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Implementation of geopolymer for stabilizing granular soil

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Abstract. River sand, despite being an available material, a low-cost, but loose sandy soil, cannot be used as a construction material in civil engineering works due to its poor grain size distribution and low bearing capacity. Geopolymer is recently considered a novel eco-friendly alternative to conventional soil enhancement and stabilization materials, such as ordinary Portland cement (OPC) and lime, which harm the environment in terms of high CO_2 emissions and energy consumption. Hence, this study investigated the potential strengthening of loose sandy soil using geopolymer. Different alkaline activator (AA) solution ratios were used with varying curing temperatures for producing the river-sand geopolymer. The river sand-geopolymer specimens were matured in the oven at different temperatures for 48 hours. A series of unconfined compressive strength (UCS) tests were carried out on the 3, 7, 14, and 28 days of curing. The results show that the UCS of the river-sand geopolymer matrix significantly increased with increasing the main ingredient of its activator solution (sodium silicate) as well as the temperature. The UCS reached 13.42 MPa when the AA solution ratio was 0, whereas it decreased up to 1.15 MPa when the AA solution ratio became 1.5 at a temperature of 60 °C and 28 days of curing. Therefore, geopolymer is feasible and sustainable material to improve problematic soil for different applications.

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1. Introduction

River sands, or loose sand, are cohesion-less soils that have a consistent and uniform dispersion of particles with no sharp edges. They are classified as poorly graded. The material's gradation characteristics pose substantial challenges when employed for construction projects, such as the construction of road and railway embankments or fills. Moreover, the compaction of this material presents significant challenges because its compaction curves have no clearly defined ideal moisture content. At very low moisture content, a minimum dry density value may be observed [1].

Furthermore, the load-bearing capacity of on-site river sand is generally insufficient for most geotechnical engineering applications. Therefore, it is necessary to utilize alternate materials. The use of alternative materials is sometimes impossible since there are no suitable alternative materials available on-site. Therefore, several techniques for enhancing soil quality and optimizing its workability for engineering applications can be investigated. Apply material processing procedures to improve the geotechnical characteristics of the flawed soil, such as durability, resistance to erosion, compressibility, permeability, physical qualities, and mechanical properties [2]. Soil stabilization refers to the method of improving the physical or chemical characteristics of soil. Techniques including mechanical compaction and the use of calcium-rich compounds can achieve this [3]. In the last three decades, notable advancements have been made in developing and broadly adopting different ground stabilization techniques in industrial projects [4]. Recycling crushed concrete is a sustainable way to improve soft soils' chemical and geotechnical properties

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[5]. Numerous techniques, such as mechanical stabilization (stone columns, preloading, dynamic compaction, or vibroflotation), chemical stabilization (using ordinary Portland cement (OPC), cement kiln dust (CKD), or lime), or geotextile stabilization have been used to improve the characteristics of weak soil [6]. The process of stabilizing weak soil generally involves chemical treatment, which requires chemical binders like OPC [7, 8]. Conventional soil stabilizers, such as cement and lime, undergo thermal breakdown of calcium carbonate found in limestone during production. This process leads to significant emissions of greenhouse gases and energy. Manufacturing each ton of cement leads to the release of about ton of carbon dioxide. The global production of CO_2 amounts to around 1 %, with an average emission of 0.95 tons of CO_2 per 1 ton of lime processing [9, 10]. The method necessitates a substantial amount of energy to sustain the elevated temperatures necessary for the manufacture of OPC, which range from 450 to 1550 °C, as well as temperatures between 100 and 1000 °C for lime production. During cement manufacturing, the raw ingredients are rapidly exhausted. According to the report, the production of 2 billion tons of cement necessitates over 3 billion tons of raw materials, with limestone accounting for 70 % of the total [11].

Therefore, it is necessary to develop innovative soil stabilizers that may function as a viable and ecologically sustainable alternative to cement in many civil engineering projects. The advancements in geopolymerization have gained significant attention as a feasible substitute for handling solid waste and by-products. These developments provide a sophisticated and economical method for dealing with various problems, especially those related to the treatment and storage of hazardous waste in environmentally sensitive circumstances [12]. The term geopolymer was initially coined in the 1970s to describe inorganic alkaline aluminosilicate-activated materials [13, 14]. This compound's synthesis occurs at ambient or slightly higher temperatures, utilizing raw materials rich in alumina and silica, such as fly ash (FA), slag, metakaolin, and calcined clay, in the presence of alkaline activators (AA). Geopolymers are becoming increasingly attractive as an alternative to soil stabilization due to their ability to address the environmental issues connected with traditional binders by producing less quantities of CO_2 during the stabilization process. On average, producing one 1 of geopolymer generates a mere 0.19 to 0.24 tons of CO_2 emissions and moderately affects global warming [15].The researcher investigated using geopolymers, specifically sodium-based AAs and FA class F, to stabilize sandy clay soil.

