Synthesis of Carbon black/geopolymer composites with high and stable electrothermal performance

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Abstract

Geopolymer/nano carbon black composite is a promising electrically conductive smart material that can be used in self-heating and self-sensing applications. This paper studies the effect of adding nano carbon black to the physical, mechanical, electrical, and electrothermal performance of metakaolin-based geopolymer. Carbon black was added at the percent of 5%, 10%, 15%, and 20% by weight of metakaolin; the compressive strength was tested at various ages of 7, 14, 28, and 90 days, and the electrothermal performance was tested using AC and DC voltages. The results showed that a compromise between suitable compressive strength and high electrothermal conversion could be achieved when a specific balance between the carbon black percent and the lowest water content is established. A composite with a compressive strength of 27 MPa and stable electrothermal performance reaching 142°C at 9V DC can be prepared using 20 wt% of carbon black and a water-to-metakaolin ratio of 0.549, which is used as a smart material in construction applications.

Keywords: Geopolymer, Nano carbon black, Metakaolin, Electrothermal, Self-heating, Smart materials.

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1. Introduction

Geopolymer is a promising alternative to ordinary Portland cement, which is a traditional building material [1]. It is characterized by its resistance to high temperature and corrosion [2,3], high mechanical performance and high durability [4–6]. Also, it is an environmentally friendly material due to the low emission of CO_2 gas from its production processes [7,8]. Because of its unique properties, geopolymer can be used in construction applications as well as in many other applications, such as heavy metal immobilization [9–11], coating applications [12], and fire resistance applications [13].

Geopolymer is manufactured from raw materials rich in alumina and silica after mixing with an alkaline solution. Geopolymer materials are generally formed by three types of polysialate 3D networks consisting of SiO_4 and AlO_4 tetrahedrons, which are polysialate (-Si-O-Al-O-), polysialate-siloxo (-Si-O-Al-O-Si-O-) and polysialate-disiloxo (-Si-O-Al-O-Si-O-Si-O-). The cavities within these networks are filled by corresponding cations (Na^+, K^+, Ca^{++}, and Cs^+) contributing to balancing the negative charge for Al^{+3} [14]. The performance of geopolymer depends mainly on the properties of its raw materials; metakaolin is considered one of the best precursors for manufacturing geopolymer due to its high fraction of silica and alumina, low impurities, stable chemical composition, and high purity compared to fly ash and slag [15–17].

Carbon black is a substance that is difficult to dispose of and is produced from various industrial processes as byproducts, in the form of a fine powder containing a high percentage of carbon; it is characterized by high specific surface area, high chemical and thermal stability, and good electrical conductivity, also this waste is usually decomposed into landfills causing soil contamination and water pollution [18].

Geopolymer is not electrically conductive in its dry state, so carbon black can be added to improve its electrical conductivity, and thus, it becomes a material that can be used in self-heating [19] and

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self-sensing [20] applications. Carbon black cannot be added in high proportions due to the negative effect on the mechanical properties [19,21,22].

Many studies have dealt with adding carbon black to improve the electric performance of geopolymers. Arif et al. made a composite material from geopolymer with the inclusion of carbon black to be used as an X-ray shield [23]. Rauf et al. added carbon black with Fe_3O_4 to improve the electrical and optical properties and gamma ray absorption of the geopolymer [24]. Gu et al. added nanocarbon black with carbon fibers to improve the electrothermal performance of geopolymers used in paving Airports [25]. Han et al. found that adding 15 vol% and 0.05 vol% of both nano carbon black and carbon fibers to the geopolymer gives the best result in terms of electrical conductivity [26]. Mizerová et al. studied the effect of adding carbon black, at a percentage not exceeding 2% by weight of fly ash, on the self-sensing property of geopolymer [27]. Irshidat et al. studied the effect of adding carbon black at percentages of 5%-40% by weight of fly ash on the mechanical and physical properties of geopolymer; they found that adding carbon black at 5% and 20% leads to an increase in compressive strength to 46.89 and 45.9 MPa, respectively, compared to the compressive strength of the reference sample at 44.79 MPa [18]. Cai et al. studied the effect of self-heating on accelerating the curing of geopolymer by adding carbon black and steel fibers at 6 and 2 vol%, respectively; they obtained a sample with the unstable electrothermal performance of 67°C at 110 DC Volts [28]. Fiala et al. studied the effect of adding carbon black to geopolymer, at 2.25% by weight of slag, on the physical, mechanical, thermal, and electrical properties by applying 40 and 100 DC volts; they obtained samples with compressive strength of 7.31 MPa, electric conductivity of 1.3×10^{-1} S/m, and electrothermal performance of 44ºC, 125ºC at 40, 110 DC volts, respectively [19].

The mechanical strength of the pristine geopolymer utilized in some of these studies is already low, as reported in [21,22] is due to the fact that the materials utilized are not really a geopolymer, based on the precise definition of the geopolymer given by Joseph Davidovits [14], but they are alkali-

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activated materials mistakenly called geopolymer, as many researchers use the two terms as synonyms. Also, the electrothermal performance reported in these studies is noticeably weak as a high voltage is required to produce low temperature, as reported in [19,28]. Moreover, the stability of the electrothermal performance of the self-heating composites isn't reported in the literature.

It is well known that the geopolymer with a well-defined composition and structure has mechanical strength higher than that of the alkali-activated materials [29]. Thus, if the geopolymer is prepared with the right composition, it is expected that a suitable percent of carbon black can be incorporated into it while maintaining acceptable mechanical strength for structural applications. Hence, a high electrothermal performance can be achieved.

The current study investigates the effect of adding nano carbon black on the electrothermal performance of metakaolin-based geopolymer as well as its mechanical, physical, and electrical properties. Carbon black was added at a weight percent of 5%, 10%, 15%, and 20%, with respect to the metakaolin content, and the compressive strength was measured at various ages of 7, 14, 28, and 90 days. The electrothermal performance was tested using AC and DC voltages up to 12 V, and the stability of this performance was also assessed.

2. Materials and Methodology

2.1. Materials

Metakaolin (SiO_2 w.t%= 54.46, Al_2O_3 w.t%= 33.68, Na_2O w.t% =0.22), nano carbon black powder (N330, RPSG Group - India), industrial sodium hydroxide flakes (99% purity, from Al-Kout Company - Kuwait), industrial sodium silicate solution (Na_2O w.t% = 13.1-13.7, SiO_2 w.t%= 32-33, United Arab Emirates), copper tape with a width of 21 mm and a thickness of 0.1 mm used as electrodes, and laboratory distilled water are the materials used for producing conductive geopolymer samples. Metakaolin was produced from the calcination of kaolin (Supplied by Al-Mishraq Company - Iraq) at a temperature of 800°C for three hours. **Figure 1(a)** shows the XRD

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patterns of the kaolin, metakaolin, and carbon black; the diffraction data are in good agreement with the JCPDS cards (00-001-0527), (00-033-1161), and (01-074-2330) of the kaolinite, quartz, and carbon respectively. D_{50} for the kaolin, metakaolin, and carbon black is (3.702, 14.99, and 4.304) μm, respectively, as can be seen in **Figure 1(b, c, d)**.

