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Experimental investigation on metakaolin/coal fly ash-based porous geopolymer grouting material for geotechnical applications

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Abstract. This research investigates the development of a porous geopolymer cement grout for soil grouting applications, aiming to reduce carbon emissions associated with Portland cement while maintaining critical performance characteristics such as strength and permeability. Class F fly ash and metakaolin were used as aluminosilicate precursors, activated by sodium silicate and sodium hydroxide solutions. The addition of hydrogen peroxide served as a foaming agent to introduce porosity. Compressive strength and porosity were evaluated, with results showing that metakaolin significantly increased compressive strength due to its smaller particle size and higher reactivity. A higher molarity of sodium silicate enhanced strength by reducing the water-to-solid ratio, creating a denser matrix. In contrast, increasing hydrogen peroxide content raised porosity but reduced compressive strength by generating gas bubbles. X-ray diffraction (XRD) analysis revealed the ongoing formation of hydration products and a growing amorphous structure in the geopolymer matrix, contributing to strength development over time. The study concludes that the geopolymer grout can be optimized for a wide range of soil stabilization applications by adjusting material composition, foaming agent concentration, and activator molarity, offering an environmentally sustainable alternative to traditional cement grouts.

Keywords: coal fly ash; grouts; metakaolin; porous geopolymer; sinkhole remediation

1. Introduction

Concrete production contributes to 8% of global CO_2 emissions, with each kilogram of concrete responsible for approximately 0.93 kilograms of CO_2 (Ramsden 2020). A significant factor behind these emissions is the high kiln temperatures required for calcining raw materials to produce Portland cement. A promising alternative to reduce Portland cement use is geopolymer cement, which is made from inorganic aluminosilicate materials such as coal fly ash, metakaolin, blast furnace slag, etc. activated by an alkaline solution to form a network of covalent bonds, mimicking the structure of Portland cement (Davidovits 2008). This process eliminates the calcination step of Portland cement, resulting in an 80% reduction in carbon emissions (Van Deventer 2010).

The raw materials, rich in aluminum and silicon oxides, react with an alkaline activator, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH), to produce a sodium aluminosilicate hydrate (N-A-S-H) gel, which imparts the mechanical properties expected from cement (Fig. 1). Each raw material contributes unique elements and structures to the binder, influencing its overall performance. Fly ash, a byproduct of coal combustion in power plants, is one of good sources of aluminosilicate in geopolymer formulations. Class F fly ash is commonly used in geopolymer concrete due to its low calcium content, which minimizes interference with hydration and reaction processes. Additionally, its high content of combined silica (SiO_2) and alumina (Al_2O_3), which can exceed 85% of the total chemical composition, makes it an ideal precursor material for geopolymer synthesis (Güllü *et al*. 2019, Guo

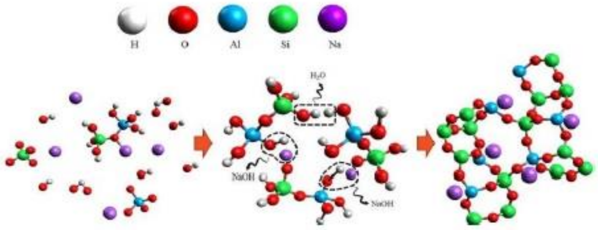

Fig. 1 Geopolymerization Process (Park and Pour-Ghaz 2018)

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Fig. 2 Grouting for Sinkhole Remediation (Foundation Services of Central Florida Inc. 2015)

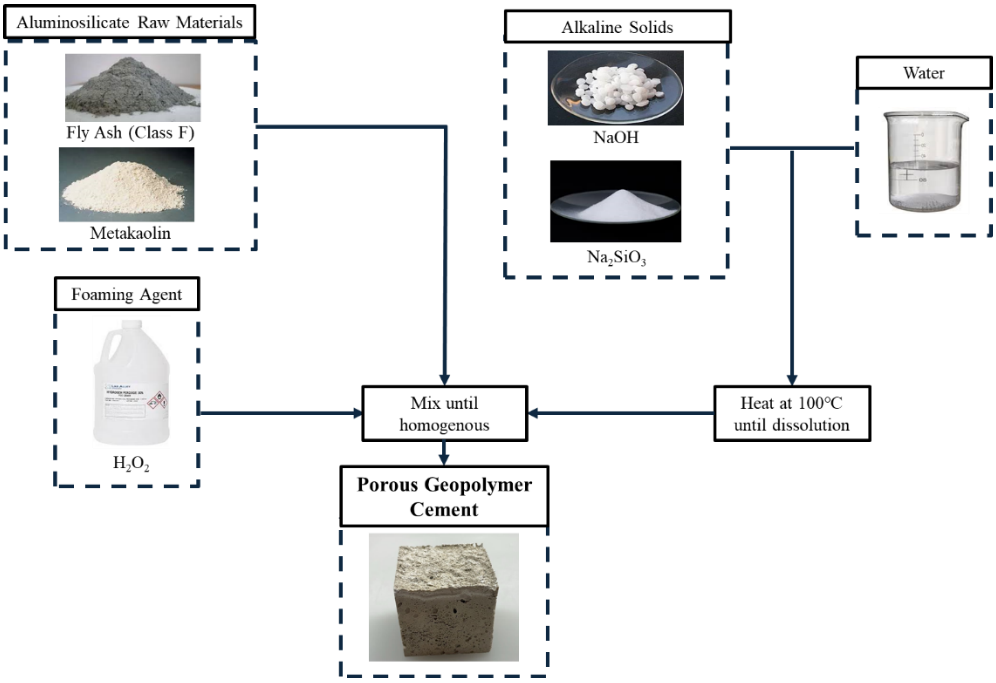


Fig. 3 Porous geopolymer grout preparation

et al. 2022). Fly ash also contains additional components such as quartz, mullite, corundum, hematite, and calcium oxide (Zhang *et al*. 2019) and exhibits an irregular block-like chemical structure that slightly influences reaction kinetics by reducing dissolution efficiency (Duan *et al*. 2023). Another essential aluminosilicate, metakaolin, is produced by heating kaolin clay above 700°C. Geopolymer can be used in various construction fields including building, infrastructures, geotechnical application. Some researchers have modified the properties of geopolymer and tried to use them as grouting materials.