Cristelo et. al. [16] studied involved a comparison with a binder that is based on cement. The ratio of activators to FA (A/FA) ranged from 1 to 2.5, whereas the ratio of FA varied between 20, 30, and 40 % of the total solids. Unconfined compressive strength (UCS) samples were created and tested after curing for 7, 28, 90, and 365 days. The results showed a significant improvement in strength when using a lower A/FA ratio, leading to a 43.4 MPa rise after 365 days of curing. The UCS results of the cement and geopolymer samples showed a significant resemblance after 28 days of curing [16]. Geopolymer treatment significantly improved the properties of medium and high plastic soils in a separate investigation. The UCS of the medium plastic soils, which included 5 % of FA, was 1.0 MPa. The pressure later rose to 2.6 MPa when the FA level was raised to 25 %. However, the UCS did not experience any changes due to the inclusion of up to 20 % FA in high plastic soil. But when the concentration of FA reached 30 %, the UCS exhibited a substantial and rapid increase of 400 % [17]. Moreover, the strength of soft soil experienced a substantial enhancement with the application of a geopolymer consisting of granulated blast furnace slag (GBFS) and basic oxygen furnace slag (BOFS). It was shown that exposing samples to temperatures between 20 and 45 °C resulted in a 42 time increase in the UCS compared to untreated soil [18]. Other researchers had utilized the geopolymer that was derived from ground-GBFS as an environmentally friendly alternative to cement in deep soil mixing applications. Their study analysed the cement-treated specimens vs. GGBS-based geopolymer samples. The analysis considered the varying levels of GGBS content, ranging from 10 to 30 %, and the activator ratio, which ranged from 0.5 to 1.0. The results showed that specimens treated with geopolymer had a greater UCS compared to those treated with cement at the exact dosage, except for the mixture with an Alkaline/Binder (A/B) ratio of 0.5; this is a consequence of the development of increased pozzolanic and geopolymeric mechanisms [19].

For silty sand soil type, Rios et al. [20] examined the characteristics of stabilized this soil type using alkali-activated cement. The researchers employed sodium hydroxide (SH) (NaOH) and sodium silicate (SS) (Na_2SiO_3) as the alkali activator solution and FA as the precursor material. The strength and stiffness tests reveal substantial enhancement beyond the 28 days of the curing process, although the short-term strength was deemed sufficient. Recent research suggests that its capacity to endure immersion and wetting-drying cycles is consistent with the existing standards for soil cement, thereby supporting its potential as a viable alternative to soil cement. In the study conducted by Hai-yan et al. [21], a geopolymer was synthesized through the combination of alkali-activated saline soil with FA, resulting in the development of environmentally sustainable construction materials. The researchers observed that the mixing of saline soil with FA resulted in enhanced mechanical and physical properties, as well as increased durability. The aforementioned attributes are further augmented as the percentage of FA rises from 20 to 60 %. Based on the findings of the study, it has been determined that the most optimal parameters for the dissolution of

SiO_2 and Al_2O_3 involve the utilization of a 5 M NaOH solution at a temperature of 60 °C over a period of 24 hours. Moreover, the use of FA significantly improves water's resilience and resistance to permeation. Their investigation uncovered that exclusively stimulating saline soil as a precursor has restricted advantages. Adding extra chemical components like alumina and silica to the product is required to get the desired characteristics [21]. The use of FA-based geopolymer as an additive in organic soils is advantageous due to its strong bonding properties, resulting in enhanced strength and long-term stability [22]. The use of FA-based geopolymer significantly increases the stiffness of soil-reclaimed asphalt pavement-fly ash (soil-RAP-FA) mixtures, with higher FA content leading to higher equivalent modulus M_{equ} [23]. The loose sand geopolymer matrix's, USC showed a significant increase within the range when the main ingredient of the geopolymer, i.e., FA, was increased. The compressive strength of the soil-geopolymer matrix was observed to increase when the FA content was 5–15 % but decreased when the FA content was 20–30 % [24]. Geopolymer, like Rafsangan natural pozzolan, CKD, and an activator, such as calcium carbide residue or NaOH, were combined to stabilize sandy soil with poor grading. The research showed that the addition of CKD and NaOH considerably improved the UCS of the soil samples [25].