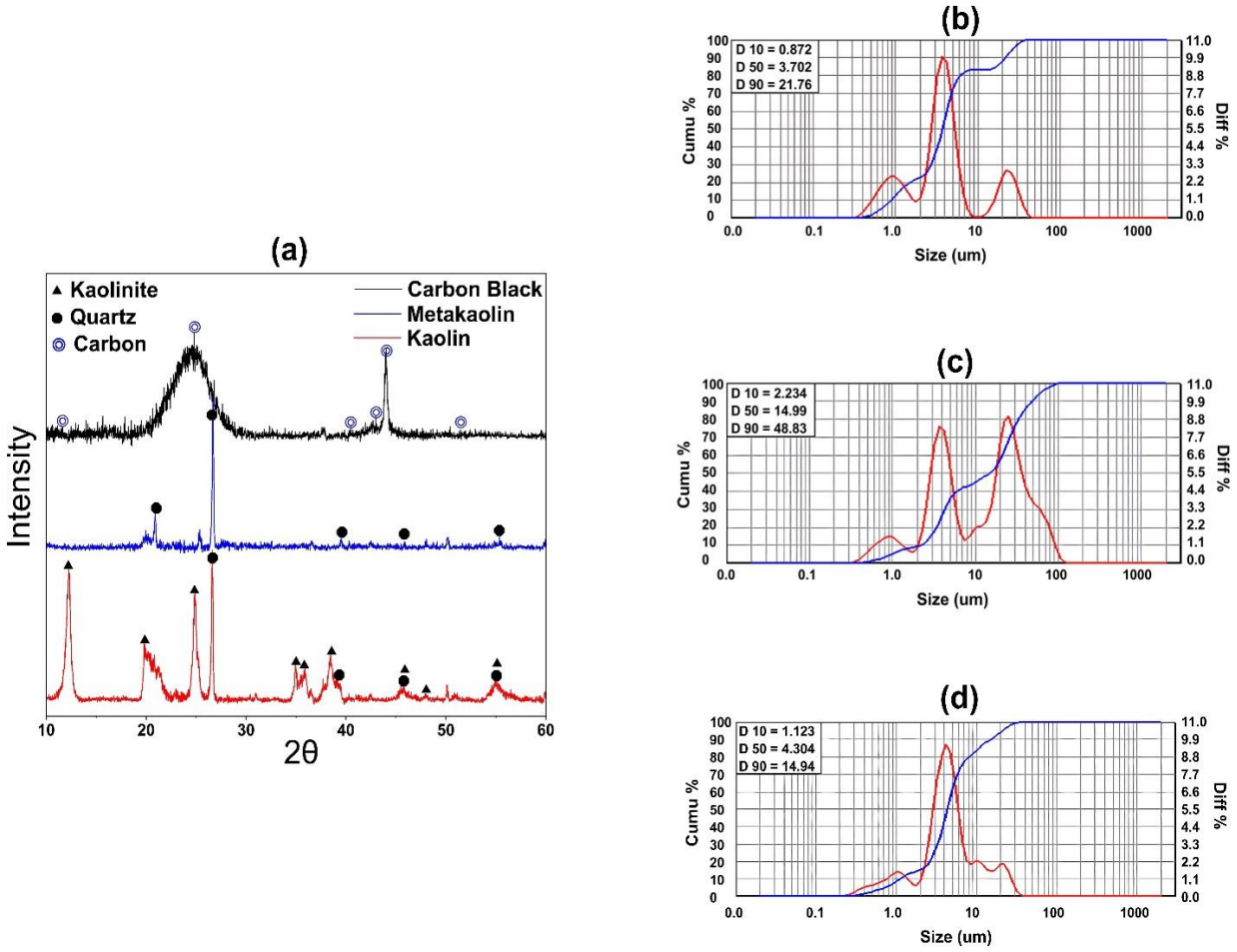

FIGURE 1 (a) XRD patterns of the kaolin, metakaolin, and carbon black; and the particle size distribution of the (b) kaolin, (c) metakaolin, and (d) carbon black

2.2. Methodology

2.2.1. Samples Preparation

Table 1 presents the weights of metakaolin (MK), carbon black-to-metakaolin ratio (CB/MK), sodium silicate-to-metakaolin ratio (SS/MK), sodium hydroxide-to-metakaolin ratio (SH/MK), and the water-to-metakaolin ratio (W/MK) used in the sample preparations for this study. For these

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samples, the geopolymer has the formula $Na_2O.\ Al_2O_3.3.6SiO_2$, which was optimized in our previous work to have a compressive strength of 117 MPa [30].

TABLE 1 Samples ID and the composition of the samples

Sample ID	MK (g)	CB/MK	SS/MK	SH/MK	W/MK
GP-0	120.812	0	0.9755	0.0934	0.116
GP-1A	90.609	0.05	0.9755	0.0934	0.549
GP-1B	90.609	0.05	0.9755	0.0934	0.632
GP-1C	90.609	0.05	0.9755	0.0934	0.715
GP-2A	90.609	0.1	0.9755	0.0934	0.549
GP-2B	90.609	0.1	0.9755	0.0934	0.632
GP-2C	90.609	0.1	0.9755	0.0934	0.715
GP-3A	90.609	0.15	0.9755	0.0934	0.549
GP-3B	90.609	0.15	0.9755	0.0934	0.632
GP-3C	90.609	0.15	0.9755	0.0934	0.715
GP-4A	90.609	0.2	0.9755	0.0934	0.549
GP-4B	90.609	0.2	0.9755	0.0934	0.632
GP-4C	90.609	0.2	0.9755	0.0934	0.715

Sodium hydroxide (99% purity, Al-Kout Co. - Kuwait) solution was prepared by dissolving sodium hydroxide flakes in 10 ml of laboratory distilled water, the desired amount of the sodium silicate solution was added to the sodium hydroxide solution, and the solution was heated up to 82±2°C for 15 minutes, under stirring at a speed of 750 rpm, and it was left to cool before use.

Carbon black (Industrial grade, N330, RPSG Group - India) powder was added to the solution resulting from the previous step and mixed for 2 minutes at a speed of 700 rpm using an electronic overhead stirrer (SL3000D - global lab. co). During mixing, water is added according to the composition given in **Table 1**, excluding the 10 ml used to prepare the sodium hydroxide solution. After that, the metakaolin powder was mixed with the mixture resulting from the previous step at

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a speed of 3000 rpm for 5 minutes. The paste resulting from the previous step was poured into molds made of silicone rubber, which are of three types: cylindrical molds with dimensions of 23x46 mm for testing compression strength, cubic molds with dimensions of 20x20x20 mm containing two longitudinal slots on opposite sides, separated by 8 mm to fix copper electrodes, used to investing the electrical properties and electrothermal performance, and rectangular molds with dimensions of 20x20x6 used for testing the physical properties and SEM examination. The copper electrodes were installed after pouring the paste into the molds through the mold slots. The samples were demolded after 72 hours and kept in the laboratory atmosphere at a temperature of 18±2°C and relative humidity of 50% until the tests; all tests were conducted 28 days after demolding the samples except the compression strength test, which is performed at different ages of 7, 14, 28, and 90 days.

2.2.2. Characterization

The bulk density, true density, apparent porosity, and water absorption of the samples were tested according to Archimedes' principle. An Impact-Automatic Console-2000 KN machine was used to test the compressive strength of samples. SEM examination was used to investigate the microstructural features of the samples using TESCAN- VEG 3 SBU nanospace machine. Hioki IM 3536 device was used to measure impedance (Z), phase angle (θ), and electrical resistance (Rdc). The EIS Spectrum Analysis software was also used to analyze the results and determine the equivalent electrical circuit for the spectrum of the tested samples by using the NM Simp algorithm and the Amplitude function. A direct and alternating voltage was applied to study the electrothermal performance of the geopolymer/carbon black samples. A device consisting of a processing unit board connected to a sensor for measuring current, a sensor for measuring the surface temperature of the sample, and an AC/DC power supply, was used to detect the surface temperature of the sample and the consumed current when a given voltage is applied. **Figure 2**

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shows the test device schematic. The operation of the device is controlled via a computer, which provides simultaneous measurement of current and temperature. The test voltage was selected based on the electrical resistance of the samples. To avoid overheating, all samples were tested at 12 volts, with the exception of GP-4A, which was tested at 9 volts. A quick test with a single heating cycle, 2 h of heating, and 0.5 an hour of cooling was conducted for all samples to determine the electrothermal performance. Subsequently, selected samples were chosen and tested over three cycles.

