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PHYSICAL, MECHANICAL, AND DURABILITY PROPERTIES OF INCORPORATION OF GRAPHENE OXIDE IN GEOPOLYMER MORTAR

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Abstract— This study examines the impact of integrating nano powder graphene oxide (GO) into ground granulated blast slag (GGBS) and fly ash class F (FA)-based geopolymer mortar (GPM). The study assesses the flowability, compressive strength, and chloride ion permeability of GPM with different GO dosages (0.02 wt.%, 0.04 wt.%, 0.06 wt.%, 0.08 wt.% and 0.10 wt.%). The findings demonstrate that the incorporation of 0.04 wt.% GO increases the compressive strength by 61.21% (early strength) and 50.75% (late strength) compared to the control specimen.

Geopolymer, Chloride Ion Permeability, Compressive Strength

Additionally, chloride ion permeability reduced by 35.3%, with elevated GO dosages. The Rapid Chloride Permeability Test (RCPT) was performed to evaluate the chloride ion resistance of geopolymer concrete enhanced with graphene oxide. The addition of graphene oxide (GO) up to 0.06% frequently decreases chloride ion permeability. The smallest results were observed at a GO content of 0.06% for both mixes with a water-to-precursor ratio (w/p) of 0.1 and 0.2. The experimental results demonstrated that the geopolymerization products exhibited remarkable compactness, and the internal porosity diminished due to the inclusion of GO. The results indicate that the integration of GO into GGBS-FA-based GPM markedly enhances its physical, mechanical and durability properties, supporting its wider utilisation in sustainable building.

I. Introduction

Ordinary Portland cement (OPC) is currently used in building structure development. Cement production constitutes 8% of total anthropogenic carbon dioxide emissions and 36% of carbon emissions linked to the construction sector [1]. Consequently, it is essential to develop alternative low-carbon binders. Davidovits, in 1994, developed a low-carbon binder named geopolymer binder. Geopolymer technology has been found to enhance the sustainable development of building materials by offering energy efficiency, outstanding durability, and reduced life cycle costs. Fly ash (FA), metakaolin (MK), ground granulated blast slag (GGBS), and agricultural waste like sugarcane bagasse

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and rice husk ash (RHA) are examples of binders explored by the researcher which to supply the necessary aluminosilicate for the development of process in geopolymer composites [2]. The incorporation of nanomaterials has garnered significant interest in recent years owing to their potential applications in geopolymer composites (GPC) [3]. Nanomaterials are distinct powder substances with particle dimensions between 1 and 100 nm [4]. The choice of alkaline activators and source materials for GPC manufacture is determined by material availability and cost [5]. The engineering of nanomaterials is progressively expanding [6]. The most beneficial nanoparticles in GPC include nano silica (NS), nano alumina (NA), and nano titanium (NT), along with nanomaterials such as graphene oxide (GO), which are available in nanoscale flake forms for application in GPC [7-16].

Error! Reference source not found. illustrates the correlation between specific surface area and particle size for multiple materials. GO is a carbonaceous material characterised by a substantial surface area and excellent solubility during dispersion, offering it significant in research [15, 17-18]. The epoxides and hydroxyl groups on the edges of graphene oxide sheets facilitate dispersion when dissolved in water [19-20]. The extensive surface area of nano GO exhibits favourable mechanical properties [21]. A small amount of GO results in greater compressive strength compared to CNT GPC [22-24]. The GO sheet is combined with FA, filling all pores and voids and enhancing the mechanical properties of GPC [19]. However, the increased surface area of GO diminished the workability of GPC when mixed, which is the primary cause for the limited utilisation of this nanomaterial [25-26]. GO has shown considerable promise in enhancing the performance of cement-based materials; however, its use in one-part geopolymer mortars designed for repair applications is still relatively underexplored.