Grouting, a process involving the injection of cement-based slurry into subsurface soils, is used to improve their mechanical properties by filling voids or fractures that could otherwise lead to collapse or subsidence (Coduto 1999, Bu 2023, Tacim 2023, Kim 2024, Sierra 2024). Fig. 2 shows the general grouting process used for sinkhole remediation. The unconfined compressive strength of soils typically ranges from 0.03 to 0.41 MPa, depending on their consistency (Saputra and Putra 2022). As a result, standard compressive strengths of grout are generally low, with a minimum compressive strength of 0.7 MPa, as specified by ASTM C 39 (American Society of Civil Engineers 2007).

Compressive strength is a key measure of the mechanical performance of grouts, typically classified into early and later strength stages. Early strength refers to the unconfined compressive strength tested within 1–3 days after grout setting, with Portland cement grouts usually ranging from 0.5 to 1.5 MPa (He *et al*. 2020). Later strength denotes the compressive strength achieved over a period of 28–56 days, which generally falls between 1.5 and 25 MPa.

In cement-based grouts, the water-to-cement ratio is a significant influencing factor, where higher water-to-cement ratios tend to reduce compressive strength. A water-to-cement ratio between 0.35 and 1.0 is considered ideal for grout applications, with an expected porosity range of between 18% and 70% (Rosquoët *et al*. 2003). Grouts often exhibit lower permeability than the surrounding soil, which can alter subsurface hydrology by modifying water flow patterns and potentially affecting soil stability by causing soil erosion to increase at areas directly surrounding the impermeable grout (Coskun and Tokdemir 2020). To minimize these impacts, using grout with porous properties similar to that of the surrounding soil can help maintain natural hydrological dynamics and prevent disruptions to existing groundwater flow patterns within the soil matrix.

Table 1 Chemical Composition of Raw Aluminosilicate Materials

Aluminosilicate Materials	Chemical Composition (wt%)								
	O	Si	Al	Ca	Mg	Na	Fe	C	Au
Fly Ash	51.86	20.98	10.37	10.04	3.64	2.56	0.51	0.03	0
Metakaolin	35.20	25.49	32.09	0.65	0	0	0	0.38	6.19

Table 2 Mixture Design of geopolymer grout sample

Sample ID	Aluminosilicate Raw Material		Alkali Activator Solution			Foaming Agent Solution
	Fly Ash	Metakaolin	Sodium Hydroxide Solution (15 M)	Sodium Silicate Solution	Sodium Silicate Molarity	Hydrogen Peroxide
F50	40%	0%	17%	43%	5 M	0%
F51	39%	0%	17%	43%	5 M	1%
F52	39%	0%	17%	42%	5 M	2%
F80	44%	0%	19%	37%	8 M	0%
F81	44%	0%	19%	36%	8 M	1%
F82	43%	0%	19%	36%	8 M	2%
M50	20%	20%	17%	43%	5 M	0%
M51	20%	20%	17%	43%	5 M	1%
M52	19%	19%	17%	42%	5 M	2%
M80	22%	22%	19%	37%	8 M	0%
M81	22%	22%	19%	36%	8 M	1%
M82	22%	22%	19%	36%	8 M	2%

The porosity of soil varies depending on the soil classification. The range of porosity of gravel is between 23% and 38% (Das 2008). The porosity of well graded sands ranges from 22% to 42%, and the porosity of inorganic clays ranges from 29% to 41% (Association of Swiss Road and Traffic Engineers 2014). Uniform organic silt has a porosity ranging from 29% to 52%. (Hough 1969). To match these soil properties to the geopolymer grout, being able to modify the pore structure in geopolymer for specific site condition is necessary.

Porous geopolymers represent a unique class of materials that merge the versatility of geopolymers with engineered porosity to meet to achieve desired properties at various practical applications. The direct foaming method is a widely used technique for creating porous geopolymer materials (Zhang *et al*. 2021). In this method, a foaming agent (hydrogen peroxide) is introduced into the slurry, which is then mechanically frothed to produce oxygen gas creating voids in the slurry. Hydrogen peroxide (H_2O_2) breaks down into water (H_2O) and oxygen gas (O_2) in the presence of an alkaline solution. The chemical equation of this reaction is shown in Eq. (1).

$$H_2O_2 \rightarrow H_2O + \frac{1}{2} O_2 \tag{1}$$

Fig. 3 illustrates the preparation steps of porous geopolymer grout. After casting into molds, the geopolymer undergoes spontaneous setting, resulting in a porous structure. This technique enables precise control over pore size and its distribution, allowing the material to meet specific strength, density, and permeability requirements (Song *et al*. 2024). Studies show that pure geopolymer matrices can naturally develop intrinsic micro- and mesopores, reaching porosity levels of up to 60% without the use of additional pore-forming agents (Ge *et al*. 2015).