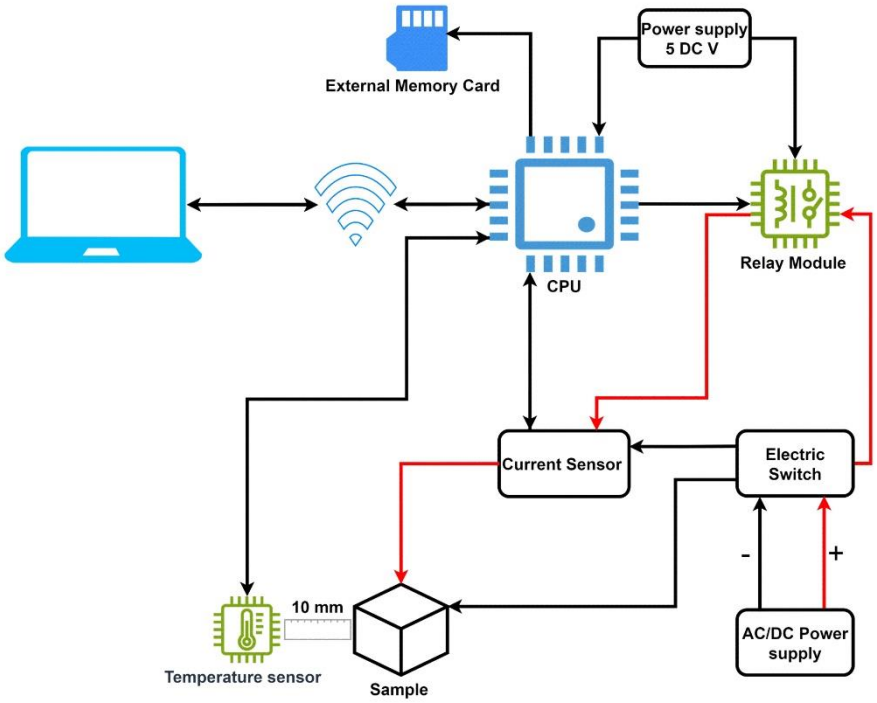

FIGURE 2 A schematic of the test device

3. Results and Discussions

3.1. Physical Properties (Bulk and True density, apparent porosity, water absorption)

Table 2 shows the values of the bulk density, true density, apparent porosity, and water absorption of the samples; it can be noted that the geopolymer samples have higher density compared to the composite samples that contain an additional percentage of carbon black. This is consistent with

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studies showing that the incorporation of conductive filler can increase the porosity and reduce the bulk density of composite materials. While the relatively low density of carbon black may partially contribute to this effect, the increase in porosity is mainly attributed to its hydrophobic nature and the way it interacts with the binder matrix, and as the percentage of conductive filler increases, the pore size increases [31,32]. Also, it can be attributed to the low density of the carbon black as compared to the geopolymer, as well as the amount of water used to utilize the preparation of the composites seems to affect the density; part of this water is necessary to wet the carbon black and, hence, facilitate the preparation process while the residual amount of that water leads to the formation of more pores and, hence, lower bulk density. Also, this water works on impeding the polymerization process leading to lower true density for the geopolymer [33]. It can be noticed that the sample GP-3B has a lower porosity among the composites, indicating that it contains a lower amount of residual water. This is consistent with the study that shows that harmonizing the water / solid fraction leads to improving density [34].

TABLE 2 The bulk density, true density, apparent porosity, and water absorption of the samples

Sample ID	Bulk density (g/cm^3)	True density (g/cm^3)	Apparent porosity (%)	Water absorption (%)
GP-0	1.5351	2.3495	34.6	22.5
GP-1A	1.2276	2.2208	44.7	36.4
GP-1B	1.1645	2.3177	49.7	42.7
GP-1C	1.1510	2.3347	50.6	44
GP-2A	1.2001	2.1531	44.2	36.8
GP-2B	1.1813	2.2250	46.9	39.7
GP-2C	1.1470	2.1855	47.5	41.4
GP-3A	1.1820	1.9343	38.8	32.9
GP-3B	1.1980	1.8673	35.8	29.9
GP-3C	1.1243	2.0628	45.4	40.4

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GP-4A	1.1261	1.9316	41.6	37
GP-4B	1.1119	1.8754	40.7	36.6
GP-4C	1.1115	1.9835	43.9	39.5

3.2. Compressive Strength

Figure 3 shows the compressive strength of geopolymer samples with different percent of carbon black. From **Figure 3(a)**, it is evident that the compressive strength of geopolymer samples is higher compared to those containing carbon black; this is because, in addition to the higher porosity of the composites, the carbon black is an inert phase within the geopolymer matrix that generates weak point via the aggregation [35], this can be clearly noticed in **Figure 3(b-e)** as the compressive strength at the age of 90 days of samples GP-1, GP-2, GP-3, and GP-4 are reduced due to the increase of the carbon black percent. Furthermore, there is a decrease in the compressive strength with increased water content for these samples due to the increase of the porosity. Notably, the samples GP-1 have the highest compressive strength among the composites due to their higher density.

Additionally, it has been observed that the increase in the compressive strength over time, which indicates the progress of the polymerization process, for GP-0 between 7 and 90 days is about 26%. For the composites, this percent varies not only with the water content, which is known to impede the polymerization but also with the percent of the carbon black; this indicates that carbon black affects the polymerization process; however, investigating its role in this process requires further studies.

3.3. Scanning Electron Microscope Images

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Figure 4 shows the SEM images of the GP-0 sample. **Figure 4(a)** confirms the presence of a continuous phase that is formed via the polymerization process; in this phase, different forms of scraps are impeded, as appears more clearly in **Figures 4(b and c)**. This scrap can be assigned to the inert phases that can't participate in the polymerization process. **Figure 4(d)** shows the un-polished surface of the sample in which the pores and the drying microcracks are clearly appeared. **Figures 5-7** show the microstructure of the composites. The aggregation of the carbon black is observed in the composites; as the percent of the carbon black or the amount of water increases, the size of the aggregates increases. Also, the images confirm the presence of microcracks that pass through the geopolymer matrix, these cracks can be assigned to the drying of the surface of the samples [36], and it can be noticed that the cracks pass through the carbon black aggregates, **Figures 5a and 6a**, this indicates that the aggregates are weaker than the interface. Also, in the case of high percent of carbon black, **Figures 6b, c and 7b, c**, a separation between the geopolymer and the aggregates is noticed; this can be attributed to the hydrophobicity of the carbon black that led to weak interaction with hydrophilic geopolymer matrix [37,38].