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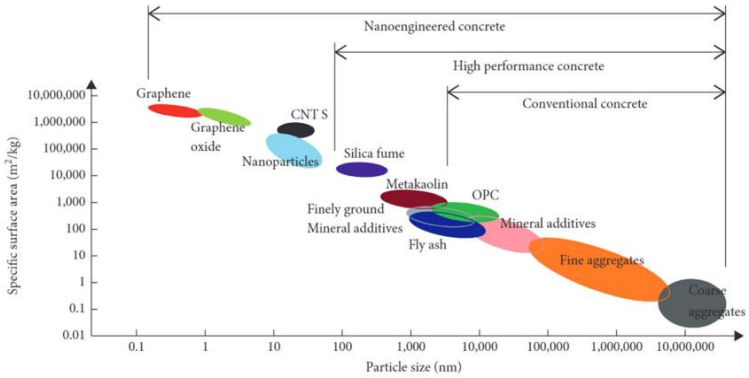

Figure 1: Correlation Between Specific Surface Area and Particle Size for Multiple Materials

This study presents a novel formulation by integrating GO into a fly ash-based two-part geopolymer system, with additional water introduced to improve flowability which is an essential requirement for efficient placement in repair works. The modified water content not only enhances workability but also supports better surface contact and compaction, which are critical in field conditions. GO, on the other hand, contributes to strength development and microstructural refinement by acting as a nanoscale reinforcement. The combined effects of GO and water content were evaluated with respect to fresh-state properties, compressive strength, and resistance to chloride ion penetration. Unlike earlier studies that typically focused on mechanical strength alone, this research highlights the interdependence of flow characteristics, durability (via RCPT), and mechanical performance in developing a more practical and robust semi-rigid repair material. This paper aims to provide an essential and thorough analysis of nano powder graphene oxide in geopolymer mortar (GPM), providing direction for future goals. The paper encompasses the impact of GO on the flowability, compressive strength and rapid chloride

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permeability of GPM composites.

II. Experimental

A. Raw Materials

Locally sourced fly ash class F (FA) and commercially ground granulated blast slag (GGBS) were employed as aluminosilicate precursors for synthesising geopolymer binders. The chemical and physical makeup of FA and GGBS that has been analysed using X-Ray Fluorescence (XRF) analysis is depicted in Table 1.

Table 1: Chemical and Physical Properties of GGBS and FA

Aluminosilicate Precursor	FA	GGBS
Silicon dioxide, $\boldsymbol{SiO_2}$	40.16	27.36
Aluminium Oxide, $\boldsymbol{Al_2O_3}$	49.35	20.48
Iron oxide, $\boldsymbol{Fe_2O_3}$	2.58	0.15
Calcium oxide, $\boldsymbol{CaO}$	1.60	42.36
Magnesium oxide, $\boldsymbol{MgO}$	0.47	5.11
Sulphur trioxide, $\boldsymbol{SO_3}$	-	1.50
Sodium oxide, $\boldsymbol{Na_2O}$	0.43	1.33
Potassium oxide, $\boldsymbol{K_2O}$	1.33	0.27
Other	4.08	1.44
Specific Gravity	2.45	2.82
Colour	Greyish	Whitish
Size	≤ 45 µm	≤ 45 µm

The alkali activators were pre-prepared using commercial 12 molar (M) sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) with a Na_2SiO_3/NaOH ratio of 2.5. The grade of sodium hydroxide and sodium silicate with Analytical Reagent (AR) and American Chemical Society (ACS) was obtained from R&M Chemical Ever Gainful Enterprise Sdn. Bhd. Graphene oxide powder is utilized as an additive in this study and was produced by a modified Hummer's Method. The powder consists of 15-20 sheets and exhibits a 4-10% edge-oxidized condition. The chemical and characterisation study indicates the presence of fixed carbon (minimum 98-99.5%) and sulfur (maximum 0.03-0.05%). The fine aggregate

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utilized in this study is has the particle size distribution of less than 600 µm, sourced from Kajang Rocks Quarry, Selangor, Malaysia.

B. Sample Preparation

The procedure for producing geopolymer mortar using Na_2SiO_3 and 12M of NaOH, with and without the addition of GO discussed in this section. Various proportions of GO were included in geopolymer mortar by mixing with the alkaline activator solution using gentle magnetic stirring prior to adding the precursor and aggregate to enhancing homogeneity during mixing and preventing agglomeration. Additional water was added prior to water-to-precursor (w/p) ratio of 0.10, and 0.20. The w/p ratios of 0.10 and 0.20 were selected based on preliminary testing and literature benchmarks to balance flowability with structural performance. These ratios were found to offer sufficient workability for practical placement while ensuring desirable compressive strength and durability characteristics, particularly in chloride-rich environments. The freshly mixed mortar slurry was poured into 50 mm cube moulds and placed on a vibrating platform for 1 minute to remove entrapped air. **Error! Reference source not found.** contains details of the mixed design.