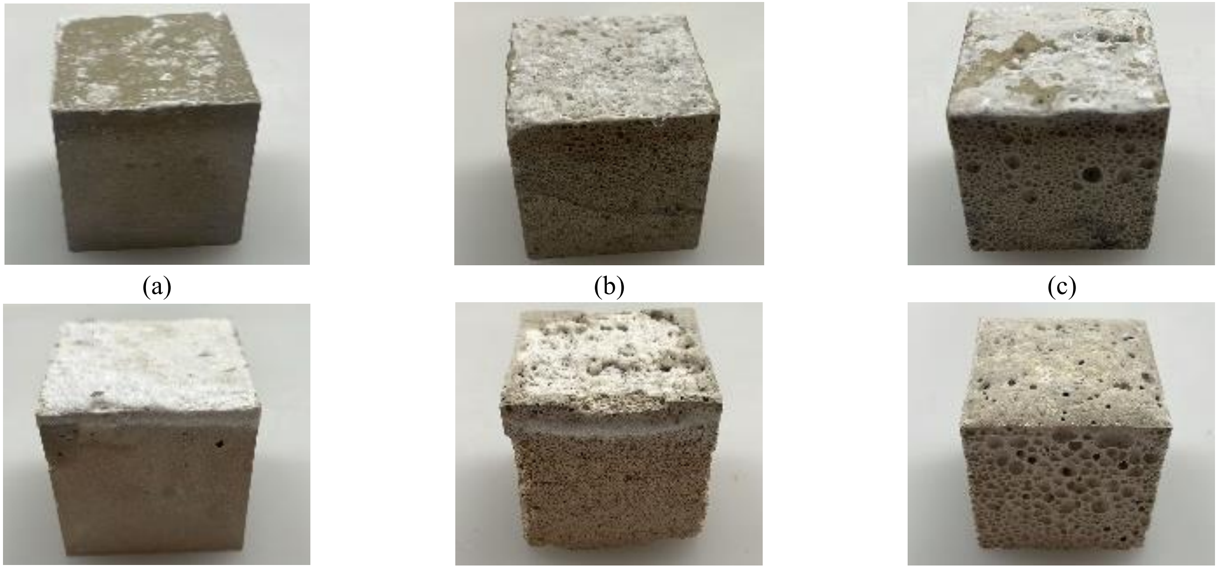
The aim of this research is to develop a porous geopolymer grout that is specifically tailored for soil grouting applications. To meet this objective, it must achieve the necessary strength properties that are essential for effective grouting, ensuring that it can withstand the mechanical stresses encountered in soil stabilization and reinforcement.

At the same time, the grout must be designed to simulate the permeability characteristics of the surrounding soil by incorporating porous geopolymer composites. This will enable the grout to integrate seamlessly with the soil, enhancing overall structural cohesion and preventing unwanted redirections of subsurface water flow. The combination of these factors will ensure the grout's suitability for a wide range of soil grouting applications, offering both strength and permeability control.

2. Materials and methods

2.1 Materials and mix design

Class F coal fly ash and metakaolin were used as the aluminosilicate raw materials. The chemical compositions shown in Table 1 were gathered through Energy Dispersive X-ray Spectrometer (EDS). As it can be observed, both



(a) (b) (c)

(d) (e) (f)

Fig. 4 Cube Samples of Porous Geopolymer Grout: (a) Sample F50, (b) Sample F51, (c) Sample F52, (d) Sample M50, (e) Sample M51, and (f) Sample M52

aluminosilicate materials have a high percentage of silicon and aluminium. High silica concentrations typically enhance the compressive strength and stability of geopolymer cement by promoting the formation of strong Si–O–Si bonds, which contribute to a dense, three-dimensional polymeric network. A high alumina content contributes to the development of Al–O–Si bonds, which add flexibility to the network structure and often accelerate the setting process.

Sodium silicate and sodium hydroxide pellets were dissolved in water at 100°C until full dissolution to create the activated alkaline solutions. Sodium hydroxide is primarily responsible for breaking down the bonds within the precursor material, accelerating the dissolution process and promoting the formation of Si–O–Al bonds. A molarity of 15 mol/L (M) was maintained for the sodium hydroxide solution. The molarity of the sodium silicate solution was either 5 M or 8 M, affecting the overall water to solids ratio. The molarity of the alkaline solutions was controlled by the mass percentage of the pellets in the alkaline solution. Hydrogen peroxide (H_2O_2) with a 30% concentration was the foaming agent solution.

The mixture design of geopolymer grout sample is shown in Table 2. The changing variables considered for the experiment are the weight percentage of fly ash, metakaolin, and hydrogen peroxide, as well as the molarity of the sodium silicate solution. In Table 2, regarding Sample ID, the first, second, and third digits represent the aluminosilicate material, the sodium silicate molarity, and the percentage of hydrogen peroxide, respectively. For example, F81 indicates that the sample was made with fly ash (as the sole aluminosilicate material), a sodium silicate molarity of 8M, and hydrogen peroxide at 1%. Similarly, M52 indicates that the sample was made with fly ash and metakaolin (50% of the fly ash was replaced with metakaolin), a sodium silicate molarity of 5M, and hydrogen peroxide at 2%. To test the effect of the aluminosilicate materials, samples using only fly ash were compared to those with a 50% weight replacement of metakaolin. The quantity of aluminosilicate material was predetermined, while the proportions of sodium silicate and sodium hydroxide were selected based on their molarity and the designated water-to-solid ratio: 0.6 for samples with a sodium silicate molarity of 5M, and 0.45 for samples with a sodium silicate molarity of 8M. The total weight percentage of hydrogen peroxide varied from 0% to 2%, and this was done to understand the effect of H_2O_2 on the porosity and compressive strength. Two different molarities of sodium silicate solutions were compared to study the effect of sodium silicate and the water-to-solid ratio of the porous geopolymer grout.