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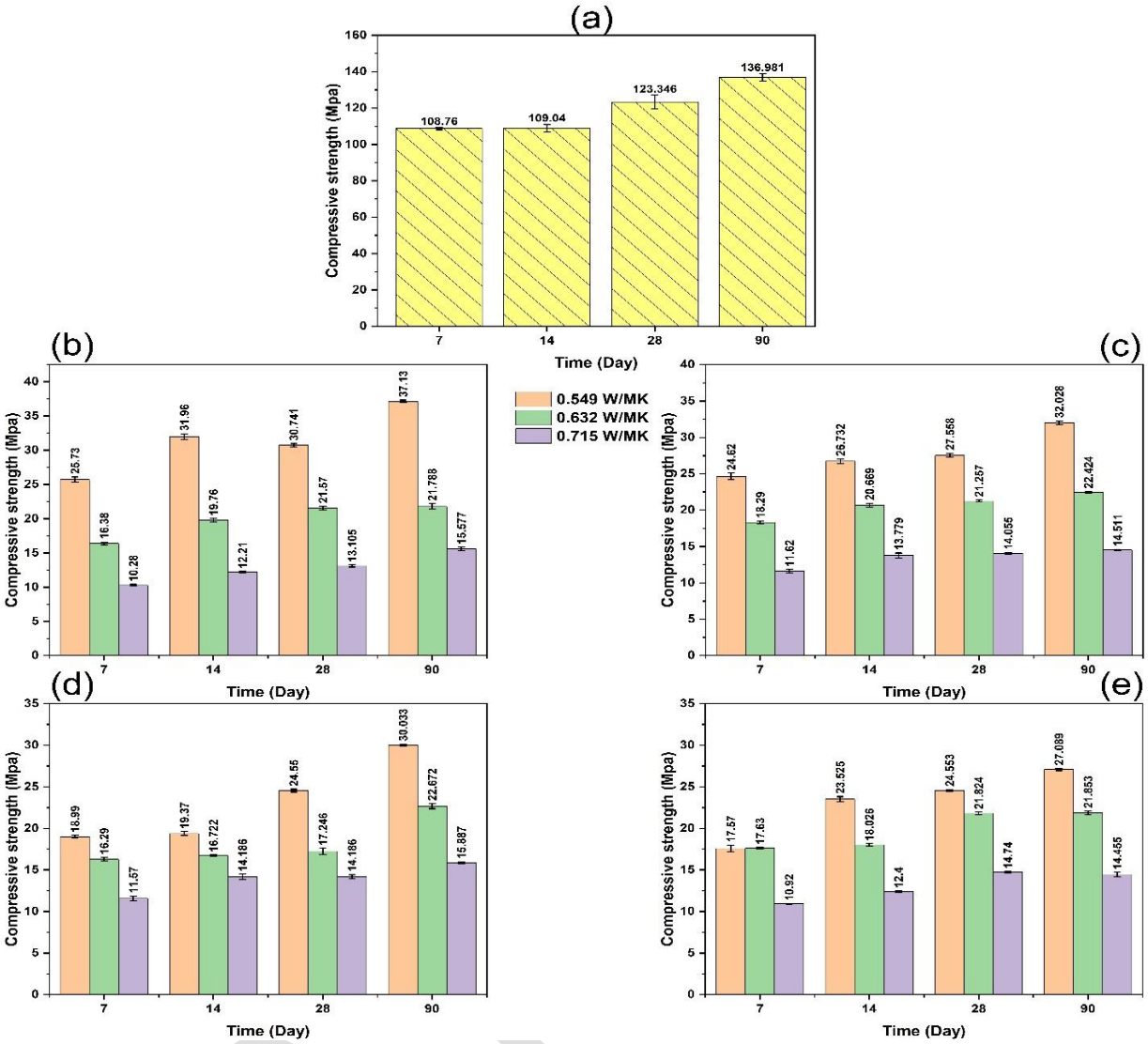

FIGURE 3 The compressive strength of geopolymer samples (a) GP-0, (b) GP-1, (c) GP-2, (d) GP-3, and (e) GP-4

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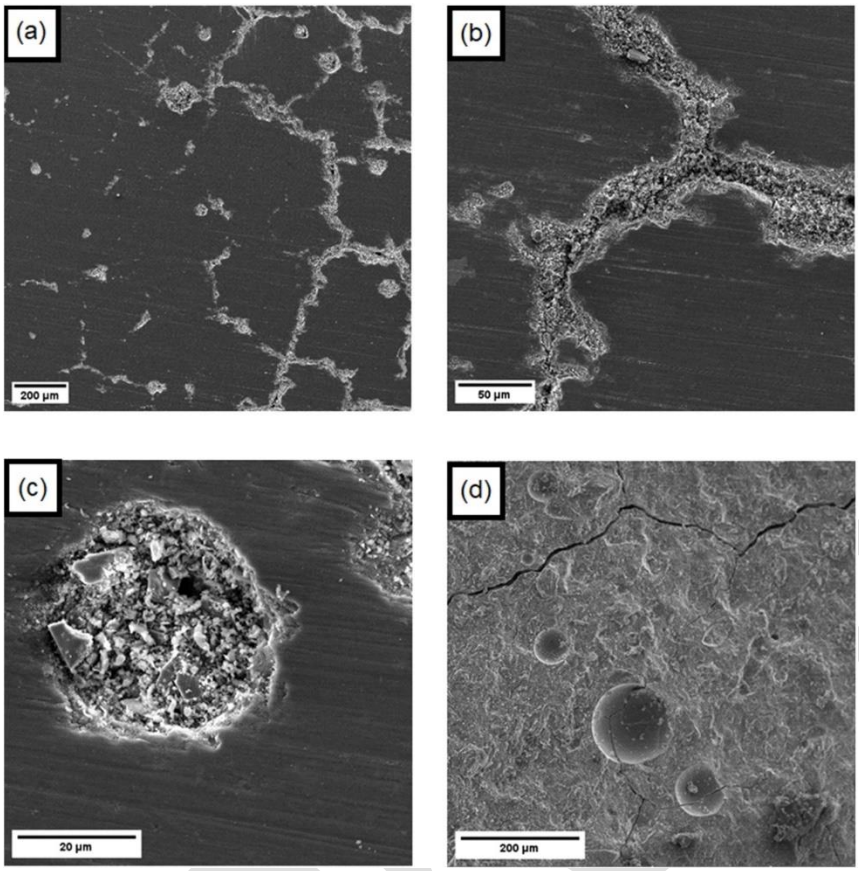