Most literature, as per our knowledge, that dealt with enhancing soil characteristics or improving its stabilization conditions by applying an alkali-geopolymer approach has an inevitable need for adding fine materials enriched with alumina and silica like FA, furnace slag, etc. Despite the growing interest in using geopolymer as sustainable materials, there is a lack of studies on their application in the field of geotechnical aspects. Therefore, this work investigated the feasibility of employing geopolymer for geotechnical stabilization of loose sandy soil as an alternative to cement, lime, or any other pozzlanic additives. The river sand soil has many pozzolanic chemical components, including silica and alumina, which make it an excellent raw material for geopolymer. This study investigated the impact of mixing river sand with varied proportions of AA solution ratios at varied temperatures on the UCS at different curing times. The aim of this work is to develop a substance that increases soil particles' adhesion and solidity (i.e., enhances its geotechnical characteristics). The produced substances might be utilized as a building material in engineering applications and infrastructure projects, as well as for impeding the displacement of sand dunes. A thorough series of laboratory tests were conducted to evaluate the strength and stiffness of the geopolymer-loose sand matrix. In addition, the sand's microstructure enhancement was analysed using scanning electron microscopy (SEM).

2. *Material and Methods*

2.1. *Soil Properties*

The river sand-soil utilized in this work was obtained from a location near the Euphrates River within Ramadi city and classified as SP by unified soil classification system ASTM D2487-2017 [26]. Fig. 1 depicts the grain size distribution of the river sand-soil according to ASTM D422-2007 [27]. Table 1 gives a summary of the physical and chemical characteristics of the river sand soil. The chemical components of the river sand soil as identified by X-ray fluorescence analysis is showed in Table 2.

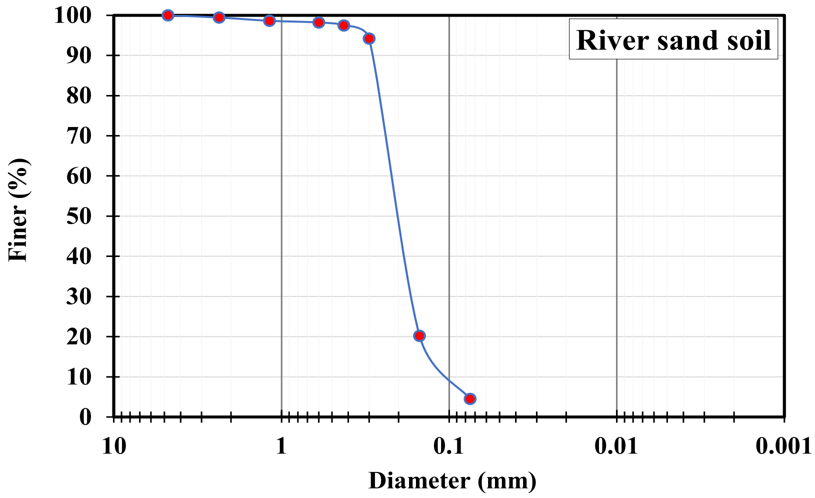

Figure 1. Grain size distribution curve of river sand.

Table 1. The properties and classification of river sand soil.

Soil property	Value
Specific gravity, G_s	2.7
Uniformity coefficient	2.3
Coefficient of curvature	1.25
D10 (mm)	0.1
D30 (mm)	0.17
D60 (mm)	0.23
Sand %	95.4
Silt & clay (%)	4.52
Plasticity	NP
pH	8
OC (%)	3.4

2.2. AA Solution

In this study, the activator used was a combination of SH and SS that was purchased from a local vendor in Baghdad. According to the product specifications, NaOH, used in the work was a white colored flake-like shell with 98 % purity, as obtained by the chemical analysis. It was characterized by its rapid dissolution in distilled water with continuous stirring. It has a molecular weight of 40 g/mol and this substance is preferred for producing geopolymer because of its abundance and higher alkalinity compared to other components. On the other hand, the specifications for SS indicate that it is in a liquid state and contains SiO_2 (32.5 %), Na_2O (13.4 %), and water (54 %). The materials are illustrated in Fig. 2.

Table 2. Chemical compositions of soil (X-ray fluorescence) analysis.

Chemical composition	Elemental Oxide
SiO_2	6.659
Al_2O_3	0.577
Fe_2O_3	4.681
Cao	7.165
K_2O	0.583
Na_2O	0.26
Mgo	0.117
SO_3	0.0005
MnO	0.0692
SiO_2	6.659

(a) (b) (c)

Figure 2. Materials: (a) Na_2SiO_3 (SS), (b) NaOH flakes (SH), c) river sand soil.

