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# Electrical conductivity and compressive strength of carbon fiber reinforced fly ash geopolymeric composites

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## HIGHLIGHTS

- Effect of carbon fiber in fly ash geopolymer on conductivity and strength.
- I-V curve, CV and EIS techniques for electrical measurement yield similar results.
- Conductivity depends on amount of CF and liquid, curing temperature, and aging time.
- Adding 0.5 wt% CF exhibits the lowest resistance and highest compressive strength.
- The improvement of these properties was due to the composite effects.

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## ABSTRACT

The effect of carbon fiber (CF) addition on the electrical behavior and mechanical property of fly ash geopolymer was investigated. The electrical resistivity of CF/geopolymer composites was systematically investigated as a function of CF concentration, liquid to ash ratio (L/A), curing temperature, aging time, measurement frequency, and measurement technique. Three different techniques used in this study for measuring electrical properties were I-V curve measurement, cyclic voltammetry, and electrochemical impedance spectroscopy. Each technique yielded similar results. The electrical conductivity was highly dependent on the CF concentration and percolation threshold. Below the threshold, the resistivity varied with curing temperature and time, but above that the resistivity decreased monotonically with respect to CF concentration irrespective of other factors. Changing the L/A shifted the percolation threshold to higher values, but the other electrical characteristics were similar. The composite with 0.5 wt% CF was found to exhibit the lowest resistance and highest compressive strength. Our findings showed that CF addition not only improved the electrical conductivity by several orders of magnitude, but also enhanced its mechanical property. The improvement of these properties was due to the combined effects as confirmed by X-ray diffraction and scanning electron microscopy techniques that the phases of matrix did not change and the fiber distribution was homogeneous and randomly oriented.


## 1. Introduction

The production of ordinary Portland cement (OPC) requires high energy and the process emits large amounts of $CO_2$ gas to the environment which contributes to the greenhouse effect [1]. As a result, many researchers have sought for new materials for reducing or replacing the use of OPC. Geopolymer is an inorganic aluminosilicate material which can be used as an alternative construction material for OPC. The structure of geopolymer is a three-dimensional network of alumina and silica [2] which provides several advantages such as high thermal stability, corrosion resistance, low shrinkage and environmental friendliness [3,4]. Geopolymer can be produced from by-products or waste materials such as fly ash, rice husk ash and blast furnace slag. Fly ash (FA) is mainly composed of alumina and silica and is a by-product

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obtained from burning coal in a power plant. It has been used as a starting material for preparing geopolymer because of its huge production and a great chemical potential for geopolymerization.

Similar to OPC, plain geopolymer is brittle and its toughness can be improved by incorporating fiber reinforcement. Considering the ease of manufacturing, handling and cost effectiveness, short fibers tend to be selected as reinforcement in civil engineering [5,6]. A number of types of fiber reinforcements have been investigated to enhance the mechanical properties of fiber/geopolymer composites such as carbon nanotube (CNT), polyvinyl alcohol (PVA) fiber, basalt fiber, polypropylene (PP) fiber, steel fiber and carbon fiber (CF) [7,8]. Recently, it was found that adding micro-steel fibers significantly improved both the ultimate flexural capacity and ductility of geopolymer composites, especially at early ages, without a negative effect on its compressive strength [9]. Moreover, incorporating PP fibers at levels up to 3 wt% in a geopolymer matrix was found to reduce its shrinkage and enhance the energy absorption of the composite [10].

Amongst the reinforcing phases for cementious materials, carbon-based materials which can be used as additives to geopolymer-based composites as well as cement based materials have gained significant interest from many research groups. In a recent review, Lu et al. summarized the use of CNT, CF, graphene and graphene oxide for improving properties of cementitious materials [11]. These composites can be exploited in several applications, for instance, in reinforcement, self-sensing, self-heating and deicing, energy harvesting [11]. CNT was also added in geopolymer mortar to reduce its drying shrinkage as well as water absorption [12]. Additionally, the fracture toughness of geopolymer was significantly improved when short carbon fibers were used during the preparation of composite materials [3].