Table 2: Mixed Design

Mix ID	FA (%)	GGBS (%)	GO (wt.%)	w/p	P:S
G-1FA60GGBS	40	60	0	0.10	1:2
			0.02		
			0.04		
			0.06		
			0.08		
			0.10		
G-2FA60GGBS	40	60	0	0.20	
			0.02		
			0.04		
			0.06		
			0.08		
			0.10		

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Note: P:S = Precursor:Sand

III. Testing

A. Compressive Strength

The freshly mixed mortar slurry was poured into 50 mm cube moulds and placed on a vibrating platform for 1 minute to remove entrapped air. The specimens underwent curing at ambient conditions for 24 hours; following that, the samples were extracted from the moulds and preserved at ambient temperature for 7, 14, and 28 days for compressive strength testing.

B. Rapid Chloride Permeability Test (RCPT)

A rapid chloride permeability test was conducted by casting the freshly mix samples in the cylindrical mold with a diameter of 100 mm and a height of 200 mm. The freshly cast samples were vibrated on a table for 1 minute to remove entrapped air. After 24 hours of curing at ambient temperature, the samples were removed and then cured for 28 days at ambient temperature. According to ASTM C1202, a precision diamond saw cut each cured cylinder into 50 mm thick discs from the middle. The sliced samples were vacuum-saturated for 3 hours at a pressure of 50 mmHg, and then the samples were submerged in de-aerated water for an additional 18 hours. The RCPT equipment comprises a test cell partitioned into two compartments by the specimen. One chamber contains a 3% sodium chloride (NaCl) solution dilution to replicate an aggressive chloride environment, while the other chamber contains a 0.3 N of NaOH solution to function as the cathode. The specimen functions as an anode. A direct current (DC) voltage is applied across the two chambers of the test cell, facilitating the migration of chloride ions from the chloride solution to the hydroxide solution through the specimen. The applied voltage is typically 60 V direct current, and the test duration is 6 hours. The chloride permeability of the mortar is evaluated by measuring the concentration of chloride ions in the hydroxide solution and

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computing the charge transmitted through the specimen as shown in Table 2. The results are generally expressed as coulombs of charge transferred per square metre of the specimen's exposed surface area.

Table 2: Chloride Ion Penetrability in Coulombs based on ASTM C1202

Charge Passed (Coulombs)	Chloride Ion Penetrability
> 4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

C. Standard and Equipment

The testing conducted, equipment/machinery utilised, and standards adhered to in this experimental study are illustrated in **Error! Reference source not found.**.

Table 3: Test and Equipment

Testing	Equipment/Machine	Standard
Flowability	Motorized Flow Table	ASTM C1437
Compressive Strength	Universal Testing Machines (UTMs)	ASTM C109
Rapid Chloride Permeability Test (RCPT)	RCPT cells; 60 V DC Power Supply; Data logger	ASTM C1202

IV. Results and Data Analysis

A. Flowability

Numerous studies have examined the integration of GO into geopolymer mixtures containing 40% Class F fly ash and 60% GGBS. Nevertheless, there is a scarcity of research on the investigation of geopolymer mortar with water-to-precursor (w/p) ratios of 0.1 and 0.2, which incorporate GO. The flowability test line graph test for a variety of w/p ratios and GO percentages (%) is depicted in **Error! Reference source not**

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found.. In general, the flowability of cementitious materials is diminished by including GO. The hydrophilic functional groups and high specific surface area of GO tend to adsorb water, thereby decreasing the amount of pure water available for diffusion. For example, the fluidity of alkali-activated GGBS systems decreases as the concentration of GO increases due to GO's water absorption capacity [27].