2.3. Compaction Test

Many laboratory tests were conducted to examine geopolymers made from river sand. The standard Proctor test, as outlined in ASTM D698-12 [28], determined the maximum unit weight and optimum moisture content (OMC) of the untreated river sand soil. Fig. 3 demonstrates that the maximum unit weight is 15.59 KN/m^3 and the OMC is 9.36 %. The moisture-density curve is not as distinct when compared to the compaction curve for cohesive soils. When compacting coarse-grained cohesionless soils (such as sands and gravels) using a standard or modified Proctor's technique, the shape formed is referred to as a humpback or camelback [29].

2.4. Sample Preparation

To create SH, 320 g of appropriate NaOH flakes were dissolved in 1 l of distilled water. The solution was mixed until it reached the desired 8 molarity (M) of concentration. It is important to note that when NaOH is added to water, it generates an exothermic reaction. Therefore, it is necessary to wait for a specific time before using the solution. This ensures that the solution does not generate heat during the mixing process, which could negatively affect its workability. To prepare the river sand geopolymer, the required amount of SS was added to the SH at least 2 hours prior its use. The amount of alkaline solution added to the dry materials was calculated based on the OMC percentage obtained from the standard Proctor test, which was approximately 9.34 %. The manufacture of the river sand-geopolymer involved the utilization of three different ratios of SH to SS (SH:SS). Additional 10 % of extra water was added to achieve the desired water content and suitable workability. Three ratios of SH:SS were used in the production of the river-sand geopolymer, these ratios of SH:SS were 0, 0.75, and 1.5 %.

The process began by combining the AA solution with dry river sand soil and stirring thoroughly for 6 to 10 min until a homogenous mixture was achieved. Table 3 provides a detailed description of the components used in the blend. The mixture was poured evenly in 3 layers into PVC molds, which were cylindrical with dimensions of 100 mm in height and 50 mm in diameter. A longitudinal incision was made on the side of the molds to make specimen extraction easier. The uppermost portions of each layer were scraped to ensure contact between the three levels. To achieve homogeneity among the three layers, a plastic rod was employed to remove any air bubbles or voids that may have formed during the pouring procedure. The entire mold was placed on a vibration plate to achieve densification. After vibrating, the specimens were cured in the oven at designated temperatures of 30, 45, and 60 °C for 48 hours. The specimens were extracted from the molds, enveloped in plastic sheets, and placed back in the oven at a temperature of 30 ° for curing until the time of testing. The UCS of each specimen was assessed at age of 3, 7, 14, and 28 days. In accordance with ASTM D2166-2006 [30], the UCS specimens were fabricated using cylindrical PVC tubes with a height-to-diameter (h:d) aspect ratio of 2:1, measuring 100:50 mm. A uniaxial machine with a loading capacity of 50 kN and a displacement rate of 0.1 mm/min was utilized to conduct the UCS test on the specimen.

The UCS may not be the best method to assess the bearing capacity of sandy soil because of its poor ability to sustain lateral pressure. This can be attributed to the lack of cohesion in the soil. As a result, the study lacks reference samples to compare with samples treated with an activated alkali solution.

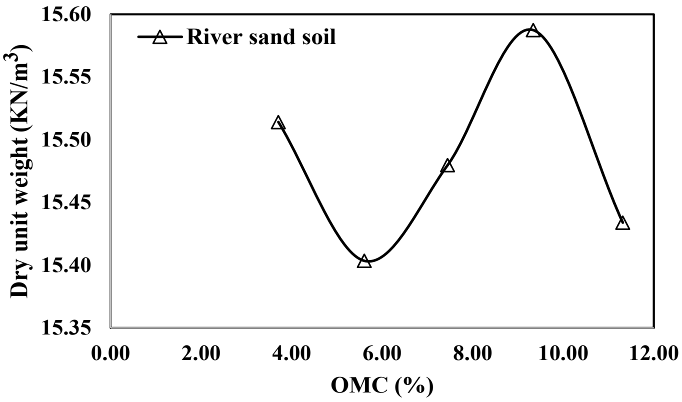

Figure 3. Compaction curve of river sand soil.

Table 3. Details of mixture used.

