THE INNOVATIVE FIBER REINFORCED GEOPOLYMER FLY ASH-BASED GEOPOLYMER IN LOOSE SAND STABILIZATION

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ABSTRACT

Geopolymer (GP) has recently emerged as a new and environmentally friendly alternative to standard soil stabilization agents such as lime and Ordinary Portland Cement (OPC) to reduce environmental concerns. The addition of fibers to treated soil limits crack propagation, enhancing its strength even further. This study used high calcium class C fly ash (CFA) reacted with 10 M NaOH as a geopolymer (GP) binder to treat weak sand soil. Polypropylene (PP) fibers with a length of 4.5 mm were used as reinforcement in amounts ranging from 0.3 to 1.5%. Microstructure and unconfined compressive strength (UCS) testing were performed on the generated specimens. The study proved the benefits of fiber inclusion in improving the mechanical behavior of the treated weak soil. Superior strength characteristics were observed in GP-treated soil mixes with a binder content of 20% and an Activator/Binder (A/B) ratio of 0.4 reinforced with 1.5% PP fibers by weight, indicating that they can be used as a sustainable alternative to traditional binders in deep soil mixing applications.

KEYWORDS

Sustainable material, Fiber, Geotechnical application, geopolymer, soil stabilization, SEM

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1. INTRODUCTION

Weak soils are found in many parts of the world and are distinguished by high natural water content combined with poor shear strength, making them unsuitable for supporting civil engineering constructions. (Han, 2015). However, Because of the significant economic activity in such places, substantial infrastructure such as multi-story buildings will be developed atop such deposits. (Porbaha, 1998). Chemical treatment with conventional binders can improve several significant engineering properties of soils (e.g., lime and cement). The carbon footprint of such binders has raised considerable environmental concerns during the last decade. The production of ordinary Portland cement (OPC) is expected to produce 7% of artificial CO2. (Pacheco-Torgal et al., 2014). With this possibility of emissions and the other unavoidable environmental disadvantages of nonrenewable raw materials, there is a motivation to find more environmentally cost-effective and friendly alternative binders to replace OPC. As a result, recycling process materials derived from aluminosilicate industrial wastes and alkali-activated cement have been prioritized. (Davidovits, 2008). Geopolymers (GP) are cementitious binders made from amorphous (Si and Al) industrial wastes such as fly ash (FA) and metakaolin (MK) and alkaline activators such as potassium/sodium silicate or hydroxide. (Singhi et al., 2016). Geopolymerization is a four-step chemical reaction that begins with ion dissolution, then moves on to diffusion, gel formation by polymerizing Si and Al compounds with an activator, and gel hardening. (M. Zhang et al., 2013a). GP can have outstanding mechanical qualities such as high strength, low permeability, long durability, and insignificant volume variations depending on the synthesis circumstances. (van Deventer & Xu, 2002). However, it may be affected by the rate of the source material, the chemical qualities of the activator, the temperature, and the curing period. The mechanics of GP. The most difficult aspect is implementing the curing temperature in the field. (van Deventer & Xu, 2002; M. Zhang et al., 2013a). Because they are processed at 60-90°C, most GP can only be utilized in dry heat-cured or steamed concrete. (Gianoncelli et al., 2013). Because treating GPs at high temperatures is impractical, geotechnical engineering uses them at room temperature. Since geopolymerization is slower at low temperatures, GP-soil has lower impact strength and takes longer to impact than cement-treated soil. (Cristelo et al., 2012a). Thus, in comparison to cement, FA-based GP requires higher activator concentrations to be appropriate for soil stabilization. The bulk activator content, on the other hand, raises the cost of this stabilization approach. (Bernal & Provis, 2014). Formerly, class F fly ash (FFA) from bituminous coal combustion was used in the FA GP study. (Phair & van Deventer, 2002). This work used FA with a high Ca concentration to increase GP reactivity and decrease activator ratio (i.e., cost-effectiveness) while retaining satisfactory room temperature curing. The calcium content of FFA and class C fly ash differs the most (CFA). Both are composed of silica and alumina. CFA is made up of GGBFS and FFA. (Duxson & Provis, 2008). Because GGBFS and FFA combinations are chosen for GP manufacturing, CFA can produce them. Brittle failure was seen in the stabilized soil as the GGBS-based geopolymer dosage was raised. (Sargent, 2015). Furthermore, the shrinkage characteristics of slag-geopolymer stabilized soil are several orders of magnitude greater than those of cement. (Collins & Sanjayan, 2001), This may limit its ability to deal with failure. As a result, reinforcing the treated soil with fibers enhances mechanical performance by minimizing crack development. (Aydın & Baradan, 2013; Syed et al., 2020). Many studies in the last decade demonstrated that introducing Polypropylene (PP) fibers into soil improves strength and ductility. (Freitag, 1986; Gaspard et al., 2003; Syed et al., 2020; L. Zhang et al., 2008; Ziegler et al., 1998) As a result, Reinforcing the CFA geopolymer with discrete PP fibers could be a feasible solution/alternative for increasing engineering properties like toughness and ductility. (Syed et al., 2020). Soil stabilization with CFA-based geopolymers and fiber addition has received minimal attention in the literature. As a result, a complete examination of the mechanical and durability performance of Fiber Reinforced Geopolymer (CFA-GP) with PP fibers in DSM technology is necessary, as disclosed in this work.