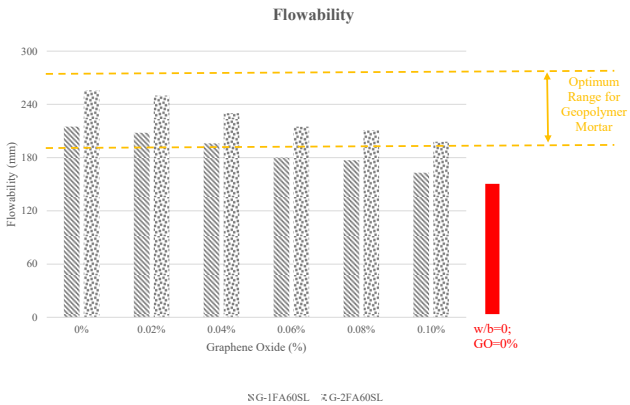

Figure 2: Results of Flowability for GPM with Different GO Dosages and w/p

The aforementioned assertions are substantiated in **Error! Reference source not found.**. The flowability is enhanced by adding water to the mixture; the maximum flowability is achieved with a w/p ratio of 0.20. Nevertheless, an excessive amount of water will exceed the optimal flowability range for structural use and repair [28]. The results for the w/p ratio of 0 and 0% GO in the mix are 153 mm, which suggests that the flowability is subpar. G-1FA60GGBS (0.04%) and G2-FA60GGBS (0.10%) are the most effective mixtures in this test, as they exhibit a 30% increase in flowability and a decent workability range compared to other mixtures. In summary, the flowability of a conventional water-based system is superior to that of an alkaline activator that is not accompanied by water. The mixture's optimisation is contingent upon the equilibrium between the activator and GO, as

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the flowability will continue to decrease due to the GO's inclusion. In the two-part geopolymer system, the liquid activator plays a direct role in determining the fresh properties, particularly flowability. Increasing the w/p ratio from 0.10 to 0.20 significantly improved the flowability of the mix, making it more suitable for repair applications where workability and ease of placement are essential [29-30]. The presence of GO further enhanced flow by promoting dispersion of aluminosilicate particles [27]. GO's surface functional groups interact with both the alkaline solution and solid precursors, reducing viscosity through electrostatic repulsion and improved particle spacing.

B. Compressive Strength

Figure 3 and Figure 4 illustrate the compressive strength of the 40% FA and 60% GGBS with varying degrees of GO dosage (0%, 0.02%, 0.04%, 0.06%, 0.08%, 0.10%) at 0, 0.10, and 0.20 w/p ratios respectively.

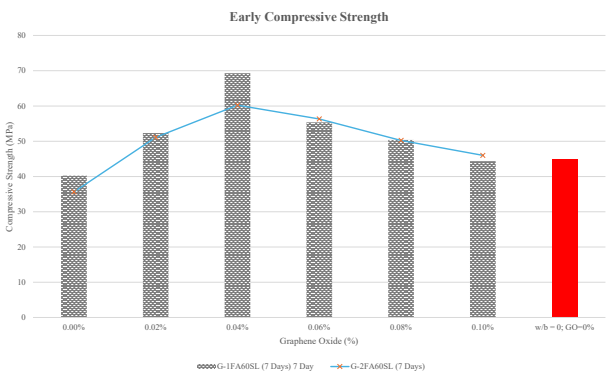

Figure 3: Results of Early Compressive Strength for GPM with Different GO Dosages and w/p

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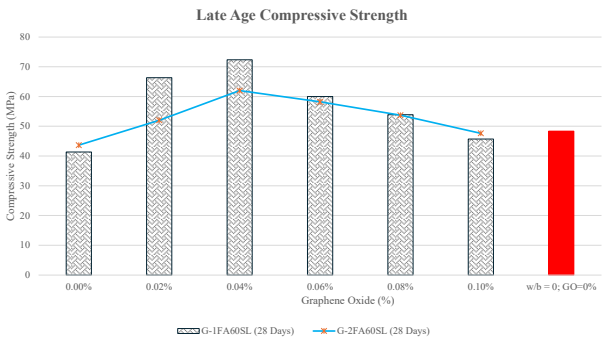