FIGURE 4 The SEM images of sample GP-0

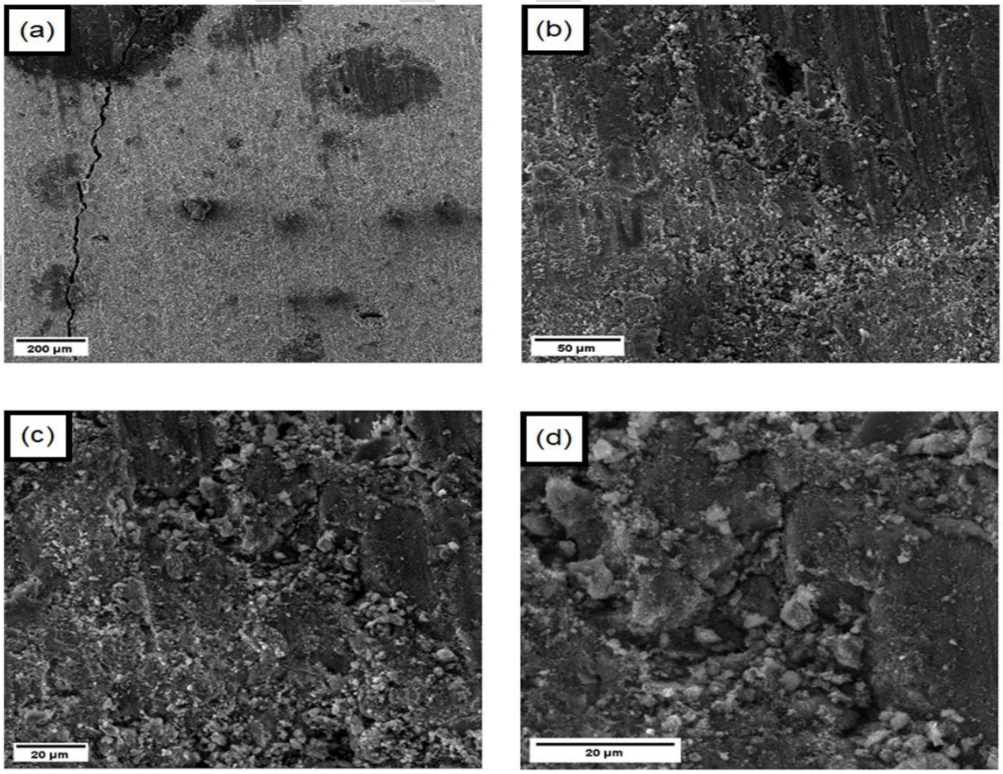

FIGURE 5 The SEM images of sample GP-2A

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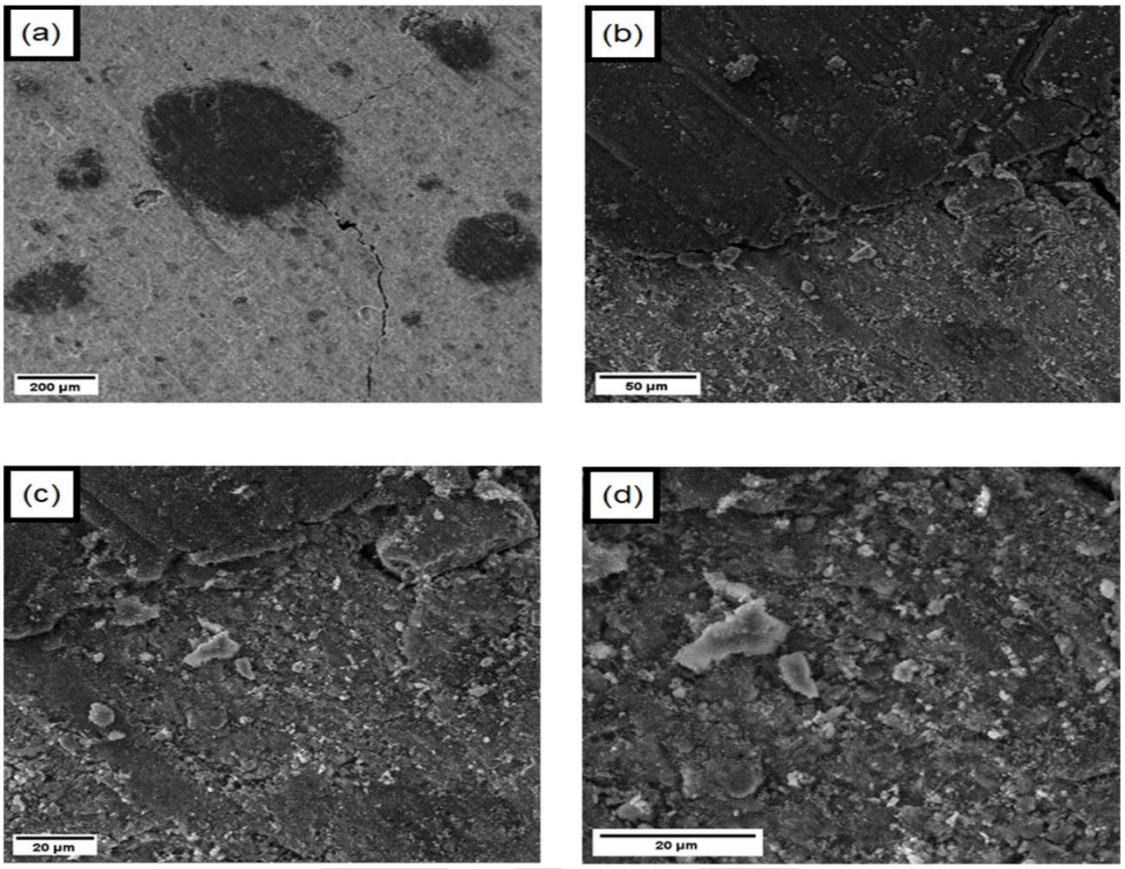

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220 **FIGURE 6** The SEM images of sample GP-2B

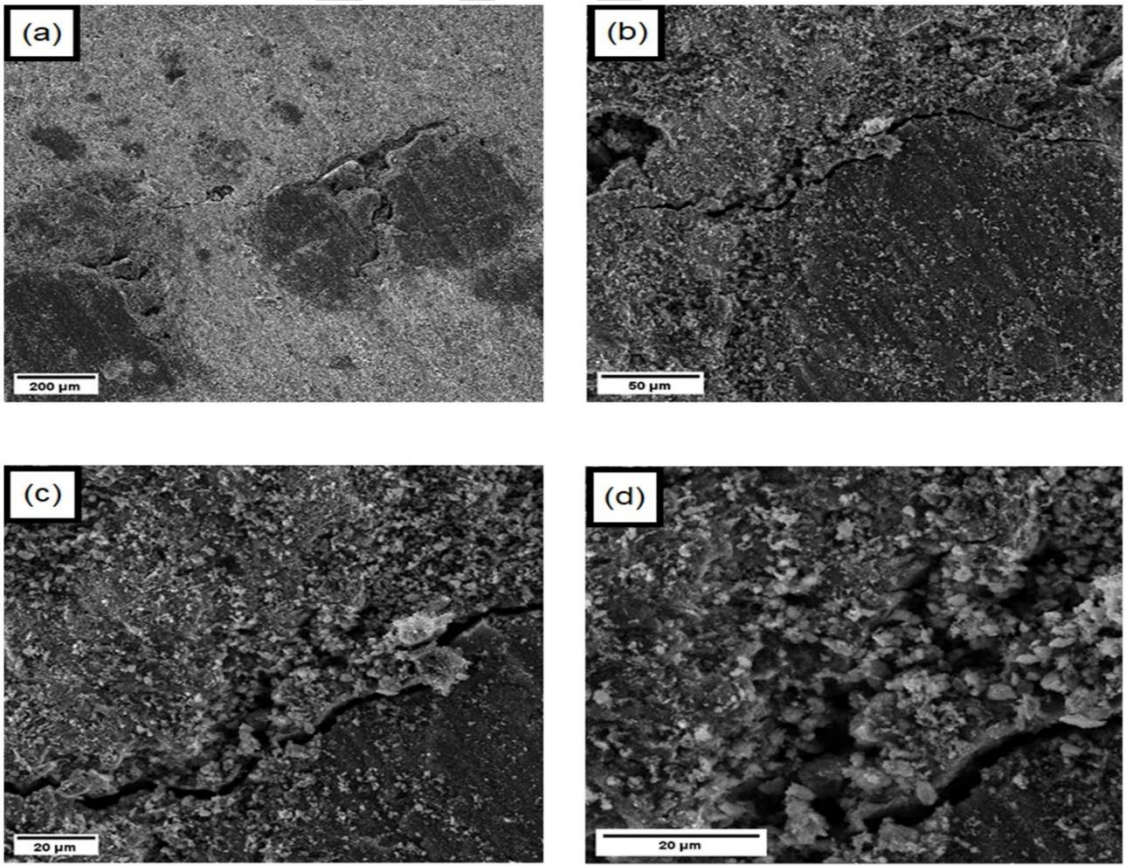

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FIGURE 7 The SEM images of sample GP-4A

3.4. Electrochemical Impedance Spectroscopy

Figure 8 shows the Nyquist plot, Bode plot, and the values of the phase angle for GP-0. It has been found, using the fitting and simulation of the Nyquist plot, that the equivalent electrical circuit that describes the geopolymer sample is $CPE_1/ (R_1+CPE_2)$. This indicates that the material has a dielectric feature. As expected, the magnitude of impedance decreases with increasing frequency. Furthermore, the phase angle between voltage and current is negative, which is a characteristic of materials with capacitive behavior.