Using the weight percentages in the mixture design, the fresh porous geopolymer grout was prepared for each mixture. First, the aluminosilicate materials, such as coal fly ash and metakaolin, are thoroughly mixed for approximately one minute to ensure even distribution and blending of the precursor powders. This initial dry mixing is essential for promoting uniform geopolymerization once the activators are introduced, as it ensures that the alumina and silica content is consistently distributed throughout the mixture. Then, the alkaline solutions were added and mixed until a homogenous fresh grout is created. These solutions act as activators, triggering the dissolution of the aluminosilicate particles and initiating the geopolymerization process. This step is crucial for ensuring that the chemical reaction between the aluminosilicate materials and the alkaline activators occurs uniformly, as any inconsistencies in mixing could lead to localized areas of incomplete geopolymerization, which negatively affecting the material's strength and porosity. The foaming agent solution is added and mixed for one minute to ensure even distribution of the gas bubbles throughout the material.

Finally, the fresh grout was cast into 2 × 2 × 2-inch cube molds for testing. Three samples were prepared for each mix. The samples of porous geopolymer grout are shown in Fig. 4 after setting for 28 days.

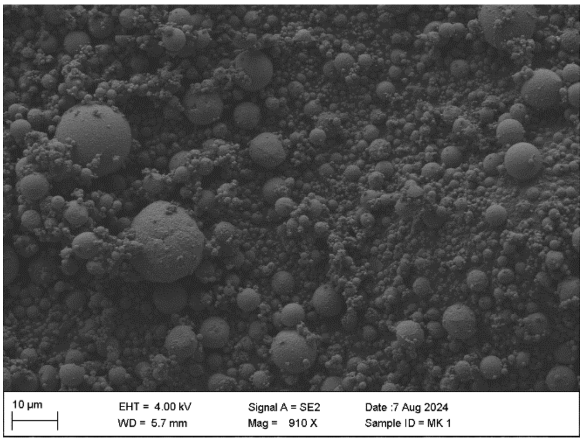
2.2 Test Methods

The compressive strength was determined with the cube specimens after curing for 7, 14, and 28 days. At each stage, the compressive strength of each sample was measured using the universal testing machine (UTM) (MTS, model E45) at UTRGV High-bay Lab. The testing followed the ASTM C109 standard testing method for compressive strength of hydraulic cement mortars.

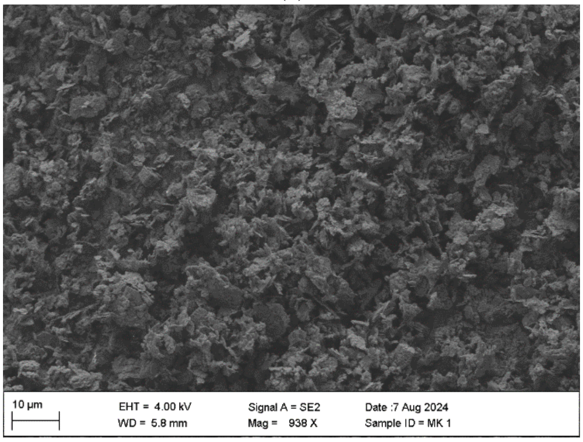
The porosity was tested after waiting for the grout to be hardened for 28 days. The samples were dried in the oven at 100°C. The samples were weighted every 24 hours until there was a minimal difference in weight, and the final oven-dried weight (W_d) recorded was used. Then, the oven-dried samples were submerged in water, and the saturated weight was noted every 24 hours until there was a minimal difference in weight. The final saturated weight (W_s) was used to measure the porosity of the sample with the following Eq. (2)

$$\text{Porosity (\%)} = \frac{(W_s - W_d) \times 100}{V} \qquad (2)$$

Scanning electron microscope (SEM) and energy dispersive X-ray Spectrometer (EDS) were employed to characterize chemical compositions and morphological properties of raw aluminosilicate materials (fly ash and metakaolin). In addition, X-ray diffraction (XRD) analysis was employed to investigate the crystal and amorphous structures of harden geopolymer grout samples.



(a)



(b)

Fig. 5 SEM Images of (a) Fly Ash and (b) Metakaolin

3. Results

3.1 Material characterization

SEM analysis was performed to observe the morphology of aluminosilicate raw materials. Fig. 5 shows that fly ash particles are predominantly spherical, while metakaolin particles exhibited irregular shapes. Additionally, the metakaolin particles are significantly smaller in size compared to the fly ash particles. The smaller size and larger surface area of metakaolin particles contribute to their higher reactivity with alkaline activators, leading to faster geopolymerization and early strength development, whereas the larger and smoother fly ash particles dissolve more slowly, contributing to strength gain over a longer period. The differences in particle morphology also influence the microstructure of the geopolymer grout. The smaller metakaolin particles can fill the voids between the larger fly ash particles, resulting in a denser matrix.

3.2 Mechanical properties of porous geopolymer

As shown in Fig. 6 and Table 3, the addition of metakaolin majorly increased the compressive strength of the porous geopolymer grout. This can be attributed to a higher Si and Al contents in metakaolin allowing the acceleration of geopolymerization. The high availability of silicate and alumina species facilitates the development of strong Si-O-Si and Si-O-Al bonds, which contributes to the densification of the geopolymer structure, leading to improved compressive strength. The smaller particle size of metakaolin compared to fly ash can also affect the compressive strength due to the filling effect that a well graded particle size distribution of raw aluminosilicate materials creates. This improved particle packing also leads to a reduction in void spaces within the geopolymer matrix. Although the density of the geopolymer matrix (excluding porosity) containing metakaolin can be higher than that of fly ash, the overall densities of samples containing metakaolin are lower than that of fly ash (Table 3 and Fig. 4) due to the higher porosity. The denser microstructure provides better load-bearing capacity, which is directly reflected in the increased compressive strength. The large surface area of metakaolin also allows for better dissolution, accelerating the geopolymerization process. Faster dissolution of metakaolin means that more reactive species, such as silicate and aluminate ions, are available for the polymerization reaction, which accelerates the formation of the geopolymer network. This faster reaction contributes to the early strength gain of the geopolymer grout, as more of the geopolymer matrix is formed at an early stage.