Utilization of carbon-based materials does not only improve the mechanical aspect of the geopolymer composite but also enhances other functionalities. For example, it was reported that electrical conductivity and piezoresistive responses were affected when CNTs were added to geopolymeric composites [4]. In accordance with [4], the electrical conductivity was non-linearly proportional to the concentration of CNT, whereas the piezoresistivity changed directly with the amount of loading. In their study, Vaidya and Allouche [13] mixed carbon fibers with geopolymer concrete and investigated its strain sensing behavior. It was found that the electrical conductivity of the carbon fiber reinforced geopolymer concrete reasonably followed the flexural deflection but for its compressive strain, a more complex behavior was observed. MacKenzie and Bolton [14] compared the effect of CNT and graphite addition on the electrical conductivity of aluminosilicate inorganic polymer composites. CNT was superior in enhancing the electrical conductivity compared to graphite but no linear relationship between the conductivity and CNT concentration was found.

The electrical behavior of geopolymeric materials can be very beneficial for smart sensing applications. In fact, conductive cementitious materials have received great interest for many years due to their useful and outstanding applications. These include electrical grounding and lightning protection for buildings, static charge dissipation for sensitive electronic devices, deicing bridges, highways, pathways and airport runways, cathodic protection for anti-corrosion in concrete and electromagnetic shielding for electronics related to electric power generation and telecommunication [11,15]. A number of reports on electrical conductivity of cements have been published, but very few for geopolymers.

In this work, we investigated the electrical response of CF reinforced fly ash geopolymeric composites. CF was selected over other carbon-based materials due to its lower cost and greater availability. It also possesses a high modulus of elasticity, tensile strength and toughness, but lower specific weight [16]. Moreover, a recent study showed that CF is superior to CNT or graphene nanoplatelets (GNP) in reducing the electrical resistivity of the cementitious composites [17]. Unlike other previous studies that adopted a more practical perspective, the current study aimed to unfold the origin of these behaviors by systematically studying the effect of CF on the electrical and mechanical properties of geopolymers. Several parameters were varied, namely, the liquid to ash ratio, concentration of CF, aging time, measurement frequency and curing temperature. Moreover, several means of measuring the electrical responses were employed, such as use of I-V curves, cyclic voltammetry (CV), and electrochemical impedance spectroscopy (EIS). Additionally, the mechanical property and microstructures of CF/-geopolymer composites were investigated using a universal testing machine (UTM) and scanning electron microscope (SEM), respectively.

## 2. Materials and methods

### 2.1. Material

High calcium lignite fly ash (FA) from the Mae Moh power plant in Lampang, Thailand was used. The chemical composition of the as-received FA ash was determined using X-ray fluorescence spectroscopy (XRF) and is presented in Table 1. The microstructure of raw FA was observed under scanning electron microscopy (SEM) and is shown in Fig. 1. FA particles were spherical in shape with smooth surfaces. Also, the particle size distribution of FA size is wide, in the range of sub-micrometers to tens of micrometers. Agglomeration of small particles was also observed.

The X-ray diffraction (XRD) pattern of the as-received FA is shown in Fig. 2. A broad XRD peak was generally observed, which is the common feature of an amorphous phase. Apart from that, several crystalline peaks were found which were attributed to Anhydrite (A), quartz (Q), hematite (F), calcium oxide (C) and mullite (M) [18,19].

Dispersed chopped carbon fiber (CF) was purchased. The properties of the CF are summarized in Table 2. Sodium hydroxide (NaOH) at a 10 M concentration and sodium silicate ($Na_2SiO_3$) with 12.53 wt% $Na_2O$, 30.24 wt% $SiO_2$ and 57.23 wt% $H_2O$ were used as alkaline activating solutions.

### 2.2. Sample preparation

To prepare the CF/geopolymer composites, the fiber was first dispersed manually in a sodium hydroxide solution for 5 min to avoid agglomeration of CF. After that, FA was added to the solution and thoroughly mixed using a mechanical blender at 1400 rpm for 5 minutes. Then, sodium silicate was added and mixed for another 5 min at the same speed. A ratio of sodium silicate to sodium hydroxide of 1.0 and the liquid to ash ratios (L/A) of 0.4 and 0.5 were selected. CFs with 0.1–0.5 wt% and 0.1–1.0 wt% were added to solutions with L/A = 0.4 and 0.5, respectively. Finally, the

**Table 1**
Chemical composition of fly ash evaluated by XRF.

| Compound | Percentage (wt%) |
|---|---|
| $SiO_2$ | 32.30 |
| CaO | 23.20 |
| $Al_2O_3$ | 17.20 |
| $Fe_2O_3$ | 10.80 |
| $SO_3$ | 3.86 |
| $K_2O$ | 2.10 |
| MgO | 2.10 |
| $Na_2O$ | 1.42 |