2. MATERIALS

Soil, fly ash class C, activator, and fiber were the primary ingredients in this investigation.

2.1. SOIL

The soil utilized in this study was locally available sand. Table 1 Its physical properties were summarized, including grain size distribution, Specific gravity, voids ratio, relative density (RD), maximum and minimum dry density, and angle of internal friction. The Unified Soil Classification System classifies this sand as (poorly graded) SP (USCS), as shown in Figure 1.

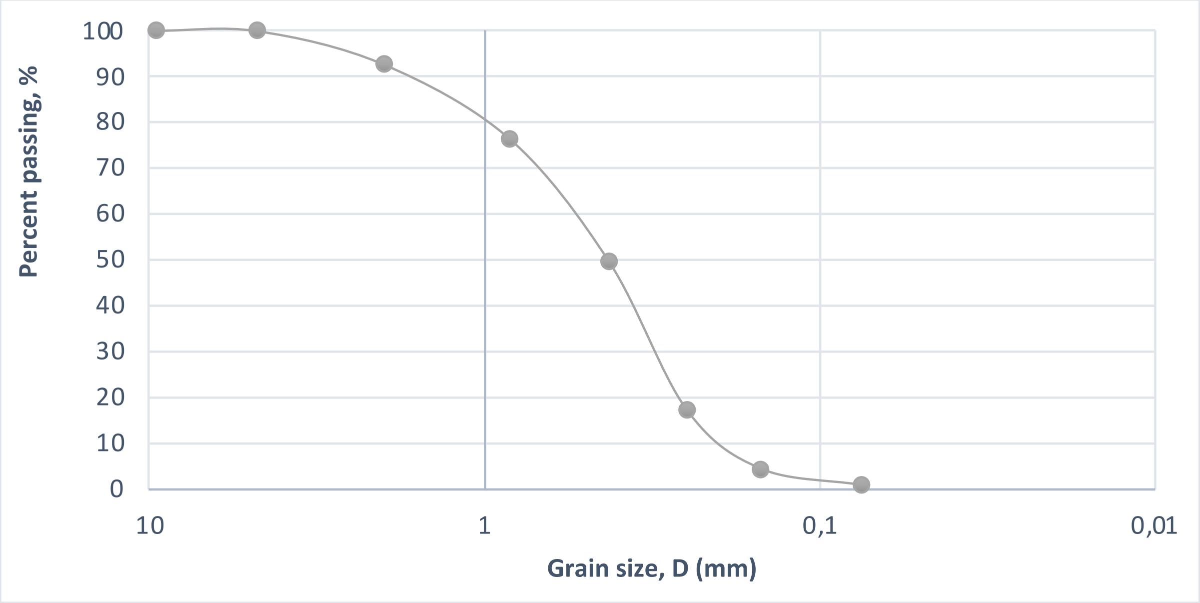

Figure 1. Grain size distribution of sand soil

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Table 1. The physical properties of sand soil

Soil property	Standard	Value
Coefficient of uniformity (cu)	ASTM D 422	2.75
Coefficient of curvature (cc)		0.81
Mean effective diameter (D50)		443
Specific gravity (Gs)	ASTM D 854-00	2.65
Maximum dry density (gm/cm³)	ASTM D 4253	1.703
Minimum void ratio		558
Minimum dry density (gm/cm³)	ASTM D 4254	1.357
Maximum void ratio		0.84
Internal friction angle φ	ASTM D 3080	36
Relative density	---------------	50