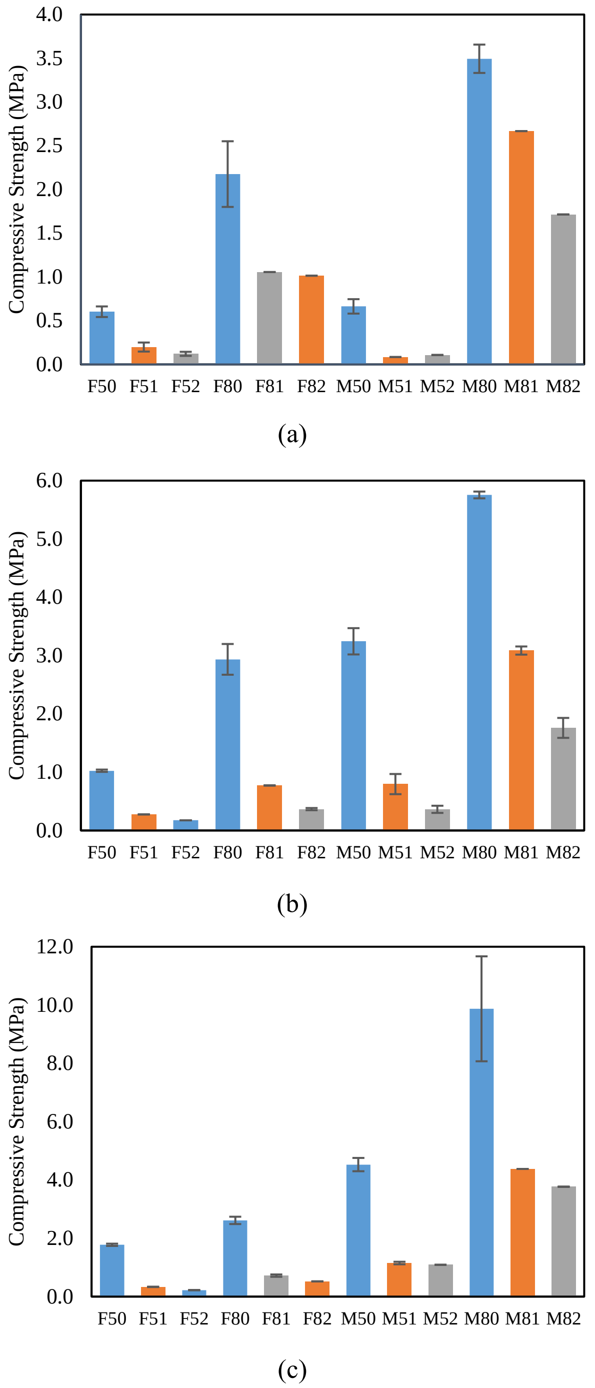


Fig. 6 Compressive Strength at (a) 7 Days, (b) 14 Days, and (c) 28 Days

The compressive strength increased with a higher molarity of Na_2SiO_3. This is due to the higher content of silica accelerating geopolymerization. The increased availability of silicate ions promotes the formation of additional Si-O-Si bonds within the geopolymer network, leading to a denser and more interconnected microstructure. This denser network enhances the material's ability to resist compressive loads, resulting in higher compressive strength. As silica content increases, the geopolymerization process becomes faster and more extensive, leading to greater mechanical strength due to the more robust gel structure formed during curing. Another explanation to the relationship between compressive strength and the molarity of Na_2SiO_3 is that the water-to-solid ratio of the overall porous geopolymer composite is affected by the molarity. At a molarity of 5 M, the water-to-solid ratio is calculated to be 0.6, and at a molarity of 8 M, the water-to-solid ratio is 0.45.

A higher water-to-solid ratio, as observed at 5 M, results in more free water in the mixture, which can lead to the formation of voids or pores as the excess water evaporates during the curing process. These voids reduce the density of the geopolymer matrix and create points of weakness, thereby lowering the overall compressive strength. In contrast, at the higher molarity of 8 M with a lower water-to-solid ratio, there is less excess water in the system, leading to fewer voids and a denser, more compact microstructure. This reduction in porosity directly contributes to the higher compressive strength observed at higher molarity, as a denser material is better able to bear loads without failing.

The compressive strength decreased as the percentage of hydrogen peroxide increased. As hydrogen peroxide concentration increases, the number of gas bubbles produced also rises, leading to a greater volume of macro-pores between the geopolymer matrix. The formation of these macro-pores results in a reduction in the overall density of the sample. A lower overall density implies that there is less solid structure available to bear loads, which in turn leads to a decrease in compressive strength. The presence of macro-pores due to the hydrogen peroxide can be understood as creating weak points within the geopolymer matrix, where stress concentrations can occur under loading conditions. These weak points increase the likelihood of crack formation and propagation, further diminishing the material's ability to withstand compressive forces.

All samples incorporating metakaolin successfully met the required minimum compressive strength of 0.7 MPa for grouting applications at 28 days, even with the inclusion of hydrogen peroxide and varying molarities of sodium hydroxide. However, among the samples that fly ash is the sole aluminosilicate material, only those without hydrogen peroxide (samples F50 and F80) achieved the required compressive strength. These results indicate that grouts can be engineered as suitable for various soil types, depending on their respective porosity characteristics.