Figure 4: Results of Later Age Compressive Strength of GPM with Different GO Dosages and w/p

The strength of the geopolymer mortar has been enhanced in both early and late periods, with and without water, due to the addition of GO. The strength of the geopolymer mortar samples was evaluated at 7 (early strength) and 28 days (late strength). The geopolymer mortar formulations exhibited a consistent increase in strength as they aged from the date of ambient curing. The physical and durability interaction between the matrixes and the alkaline activator primarily determines the compressive strength of geopolymer mortar samples. Compared to geopolymer mortar without additional water and GO for 7 and 28 days, the compressive strength of G-1FA60GGBS without GO with 0.10 w/p ratio was reduced by 6.44% and 13.85%, respectively. The compressive strength was reduced by 17.14% and 9.06% at 7 and 28 days compared to a mixture without additional water and 0% GO for a w/p ratio of 0.2.

Previous studies have shown the same results, which indicate that compressive strength decreases as the water-to-geopolymer solid ratio increases. For instance, Khale and Chaudhary conducted a study demonstrating a decrease in compressive strength as the ratio of water-to-geopolymer solid by mass increased. This phenomenon is analogous to the w/p ratio in conventional Portland cement concrete [27]. Compared to the mixture

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without a w/p ratio, the compressive strength was improved at 7 and 28 days (61.21% and 50.75%, respectively) by incorporating 0.04% GO with 0.1 w/p ratios. Nevertheless, the compressive strength was reduced by 13.11% and 14.34% for 7 and 28 days, respectively, while a 0.2 w/p ratio was used in conjunction with 0.04% GO. Furthermore, the compressive strength would be reduced by an excessive concentration of GO in the composite. The compressive strength was reduced from 0.06% to 0.10% of GO for all curing times at w/p ratios of 0.1 and 0.2, as illustrated in Figure 3 and Figure 4. The compressive strength of geopolymer mortar can be diminished by incorporating an inordinate amount of GO. Various factors can contribute to this issue. The mortar may develop detrimental pores as a consequence of an excessive quantity of GO content, as indicated by previous research [14][16][31]. Hence, the compressive strength and overall density are diminished. Furthermore, higher GO concentrations may increase the air content in the mixture, leading to inadequate compaction and reduced mechanical strength. In terms of compressive strength, the incorporation of GO led to substantial improvement, particularly in mixes with lower w/p ratios. The enhancement is attributed to GO acting as a nucleation site during geopolymer gel formation, accelerating the polycondensation reaction and producing a denser gel network. In addition, GO's nanostructure facilitates crack-bridging and stress transfer, contributing to improved mechanical integrity. At higher w/p ratios, while flowability increases, some reduction in compressive strength is expected due to increased porosity [32]. However, the presence of GO mitigates this loss by refining the pore structure and increasing gel cohesion.

C. RCPT

Figure 5 shows the results of the RCPT test. Based on the figure, the incorporation of GO

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up to 0.06% typically diminishes chloride ion permeability. It was shown that the minimum values were recorded at a GO concentration of 0.06% for both mixtures with added water at a 0.1 and 0.2 w/p. G-1FA60GGBS exhibits a more significant decrease in chloride permeability with GO compared to G-2FA60GGBS, particularly at concentrations of 0.04% and 0.06%. Incorporation of GO at these concentrations yields moderate RCPT values based on ASTM C1202, with RCPT data of 1863 Coulombs and 1469 Coulombs, respectively. This suggests that the G-1FA60GGBS matrix may benefit more from the densifying effect of GO. The control sample with 0% GO and no water added additionally displayed the highest chloride ion penetration (3261 C), which proves that GO and an optimal w/p ratio are important for making it more durable. The use of graphene oxide markedly enhanced the chloride ion resistance of both G-1FA60GGBS and G-2FA60GGBS geopolymer mortars.