2.2. FLY ASH

Local fly ash was used in this investigation, which was supplied by the Nasiriya power generating facility as a byproduct waste material generated during the generation of electricity. Figure 2 depicts a picture of fly ash and the particle distribution as determined by the hydrometer test

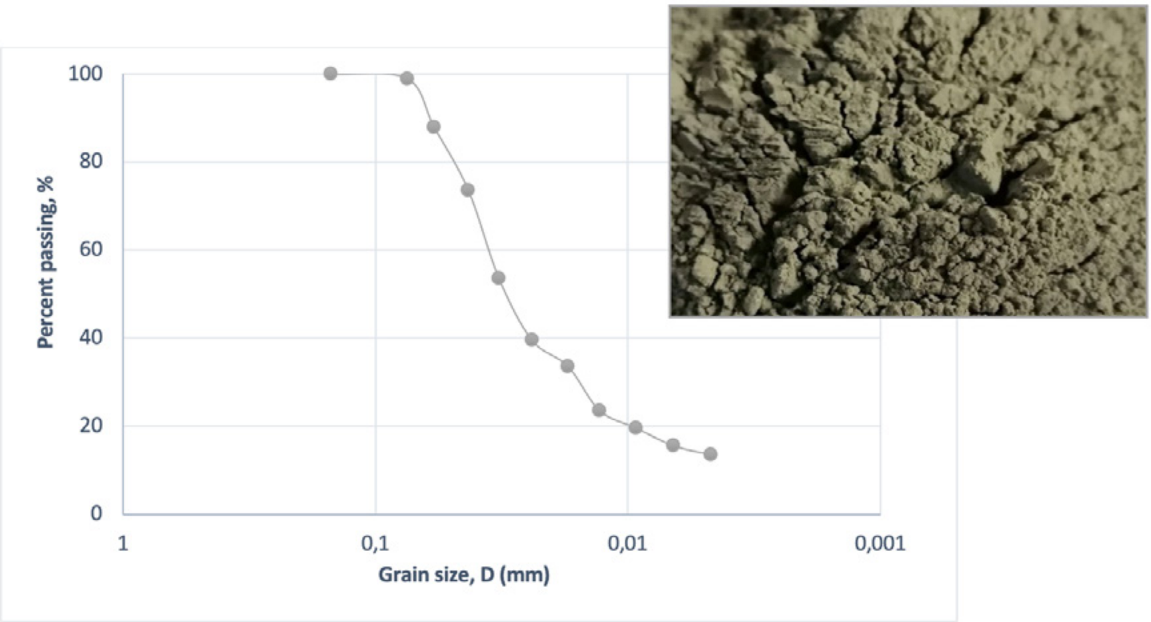

Figure 2. The particle size distribution curve of fly ash

2.3. ALKALI ACTIVATOR

In this work, sodium silicate and sodium hydroxide (NaOH) were employed to make the alkaline activator solution since they were less expensive and more readily accessible than a potassium-based solution. Moreover, NaOH has a high ability to release silicate and aluminate monomers. 98 percent pure sodium hydroxide pellets were acquired. Sodium silicate was bought in liquid form. A precise amount of sodium hydroxide pellets was dissolved in distilled water to make a NaOH solution. Throughout the investigation, the molarity of the NaOH solution was held constant at 10 M. The solution's molarity was obtained by dissolving 400 grams of NaOH pellets in one liter of distilled water. In this investigation, the weight ratio of sodium silicate to sodium hydroxide was 2.0.

2.4. FIBER

Commercially available fiberglass was used in this study, as shown in Figure 3.

Table 2 illustrates some of its properties.

Table 2. Fiberglass properties

Properties	Value
Length (mm)	4.5
Diameter (µm)	10
Strength (MPa)	650

Figure 3. Used Fiber

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3. METHODOLOGY

3.1. COMPRESSIVE STRENGTH (UCS)

To study the compressive strength of geopolymer-treated soils, a series of unconfined compressive strength tests were performed on treated samples that had been cured for 28 days. The UCS test samples were manufactured from 50 mm diameter and 100 mm height (PVC) cylindrical split tubes with a height-to-diameter aspect ratio of 2:1. This sort of plastic mold has been recommended by several researchers because it is more resistant to the alkali mixture. A longitudinal incision was made to ease sample extraction. Before compaction, the mold was constrained by three stainless steel clamps to avoid volumetric expansion produced by compaction and movement.