Toughness, which is another mechanical property, was also determined to understand the engineering performance of porous geopolymer samples to represent the material's ability to absorb and dissipate energy before failure. The toughness of each sample was determined by calculating the area underneath the stress–strain (σ–ε) curve obtained by the UTM results when testing the compressive strength. As illustrated in Fig. 7, samples with lower hydrogen peroxide concentrations demonstrated enhanced toughness, which can be attributed to reduced porosity levels. Hydrogen peroxide, acting as a foaming agent, decomposes into water and oxygen gas, thereby generating pores within the geopolymer matrix. At lower concentrations, the decomposition produces fewer gas bubbles, yielding a

Table 3 Compressive Strength and Porosity Data

Sample ID	Compressive Strength (MPa)			Toughness at 28 days (MPa)	Density at 28 days (g/cm^3)	Porosity at 28 days (%)
	At 7 Days	At 14 Days	At 28 Days			
F50	0.60	1.02	1.78	0.062	1.75	21.12
F51	0.20	0.28	0.33	0.011	1.12	36.85
F52	0.12	0.17	0.22	0.002	0.96	38.10
F80	2.18	2.93	2.61	0.130	1.90	14.49
F81	1.06	0.77	0.72	0.039	1.22	18.69
F82	1.01	0.37	0.52	0.020	0.85	21.65
M50	0.66	3.24	4.53	0.386	1.48	33.09
M51	0.08	0.80	1.15	0.072	0.89	42.03
M52	0.11	0.36	1.09	0.030	0.42	51.67
M80	3.49	5.75	9.87	0.684	1.78	22.81
M81	2.67	3.09	4.38	0.227	1.15	39.22
M82	1.71	1.76	3.77	0.165	0.95	44.25

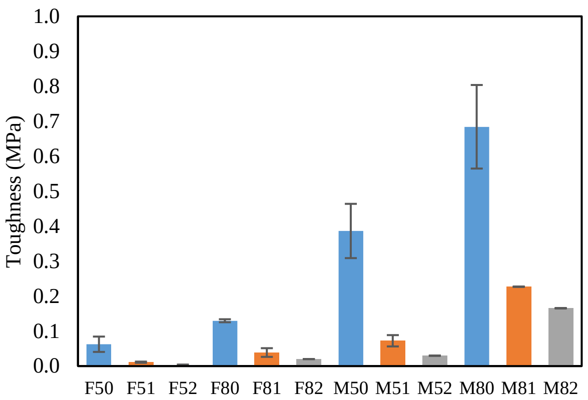


Fig. 7 Toughness at 28 Days

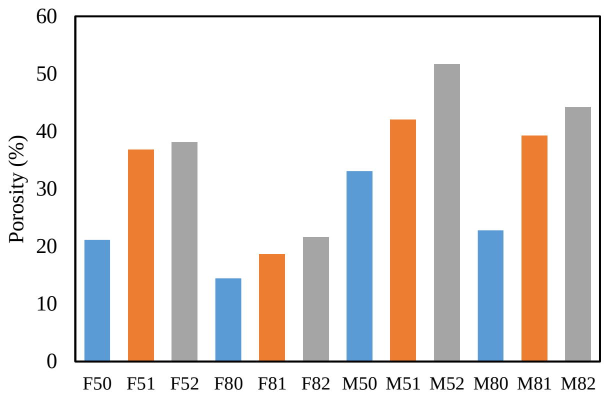


Fig. 8 Porosity at 28 Days

denser, more solid matrix. This reduced porosity enhances the material's ability to absorb and dissipate applied energy, thereby increasing toughness. In contrast, higher hydrogen peroxide concentrations generate a greater number of internal macro-pores, compromising geopolymer matrix integrity and decreasing the material's fracture resistance.

The combination of fly ash and metakaolin also strengthens microstructural bonding within the geopolymer network, resulting in increased toughness. Conversely, fly ash alone, with its larger spherical particles, yields a slower geopolymerization rate and a less dense microstructure, leading to lower toughness.

Samples synthesized with a higher molarity sodium silicate solution and a lower water-to-solids ratio exhibited superior toughness. Higher sodium silicate molarity provides an increased silica content, fostering extensive cross-linking within the geopolymer network. This increased cross-linking contributes to a denser gel structure, enhancing the material's energy absorption capacity and thereby improving toughness. Furthermore, a lower water-to-solids ratio minimizes the presence of excess water, which reduces void formation during curing. Consequently, a denser and more robust matrix is achieved compared to a higher water-to-solid ratio sample, offering greater resistance to fracturing under stress. In contrast, a high water-to-solids ratio caused by hydrogen peroxide introduces additional macro-pores due to water evaporation, forming weak points within the structure that decrease toughness.

3.3 Porosity and density

Fig. 8 shows that as the hydrogen peroxide content increases, the porosity of the grout increases. With higher hydrogen peroxide content, more voids are created. This phenomenon can be attributed to due to the foaming action of hydrogen peroxide decomposing during the curing process to release oxygen gas. The generation of gas bubbles leads to the formation of voids within the fresh grout. These voids increase the overall porosity of the material, resulting in a lighter and more permeable product.