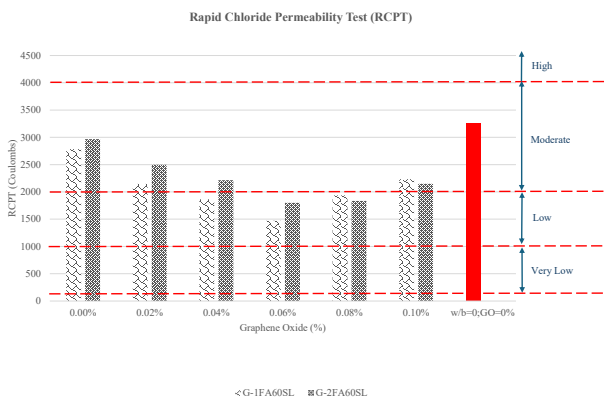

Figure 5: Results of RCPT for GPM with Different GO Dosages and w/p

Optimal performance was attained at 0.06% GO concentration, where both mixtures exhibited 'Low' chloride ion penetrability by ASTM C1202. Hence, these findings underscore the significance of optimising GO dosage to improve durability in geopolymer systems. Specimens containing GO exhibited lower total charge passed, indicating

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enhanced resistance to ionic transport. This can be explained by the pore-refining ability of GO, which blocks capillary channels and hinders chloride ion mobility. Moreover, GO's interaction with geopolymer gel components forms a more continuous and compact matrix, which serves as an effective barrier against external aggressive agents [33]. While higher w/p ratios generally lead to increased permeability, the addition of GO in the two-part system helps counteract this effect. The dense microstructure developed through GO-enhanced gel formation reduces connectivity between pores, thus lowering ion transport even when water content is relatively high. This synergy between GO and optimized water content results in a durable, flowable, and mechanically reliable repair mortar suitable for aggressive environments, such as chloride-rich or coastal infrastructures.

V. Discussion

The geopolymer mortar, modified with graphene oxide, fly ash class F (FA), and ground granulated blast slag (GGBS), exhibited superior compressive strength and reduced chloride permeability compared to the control mix cured at ambient temperature. From the experimental data, the geopolymer mortar, modified with graphene oxide, fly ash class F (FA), and ground granulated blast slag (GGBS), exhibited superior compressive strength and reduced chloride permeability compared to the control mix cured at ambient temperature. Besides, the use of graphene oxide into GGBS based geopolymer mortar resulted in enhanced compressive strength relative to the reference mixture. Among different percentages of GO (0.02%, 0.04%, 0.06%, 0.08%, and 0.10%), geopolymer mortar samples with a 0.04% GO addition shown an improvement in compressive strength.

The rapid chloride permeability test demonstrated the exceptional resistance of graphene-modified geopolymer mortar samples to chloride ion permeability. In addition to an optimal amount of graphene

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oxide (0.04% and 0.06%) in geopolymer sample with w/p ratio of 0.10, the permeability to chloride ions is significantly lower than in other mixtures.

These results highlight the potential of GO-geopolymer systems for practical applications in infrastructure rehabilitation, particularly in inland. Future research should explore the long-term durability of such systems under real field conditions, including freeze-thaw resistance, sulfate attack, and bond strength with aged substrates. In addition, life cycle assessments and scalability studies could support the practical implementation of GO-modified geopolymer mortars in large-scale repair projects.

VI. Conclusion

This investigation revealed some noteworthy findings that affect the properties of graphene oxide, modified FA, and geopolymer mortar based on GGBS. Further investigation should identify potential applications for geopolymer technology utilising GO. This would result in findings that are specifically aimed at ensuring the sustainable use of industrial by products in technical applications. Beyond the production of concrete, geopolymer technology has the potential to expand into other areas of the community's structural development. In addition, the addition of GO influences the geopolymer matrix at both chemical and physical levels. GO contains oxygen-rich functional groups (e.g., hydroxyl, epoxy, and carboxyl) that can interact with alkaline activators and aluminosilicate species during geopolymer gel formation. These interactions are believed to promote nucleation sites for aluminosilicate gel growth, accelerating the geopolymerization process. Furthermore, GO’s high specific surface area aids in refining the pore structure by physically filling voids and bridging microcracks, which enhances matrix densification. This denser structure limits the ingress pathways for chloride ions, thereby reducing the charge passed in RCPT results. Additionally, the incorporation

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of GO improves the continuity of the geopolymer network, which translates into improved compressive strength due to enhanced load transfer and microstructural integrity.

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