A compressive strength test was performed on treated soil specimens using a uniaxial machine with a loading capacity of 50 kN by (ASTM D1633-00, 2007) as eq (1). The applied load and consequent displacements were determined using a load cell and a Linear Variable Displacement Transducer (LVDT). The displacement rate for all UCS tests was 0.1 mm per minute. Table 3 depicted the details of the samples.

$$UCS = \frac{P}{A} \tag{1}$$

where P = applied load (N) and A = cross sectional area of specimens (mm2).

3.2. FLEXURAL STRENGTH (FS)

Three-point bending tests were performed on specimens according to ASTM 1635/ D1635M-19, 2019, using an ARD-Auto flexural testing machine with a loading capacity of 50 kN to investigate the flexural strength of the geopolymer-treated soil. Samples with 35 x 35 x 130 mm dimensions were processed in rectangle molds. The resulting displacements were measured using an LVDT. The load and its corresponding displacement were recorded at a given time offset period. The flexural strength of samples was calculated using the equation below:

$$\mathrm{Fs}_s = \frac{3Pl}{2bh^2} \tag{2}$$

Where FS is flexural strength (MPa),

- P is the breaking load (N).
- l is the span of the simple supports (mm).
- b is the width of the specimen (mm).
- h is the thickness of the specimen (mm)

Table 3. Details of samples

Mixture No.	Mixture ID*	Fly ash (%)	Activator/Fly ash (A/FA)	Fiber (%)
1	M (f0.25)	20	0.4	0.25
2	M (f0.5)			0.5
3	M (f0.75)			0.75
4	M (f1.25)			1.25
5	M (f1.5)			1.5

*The combinations were identified using M(*f*). The letter M is a shortened version of the word "Mixture," followed by the ratio (fiber), denoted by brackets.

3.3. MICROSTRUCTURE ANALYSIS

Field Emission Scanning Electron Microscope (FESEM) with Energy-Dispersive Spectrometer was used to evaluate the microstructure samples (EDS). That test was carried out using small prepared samples collected from UCS samples.

4. RESULTS AND DISCUSSIONS

4.1. COMPRESSIVE STRENGTH

The key factor influencing the efficiency of a fly-ash-based geopolymer as a binder is temperature. The effects of fiber ratios on soil stabilization were investigated to identify a viable geopolymer mixture for soil stabilization and to evaluate the dependability of employing these new binders in weak soil stabilization. The unconfined compressive strength (UCS) test was chosen according to the methodology to investigate the degree of reactivity of different geopolymer content fiber components in treated soils.

To examine the influence of fiber inclusion on soil-geopolymer strength behavior, the UCS of treated fibers of the geopolymer-soil was tested using different fiber ratios (0,0.25, 0.5, 0.75, 1,1.25, and 1.5%). The UCS of geopolymer-treated fibers was determined for the above fiber ratios (1.85,2.15,2.3,2.55,2.62,2.75, and 2.81) MPa.

From Figure 4 the UCS of the specimens has improved with an increase in fiber content from 0% to 1.5%. The increased strength can be due to the uniform distribution of fibers throughout the treated soil matrix, which reduced the formation of micro-cracks under loading. This could be attributable to an increase in ductility of the treated samples as the fiber content increases. Among the various fiber contents tested, the treated specimens reinforced with 1.5% fiber content had the highest ductility. Figure 5 shows that at (0.25, 0.5, 0.75, 1, 1.25, 1.5%) fiber content, the treated fibers reinforced geopolymer-earth resulted in an approximate 116, 124, 137,141, 148, and 152% increase in UCS compared to untreated fibers. Although increasing the treated fiber ratios increased UCS, the rate of improvement became slower after (0.75) fiber ratio. As a result, it is approved for use in the soil remediation process.