With a lower molarity of the sodium silicate solution, the porosity of the porous geopolymer grout increases. Due to the difference of water-to-solid ratios, the grout with a molarity of 5 M formed more voids increasing the porosity. A lower molarity results in a higher water-to-solid ratio,

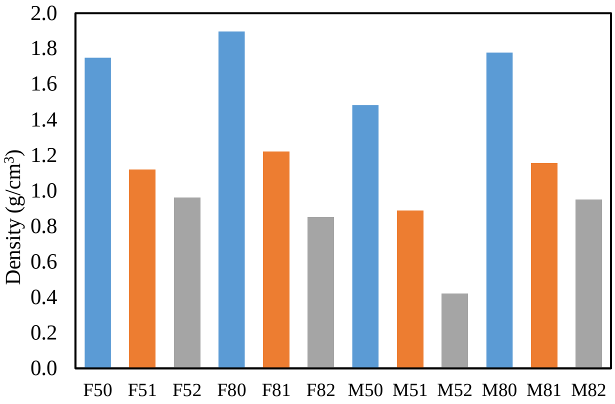


Fig. 9 Density at 28 Days

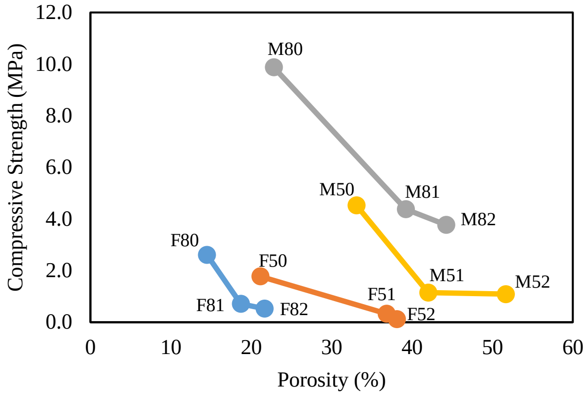


Fig. 10 Porosity vs Compressive Strength at 28 days

leading to an excess of water in the mixture. As the grout cures, this excess water can escape, creating additional voids that contribute to the overall porosity. In contrast, a higher molarity solution tends to reduce the water-to-solid ratio, which can lead to a denser sample with fewer voids.

Samples with metakaolin added to them showed a higher porosity than those with only fly ash. Fly ash is generally denser than metakaolin, which results in less air being trapped in the grout during mixing and before setting. The higher density of fly ash contributes to a more compact packing of particles, reducing the likelihood of void formation. In contrast, the smaller, irregularly shaped metakaolin particles create an inconsistent packing structure within the mixture. This irregular packing can lead to increased air entrapment, resulting in a greater number of voids and thus higher porosity in the final product. This characteristic contrasts with the smoother, more spherical particles typically found in fly ash, which tend to pack more uniformly and leave less space for air pockets.

As shown in Fig. 9, the inverse relationship between density and porosity across the samples is clear, as porosity introduces air-filled voids that decrease the material's mass per unit volume. Samples with lower hydrogen peroxide content exhibited higher density due to the reduced foaming effect, resulting in fewer internal voids. A higher hydrogen peroxide concentration produces more gas bubbles, increasing porosity and reducing density by creating a less compact internal structure.

The substitution of fly ash with metakaolin reduced the density of the samples. This can be explained by differences in the morphology and particle packing efficiency of the two aluminosilicate materials. Fly ash particles are typically spherical and denser, enabling more efficient packing and reducing the volume of air entrapped in the mix. In contrast, metakaolin particles have an irregular and angular shape, which tends to increase air entrapment during mixing, resulting in a more porous and less dense microstructure.

Samples with higher sodium silicate molarity and lower water-to-solids ratio exhibited higher density. This outcome can be attributed to the reduced water content, which leads to fewer voids as excess water is minimized. The higher silicate concentration enhances geopolymerization, producing a denser gel matrix with increased cross-linking of Si–O–Si and Si–O–Al bonds. This denser network minimizes microvoids, leading to higher density. In contrast, a higher water-to-solids ratio at lower sodium silicate molarity introduces excess water, which, upon evaporation, leaves behind voids that increase porosity and reduce density.

As observed in Fig. 10, there is a clear relationship between the porosity and compressive strength of the porous geopolymer grout after 28-day curing. As the porosity levels increase, the compressive strength of the grout decreases. While these voids can be advantageous in certain contexts, they simultaneously create areas of weakness within the otherwise solid matrix. As the porosity rises, the overall density of the grout decreases, which compromises its ability to bear loads. This reduced density means that there is less solid matrix available to resist compressive forces, ultimately resulting in lower compressive strength.

All samples containing metakaolin met the compressive strength requirements and exhibited porosity levels suitable for classification across various soil types. Sample M50, due to its porosity percentage, is applicable to a wide range of soil types, including gravel, well-graded sands, uniform organic silts, and inorganic clays. Sample M51 aligned with the higher porosity values for well-graded sands and the median porosity range for uniform inorganic silts. Sample M52 fell within the upper porosity range characteristic of uniform inorganic silts. Sample M80 corresponded to the lower porosity range typical of well-graded sands. Sample M81, with a porosity of 39%, was appropriate for use in well- graded sands, uniform inorganic silts, and inorganic clays. Sample M82 exhibited porosity levels suitable for soils classified as uniform inorganic silts.