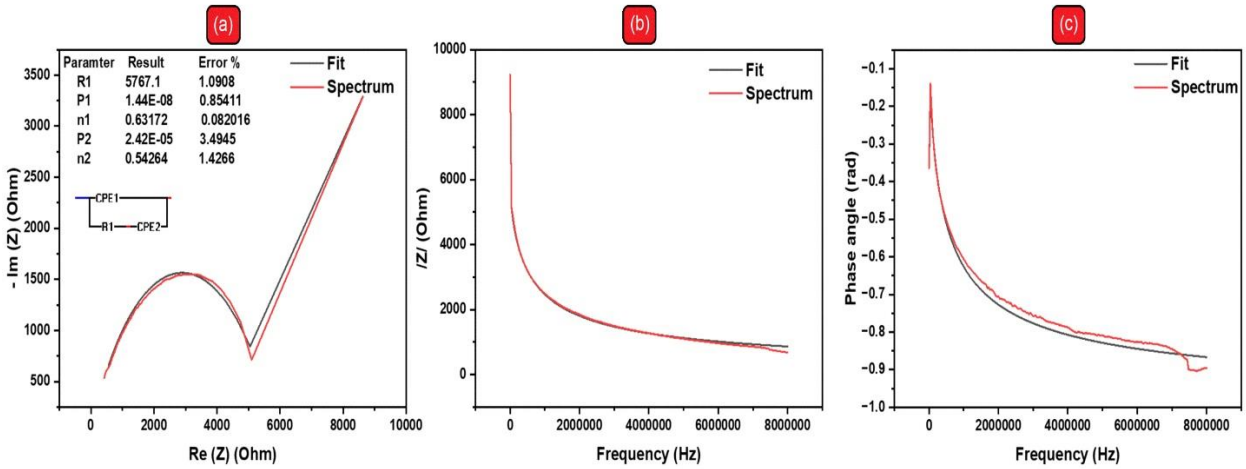

FIGURE 8 Nyquist plot (a) and (b-c) Body plot from EIS of GP-0

Figures 9 show the Nyquist plot, Bode plot, and the values of the phase angle for geopolymer composites with various carbon black percent. The equivalent electrical circuit that describes each composite is given below:

- GP-1A: $(CPE_1/(R_1 + CPE_2/R_2))$
- GP-1B: $CPE_1/(R_1/CPE_2)$
- GP-3C: $(R_1/CPE_1 + (R_2 + CPE_2))$

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- GP-4B: $(CPE_1/R_2) + (R_1/CPE_2)$

From the EIS results, the presence of more than one resistance in equivalent electrical circuits has been noticed; this indicates the presence of more than one process area that affects the transfer of charges. These resistances are the result of the simple ohmic resistance resulting from the flow of current through the material, the resistance of the material, the resistance to the transfer of charge from the electrode to the material, and the resistance to the diffusion of charges [39]. In addition, the presence of more than one value for the constant phase element (CPE) was noticed; this indicates the presence of electrical complexities within the material that affect the electrical behavior; the causes of these complexities are electrochemical reactions on the surfaces of the granules and the surfaces of the pores, corrosion reactions, and the presence of thin films [39].

It should be noted that the equivalent electrical circuit, which describes each of GP-1C, GP-2A, GP-2B, and GP-2C, is the same equivalent electrical circuit that describes the sample GP-1B. Similarly, the equivalent electrical circuit that describes each of GP-3A, GP-3B, and GP-4A is the same equivalent electrical circuit that describes sample GP-3C. The GP-4C is described by the same equivalent electrical circuit as the GP-4B. Also, it should be noted that only the values of the elements forming the equivalent electrical circuit change with changes in the addition percent and water content. This is due to the increased electrical complexities within the material resulting from changes in density and porosity [39].

The Bode plots for GP-1, GP-2, GP-3, and GP-4 composites showed that the impedance decreases with increasing frequency across all water content. As for the phase angle, it remains negative for all samples at all frequencies; this behavior is due to the fact that the phase angle is negative, meaning that the material has capacitive behavior.

3.5. Electric Resistance (Rdc)

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Table 3 shows the electrical resistance values of geopolymer and geopolymer/carbon black composites. It is noted that the value of electrical resistance decreases with the increase in the percent of carbon black added; this is an expected result of the increase in conduction paths within the material**.**

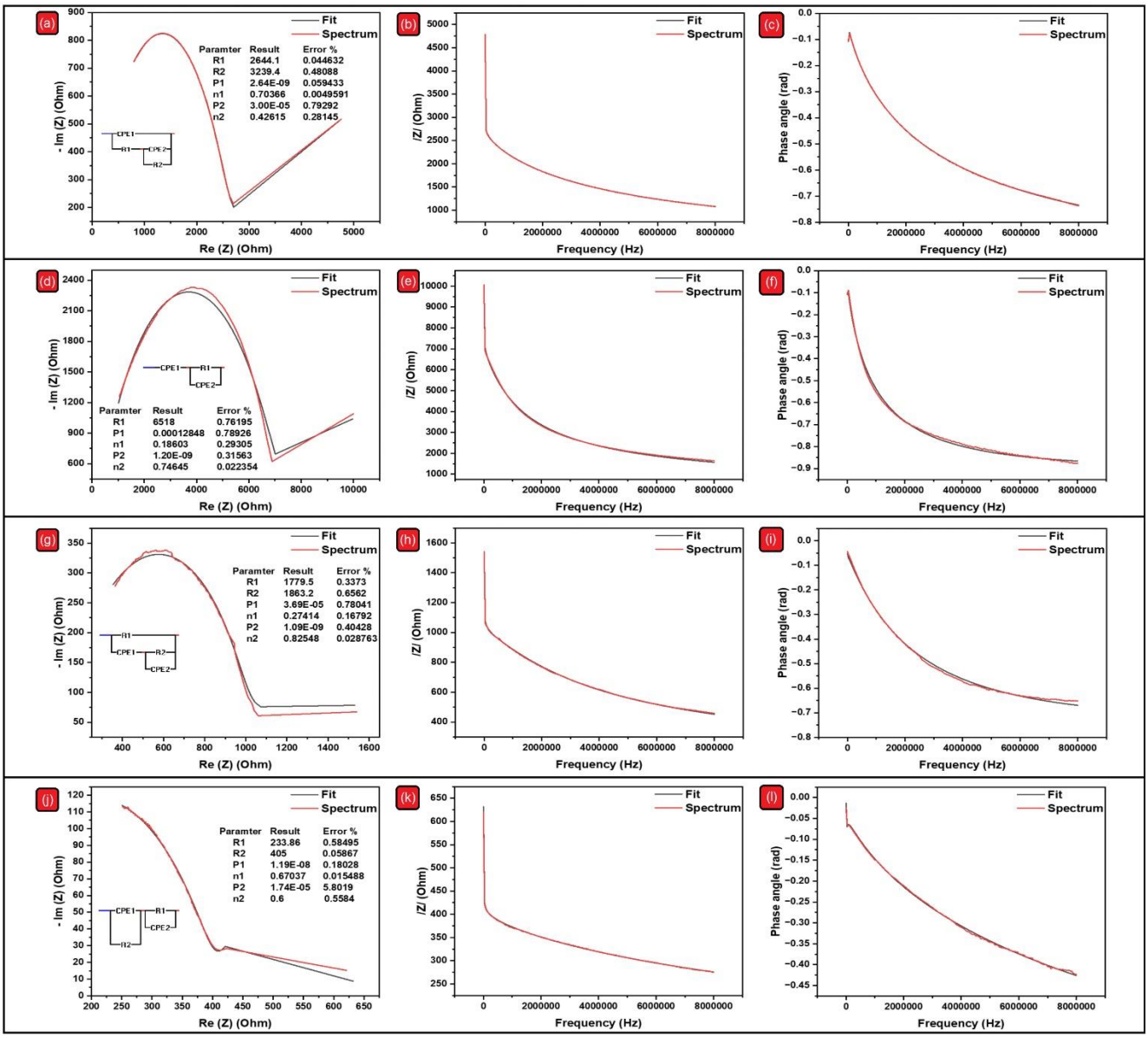

FIGURE 9 Nyquist plots (a, d, g, j) and (b-c; e-f; h-i; k-l) Body plots from EIS of GP-1A, GP-1B, GP-3C, GP-4B, respectively.