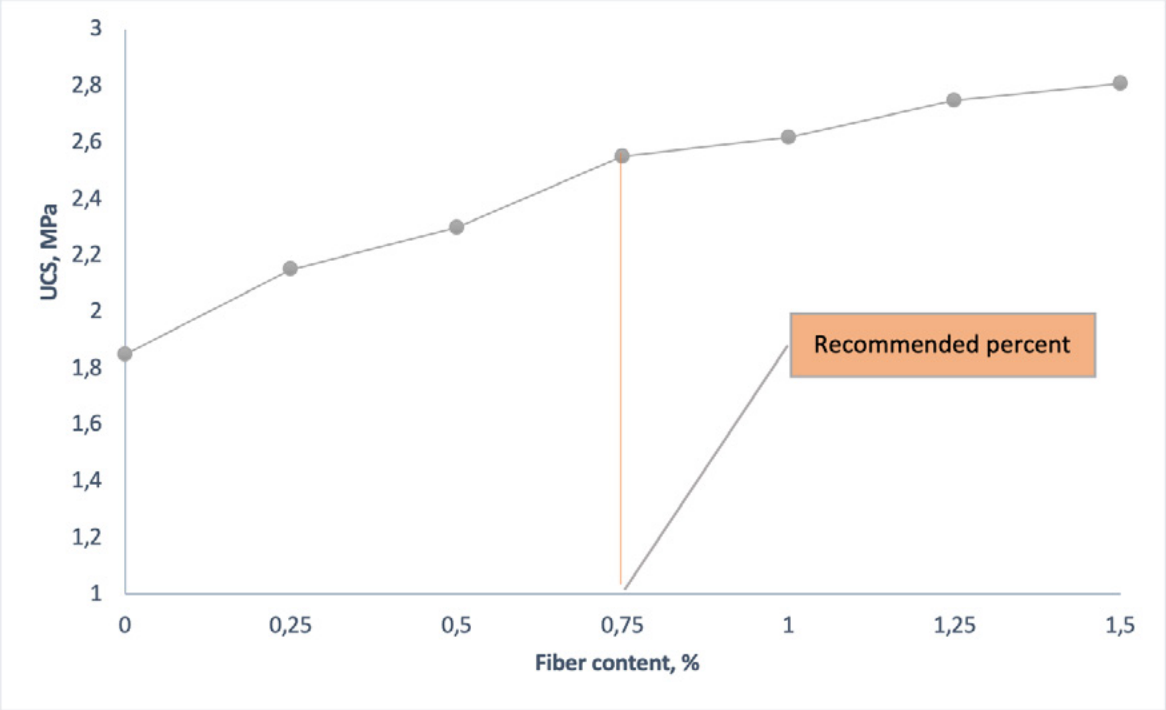

Figure 4. UCS values of fiber-reinforced specimens treated at geopolymer content (20%FA and 0.4 A/F)

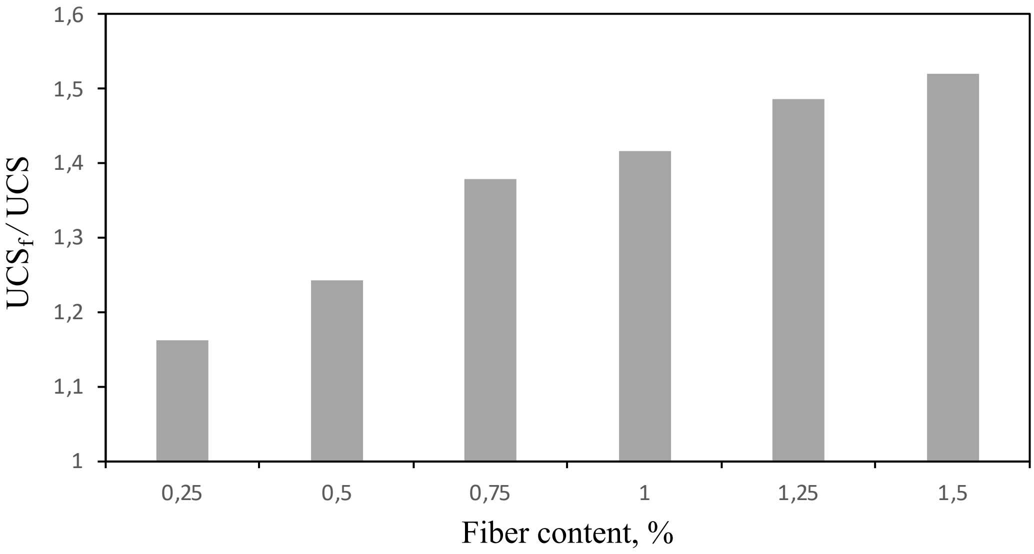

Figure 5. Variation UCS for treated and untreated fibers reinforced geopolymer- soil at the different fiber content

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4.2. FLEXURAL STRENGTH

Beams of geopolymerized loose sand based on the selected ratio of fly ash 20% and A/F 0.4 were tested to investigate the flexural strength considering six different percentages of fiber content (0.25, 0.5, 0.75, 1, 1.25, and 1.5).

