchi method was to obtain superior conductivity and mechanical properties. The results revealed that the optimum mix for the maximum electrical conductivity has a cement content of 400 kg/m^3, w/c of 0.55, ECM volume of 6%, and ECM combination of 40/60. However, the optimum mix to secure the highest compressive strength corresponded to a 300 kg/m^3 cement content, w/c of 0.50, ECM volume of 2%, and ECM combination of 30/70.



(a)



(b)

Fig. 3: Mean of S/N ratios for (a) electrical conductivity and (b) compressive strength.

4. Conclusion

This study aimed at utilizing the Taguchi method to optimize the mixture proportions of concrete incorporating carbon fiber (CF) and graphene powder (GP). The electrical conductivity and compressive strength were the respective resistivity and mechanical characteristics. A total of four different factors, including the cement content, water-to-cement ratio, volume of electrically conductive materials, and combination of electrically conductive materials were considered in the design of experiments by adopting an L_9 orthogonal array. Results showed that mix L7 incorporating ECM volume of 6% yielded superior electrical conductivity, whereas mix L9 made with a w/c of 0.5 exhibited the highest compressive strength. The ANOVA revealed that the volume of ECM, and w/c were key factors affecting the durability and mechanical properties of CF-GP blended electrically conductive concrete, respectively. The Taguchi approach illustrated that the optimum mix for superior electrical conductivity consisted of 400 kg/m^3 cement content, w/c of 0.55, ECM volume of 6%, and ECM combination of 40/60, while for superior strength it has a cement content of 300 kg/m^3, w/c of 0.50, ECM volume of 2%, and ECM combination of 30/70.

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