It is also noted that the value of electrical resistance increases with increasing water content, and this behavior is due to the increase in porosity, which is observed in all samples except for (GP-

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2B, GP-3B, GP-4B), where there is a heterogenous distribution of additive within the samples, as appear more clearly in **Figures 10**. The electrical resistance of the composites is the result of the (i) formation of the conductive paths that reduce the electrical resistance, (ii) the presence of the pores filled with carbon black, which behave as a junction that facilitates the connection between the conductive paths, and (iii) the presence of empty pores which cut the conductive paths. The time factor must be taken into consideration when examining electrical resistance, as its value increases with time as a result of the loss of water that participates in the electrical conduction process as the polymerization process continues [40], or its value decreases with the loss of water present in the pores, and thus the conductive filler agglomerates and forms additional paths [41].

TABLE 3 The values of the electrical resistance of the samples

Sample ID	Rdc (Ω)	Sample ID	Rdc (Ω)
GP-0	8638	**GP-3A**	497.655
GP-1A	4307.18	**GP-3B**	919.06
GP-1B	8995.58	**GP-3C**	1413.838
GP-1C	12508.2	**GP-4A**	142.009
GP-2A	2549.53	**GP-4B**	535.039
GP-2B	8657.59	**GP-4C**	675.497
GP-2C	4060.5		

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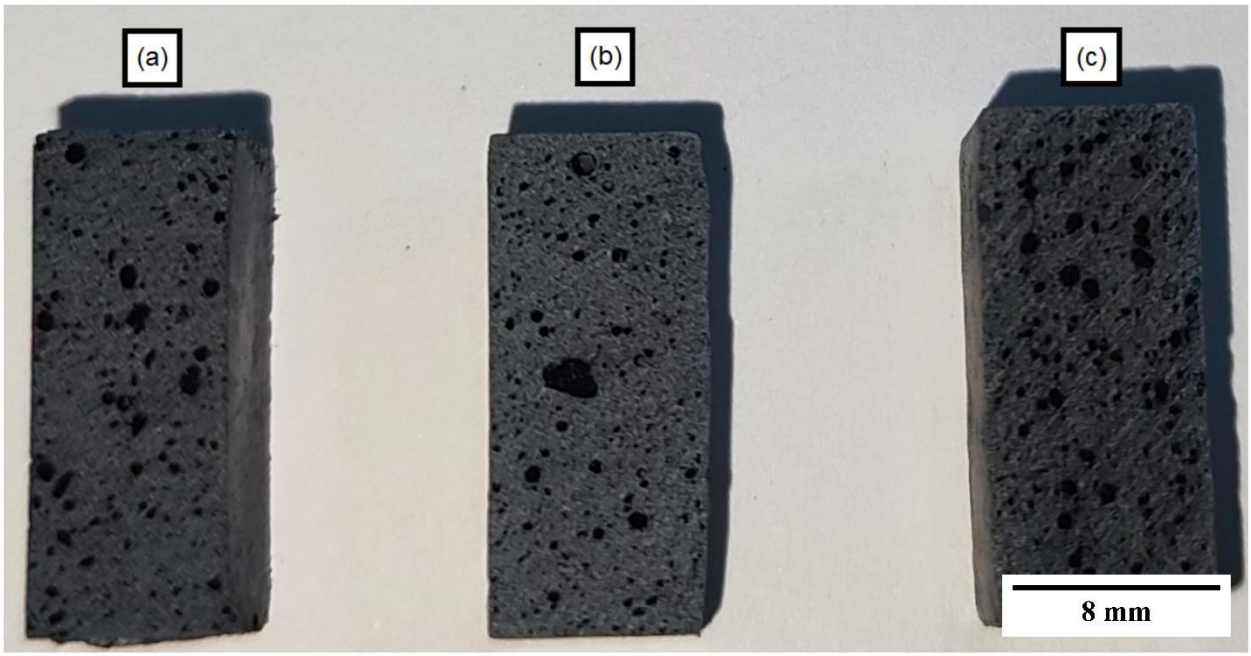

FIGURE 10 Distribution of carbon black (a) GP-2A, (b) GP-2B, (c) GP-2C

3.6. Electrothermal Performance

Due to the high electrical resistance of the GP-0, its electrothermal effect hasn't a practical value. **Figure 11** shows the electrothermal effect of the geopolymer composites tested over a single heating cycle of two hours and a cooling period of half an hour, with both AC and DC voltages. It has been found that GP-1 samples can reach a temperature of around 32.75°C, GP-2 samples achieve a temperature of 32-34°C, GP-3 samples reach a temperature of 34-44°C, and GP-4 samples achieve a temperature of 37-50°C by an applied voltage of 12 volts, with the exception of GP-4A sample that reaches to a temperature of 62°C by an applied voltage of 9 volts. It has been observed that the electrothermal effect with AC voltage is better when compared to DC voltage. Also, the consumed energy in the case of DC voltage is found to be higher than that consumed when AC voltage is applied, and this is because of the Joule effect. Also, it has been observed that the higher the amount of water used in the preparation of the sample, the lower the electrothermal effect obtained; this is related to the higher porosity obtained and, hence, the higher electrical resistance achieved.

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An important issue was noticed regarding the stability of the electrothermal performance of the samples. It has been observed that the samples gradually lose their ability to convert the electrical field into heat. The rate at which this happens depends on the type of the applied voltage; the AC voltage reduces that rate lower than the DC voltage. This indicates that something is changed in the electric circuit when the electric field is applied. Keep in mind that the mechanisms of electrical conduction in geopolymer depend either on the movement of sodium or potassium ions, the movement of free electrons, or the movement of hydroxide ions resulting from the water content when an electric field is applied [42–44]. Two possible reasons can explain this: the first is the increase of the electrical resistance due to the destruction of the conductive paths, and the second is the generation of a barrier between the sample and the electrode. Zhang et al. claimed that the decrease in the electrothermal effect of a sample containing 100 w.t% graphite, whose electrothermal performance was tested at 7 days, is due to the first reason: they suggested that the evaporation of water during the heating cycle leads to a shrinkage of the gel in the geopolymer and, consequently, to a destruction of the conduction network [45]. However, such a scenario may be accepted for the samples at an early age, when the polymerization process is going on and its byproduct, water, is formed. Nevertheless, that scenario is less probable when the sample is tested after the age of 28 days.

In the current study, it has been found that a barrier layer is formed between the copper electrode and the sample surface, as shown in Figure 12; after removing this layer via polishing, the circuit restored its electrothermal performance. The presence of this layer suggests that there are mobile ions in the sample that can be drifted via the electric field and react with the copper electrode to form that layer. The presence of such ions in the geopolymer was proved by Cui et al. [46].