Figure 6 showed the variation between the flexural strength and the fiber content. Fiber content has an important role in increasing flexural strength. For example, with increasing fiber content from 0% to 0.25, 0.5, 0.75, 1, 1.25, and 1.5%, the flexural strength increased from 0.22 MPa for unreinforced sand to 0.27, 0.37, 0.56, 0.63, 0.67, and 0.72 MPa respectively. This means that the flexural strength increased by 122, 168, 254, 286, 304, and 327% respectively compared with the unreinforced geopolymerized sand. These observations are in line with the results reported by (Sakthivel et al., 2019; Sukontasukkul & Jamsawang, 2012).

When the untreated soil beam was exposed to flexural loading, just as concrete, there was a tendency for flexural stress to develop, leading to fracture when the soil carrying capacity was exceeded. The load developed approximately linearly with the deflection until fracture. Finally, failure occurred when a fracture developed at the bottom of the beam owing to stress. With the existence of fibers as reinforcements, the external load could be transferred to such fibers through the interfacial bonding between the fibers and the geopolymer soil matrix. Treated fibers were able to restrain the crack propagation and traverse across the cracks to transfer internal force, and the fibers and the geopolymer soil matrix sustain a higher load.

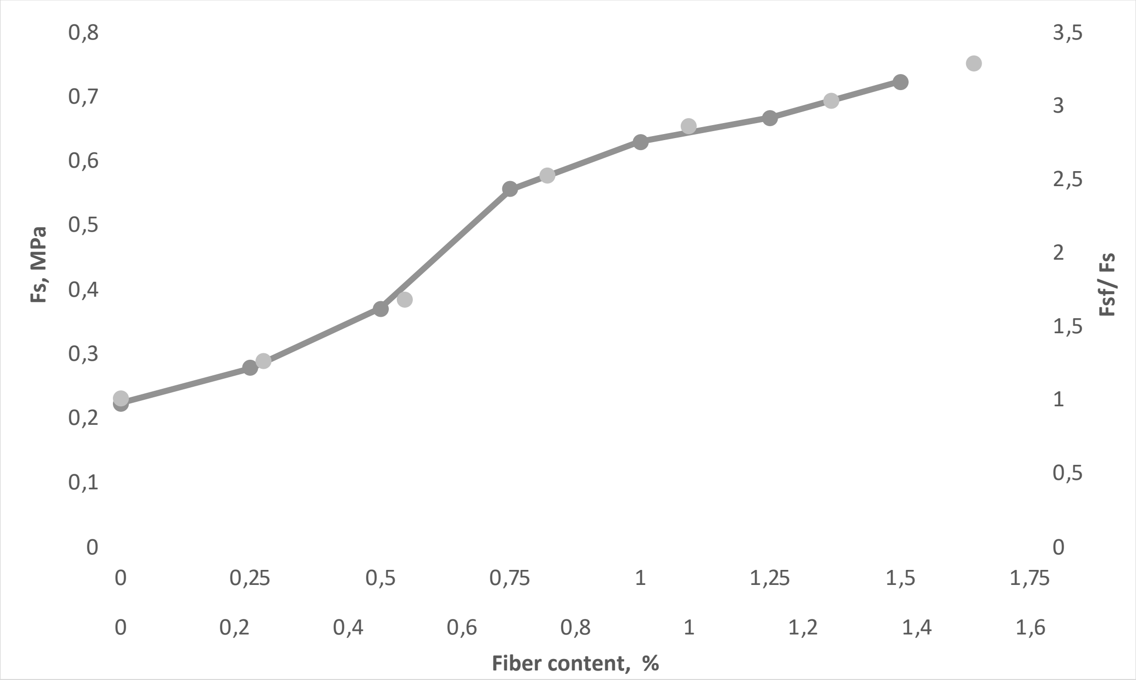

Figure 6. Flexural strength values for different fiber content samples

4.3. SEM OF GEOPOLYMER STABILIZED SOIL

The compact, stable structures of geopolymer-treated samples improved engineering properties. This primary reinforcement is caused by industrial soil bonding reinforcement materials. In geopolymer, an alkaline media dissolves silica and alumina oxides from fly-ash particles, creating Sodium Aluminum Silicate Hydrate (N-A-S-H), which hardens and cement soil