3.4 XRD analysis

XRD analysis was used to observe the reactivity and amorphous structure content of the porous geopolymer grout. In Fig. 11, the x-axis and y-axis of the XRD analysis graph represent the angle of diffraction (2θ) and the intensity of the diffracted X-rays detected by the instrument, respectively. The intensity value on the y-axis measures how many X-rays are scattered by the sample at a

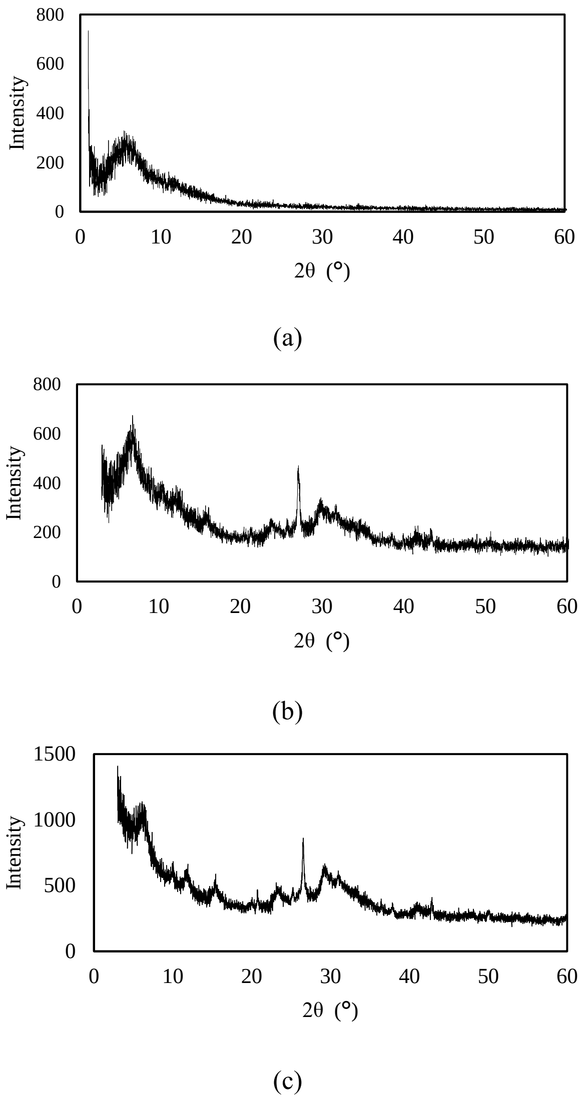


Fig. 11 XRD Analysis of Sample M80 at (a) 7 Days, (b) 14 Days, and (c) 28 Days

specific 2θ angle. This intensity is linked to the crystal structure and phase composition of the sample, where sharper and higher peaks generally indicate well-defined and abundant crystalline structures. If there is a broad hump instead of sharp peaks, it may be a result of the extensive presence of a highly disordered amorphous structure.

Silicate and alumina compounds in coal fly ash and metakaolin that exist in the form of glass could be dissolved in alkaline solution and form inorganic amorphous structures over coal fly ash and metakaolin particles. The results of XRD analyses shown in Fig. 11 indicate those amorphous structures in the porous geopolymer grout sample were detected as indicated by broad hump. The 5–10° and 28–32° 2θ broad humps of these geopolymer matrices indicated the presence of highly disorder amorphous structure in porous geopolymer grout samples. The notable increase in the intensity of these board humps with extended curing periods, suggesting that hydration products were continually generated. This phenomenon is indicative of ongoing chemical reactions within the geopolymer matrix, contributing to the formation of inorganic amorphous structures that enhances the overall mechanical properties of porous grout geopolymer samples.

The observation of a growing number of broad humps within the XRD analysis further signifies that the porous geopolymer grout is developing a higher amorphous content over time. The presence of amorphous phases is particularly advantageous in geopolymer materials, as they tend to be more reactive than their crystalline counterparts. As a result, the continuous generation of hydration products contributes to the development of a robust and interconnected network within the grout, ultimately enhancing its compressive strength.

4. Conclusions

In conclusion, the research demonstrated that porous geopolymer cement grout, tailored for soil grouting applications, can meet the dual objectives of achieving necessary strength and simulating soil permeability. Geopolymer production generates substantially lower CO_2 emissions due to the absence of high-temperature clinker production, which is a major contributor to greenhouse gas emissions in traditional cement manufacturing. Thus, implementing geopolymer grouts as a replacement for conventional cement-based grouts can contribute to sustainable construction practices, reducing the environmental impact associated with soil stabilization and infrastructure projects. The use of Class F fly ash and metakaolin as aluminosilicate sources, along with sodium hydroxide and sodium silicate as activators, resulted in effective geopolymerization. The inclusion of metakaolin significantly improved the compressive strength due to its smaller particle size, which enhanced dissolution and the formation of a denser geopolymer matrix. The experiments revealed that a higher molarity of sodium silicate led to increased compressive strength by promoting a lower water-to-solid ratio and improving the density of the porous geopolymer grout sample.

Conversely, an increased concentration of hydrogen peroxide resulted in higher porosity but reduced compressive strength due to the formation of gas bubbles during curing. A clear inverse relationship between porosity and compressive strength was observed, with higher porosity leading to decreased material strength. However, the ability to control porosity through foaming techniques and molarity adjustments highlights the material's versatility. The findings suggest that by adjusting the aluminosilicate composition, sodium silicate molarity, and foaming agent content, it is possible to create geopolymer grouts with a wide range of compressive strengths and porosity levels, making the material adaptable for various soil stabilization needs.

All metakaolin-based samples achieved the required compressive strength for grouting applications at 28 days, irrespective of hydrogen peroxide content or sodium hydroxide molarity. In contrast, among the fly ash-only samples, only those without hydrogen peroxide met the strength criteria. Samples M50, M51, M80, and M81 exhibited porosity levels within the range associated with well-graded sands, while M50 also aligned with the porosity of gravel. Additionally, M51 and M81 demonstrated porosity values suitable for application in inorganic clays. Samples M50, M51, M52, M81, and M82 met the porosity requirements for soils classified as uniform inorganic silts.

Moreover, XRD analysis confirmed ongoing chemical reactions and increasing amorphous geopolymeric microstructure within the geopolymer matrix over time, contributing to enhanced mechanical properties. These results underscore the potential of porous geopolymer cement as a sustainable alternative to conventional Portland cement-based grouts, offering both environmental benefits and the ability to tailor mechanical properties for specific grouting applications.

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