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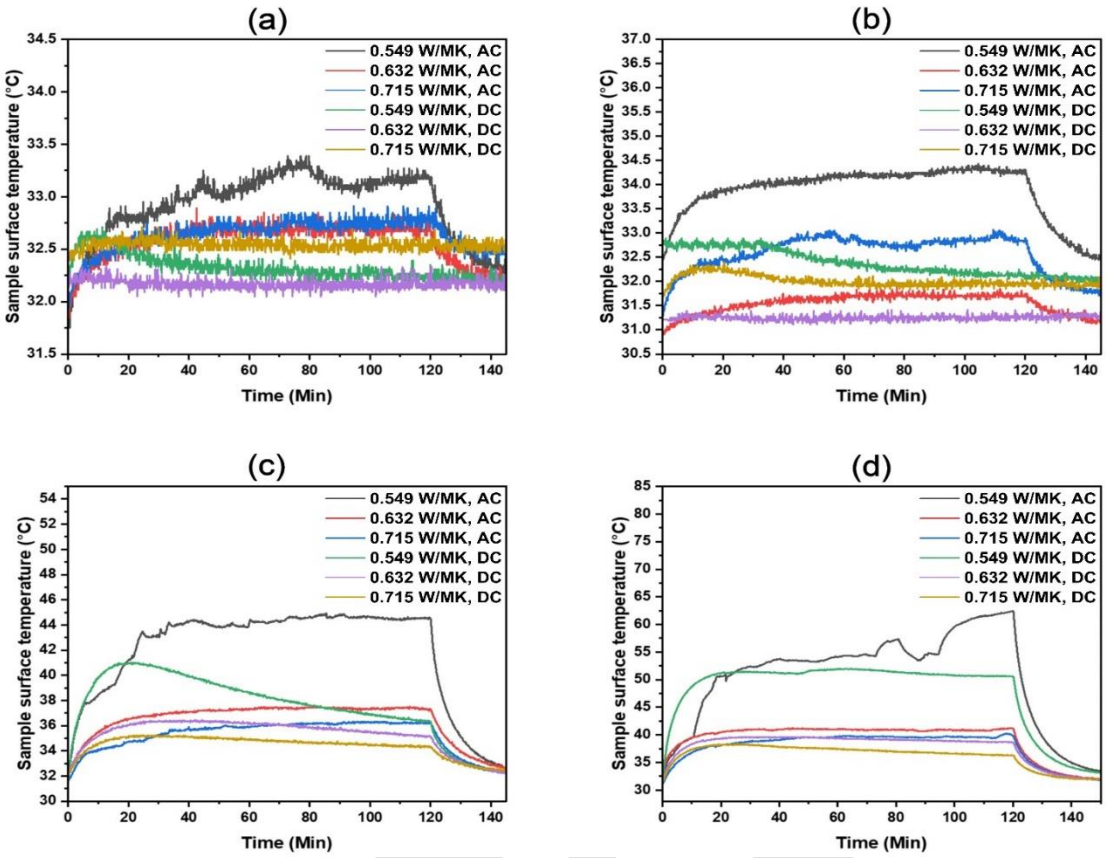

FIGURE 11 The electrothermal effect of geopolymer samples (a) GP-1; (b) GP-2; (c) GP-3; (d) GP-4

FIGURE 12 The barrier layer formed between the electrode and the sample

In order to support this scenario, the electrothermal behavior was evaluated after immersing the samples in deionized water for 24 hours to remove the free ions and drying them at 100°C for 3 hours. **Figure 13** illustrates the electrothermal behavior of the chosen samples over three cycles;

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it can be seen that the electrothermal behavior of the sample is noticeably stable over the three cycles; this confirms that the formation of the barrier layer is the reason behind the loss of the electrothermal behavior of the samples. It should be noted that the electrical resistance of samples GP3-A and GP-4A decreased after removing the free ions to become 141.5 and 23.4 ohms, respectively, and a temperature of 58 and 142°C could be achieved using 12 and 9V DC. This electrothermal performance is superior as compared to that reported in the literature [19,28,45].

4. Conclusion

The current study aimed to study the effect of adding carbon black to the metakaolin-based geopolymer. The following conclusions can be driven:

1- With the increase in the addition of carbon black, the compressive strength decreases and the electrical conductivity increases. However, using the right formula of the geopolymer along with the balance between the carbon black percent and the lowest water content possible, a conductive geopolymer with high compressive strength can be obtained.
2- The electrothermal performance of conductive geopolymer samples can be improved by increasing the percent of the carbon black and lowering the water content. However, increasing the addition percent increases energy consumption; thus, a compromise is needed between the desired temperature and the energy consumption. Additionally, the electrothermal performance is better with AC voltage compared to DC voltage applied.

The reason for the deterioration of the electrothermal performance is the formation of a barrier layer between the electrode and the sample surface. This can be avoided by removing the free ions from the sample via washing.

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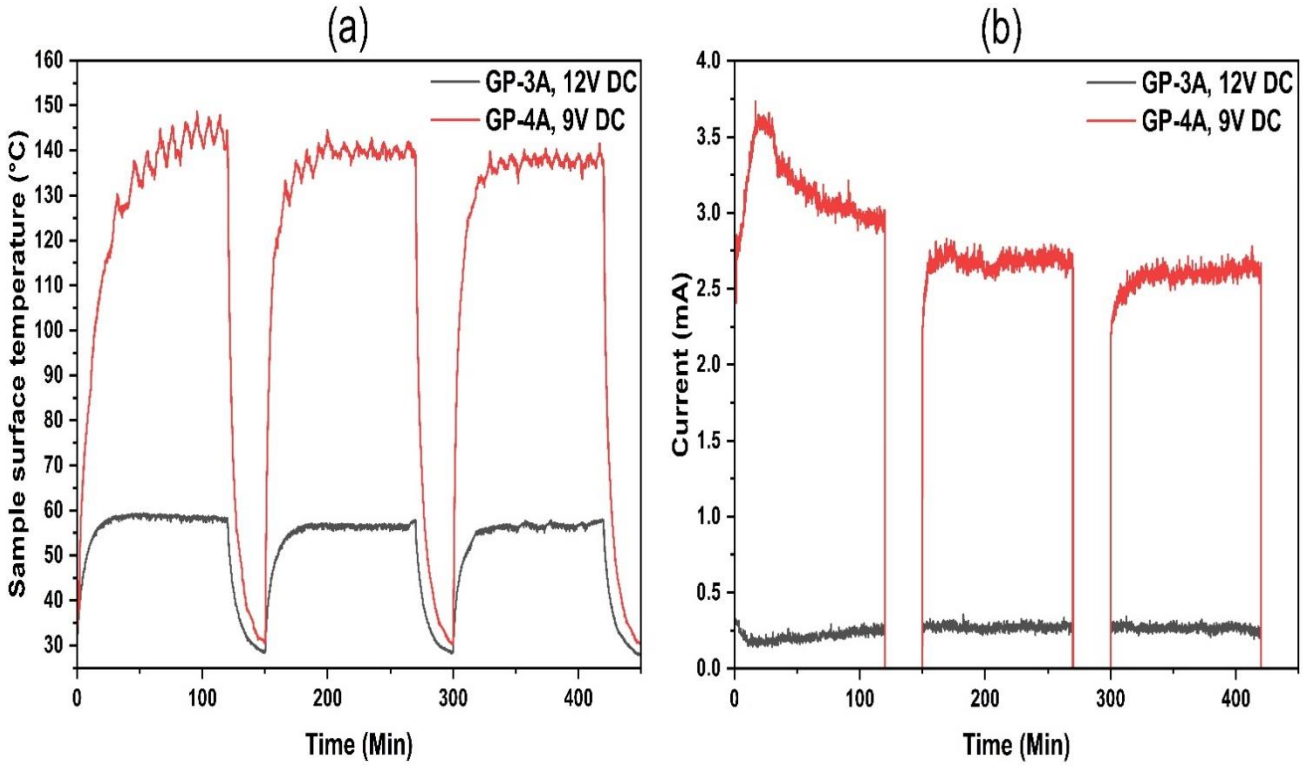

FIGURE 13 (a) electrothermal behavior and (b) energy consumption of GP-3A, GP-4A after removing the free ions

5. Recommendation

It is recommended to carefully evaluate the homogeneity of the composite geopolymer and to perform measurements of the compressive strength, electrical performance and electrothermal performance of the homogeneous geopolymer well to ensure the reliability of performance assessment.

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