particles. (Cristelo, Glendinning, Miranda, et al., 2012b; Phummiphan et al., 2016). Figure 7 shows an SEM analysis of a soil-geopolymer sample with 20% fly ash and a ratio of activator/fly ash (0.4). A higher fly ash ratio increases dissolution rate and binding activity, resulting in the most compact form. (Figure 7). Typically, fly ash gaps carved by silica and aluminum breakdown are filled by smaller particles and cementitious products, forming a thick matrix. This technique modifies the soil structure and strengthens the treated soil., similar to geosynthetic soil research (Abdullah et al., 2019; Cristelo et al., 2013; M. Zhang et al., 2013b).

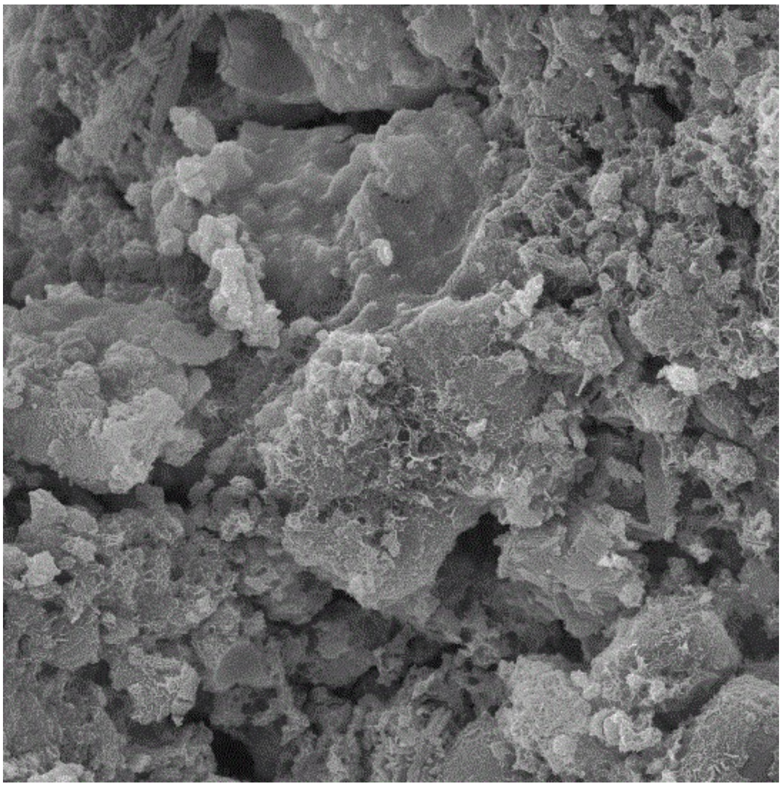

Figure 7. SEM images of geopolymer sample (20% fly ash, 0.4 activator)

5. CONCLUSIONS

1. In the first stage of this work, UCS tests on treated specimens were used to assess the strength and stiffness improvement of sand soil treated with various combinations of fly-ash, activator, and/or fiber. The effect of the fiber-to-fly ash ratio was the major variable explored here. The addition of fiber greatly

improved the strength and stiffness characteristics of soil treated with fly ash-based geopolymer. According to the findings of the studies, the ideal fiber ratio for sand soil was 1.5%.

2. The increase in flexural strength values follows the same pattern as the increase in compressive strength. When the fiber content was increased, the flexural strength increased. Flexural strength increases from 0.22 MPa to 0.72 MPa when fiber content increases from 0% to 1.5%.

3. The cementitious products on the fly ash surfaces are observed in FESEM analysis, indicating a geopolymerization response. The etched holes in fly ash surfaces created by silica and aluminum breakdown are generally filled with smaller particles, resulting in a thick matrix.

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