Sample	Soil (%)	AA	SH:SS	Temperature (°)
S-AA 0 T30°	100	0	0:100	30
S-AA 0 T45°	100	0	0:100	45
S-AA 0 T60°	100	0	0:100	60
S-AA 0.75 T30°	100	0.75	43:57	30
S-AA 0.75 T45°	100	0.75	43:57	45
S-AA 0.75 T60°	100	0.75	43:57	60
S-AA 1.5 T30°	100	1.5	60:40	30
S-AA 1.5 T45°	100	1.5	60:40	45
S-AA 1.5 T60°	100	1.5	60:40	60

Sample codes: SH:SS(SH = NaOH, SS= Na_2SO_3)

3. Results and Discussion

3.1. UCS

3.1.1. Effect of Curing Time of Soil –Geopolymer

The UCS of river sand-geopolymer tends to increase with the passing of time. This trend was observed across different temperatures and curing durations of 3, 7, 14, and 28 days for soil stabilization with AAs. Several researchers have found similar observations regarding the impact of cure time on geopolymer [18, 31–33] . In this study, the highest UCS values were recorded for stabilized soil specimens that had been incorporated with all ratios of AAs at different temperatures after 28 days of testing. For example, for an AA of SH:SS = 0:100 at 60°C, the UCS values increased from 5 to 13.42 MPa over a period of 28 days, with intermediate readings of 9 MPa at 7 days and 12.39 MPa at 14 days. This increasing trend was observed across all other mixtures as well. The strength of the geopolymer material increases over time, indicating a continuous build-up of bonding as the polymerization process progresses, as demonstrated in Fig. 4.

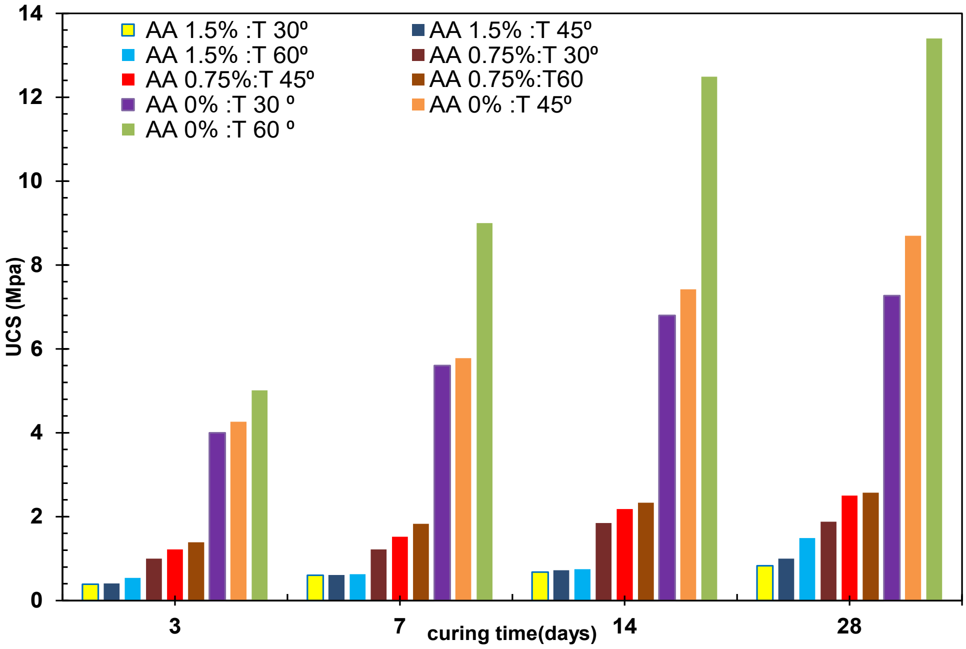

Figure 4. The effect of curing time on UCS of the river-sand geopolymer.

3.1.2. Effect of curing temperature of geopolymer

The UCS of stabilized soil mixed with an AA (river-sand geopolymer) improves significantly with an increase in the curing temperature. Many researchers have also studied the effect of temperature on geopolymers [18, 31–33]. The observed enhancement in strength with increasing curing temperature can be attributed to the dehydroxylation, disintegration, and polycondensation mechanisms of the aluminosilicate polymer that take place between the soil-precursor particles and the alkaline solution. The present investigation provides confirmation that elevated curing temperatures have a positive impact on the dissolution of aluminosilicate, resulting in a homogeneous dispersion of gel formation. This results in a bridging of the gaps between interface transition zones and an increase in compressive strength as in the previous studies [34,35] , as shown in Fig. 5. For example, the UCS of mixture AA of SH:SS = 0:100 increased from 6.81 to 8.69 and 12.39 MPa with increasing curing temperature from 30 to 45 and 60 °C, respectively. Thus, higher temperatures enhanced the effectiveness of dissolving features in aluminosilicate precursors, which could explain the significant increase in strength [36].

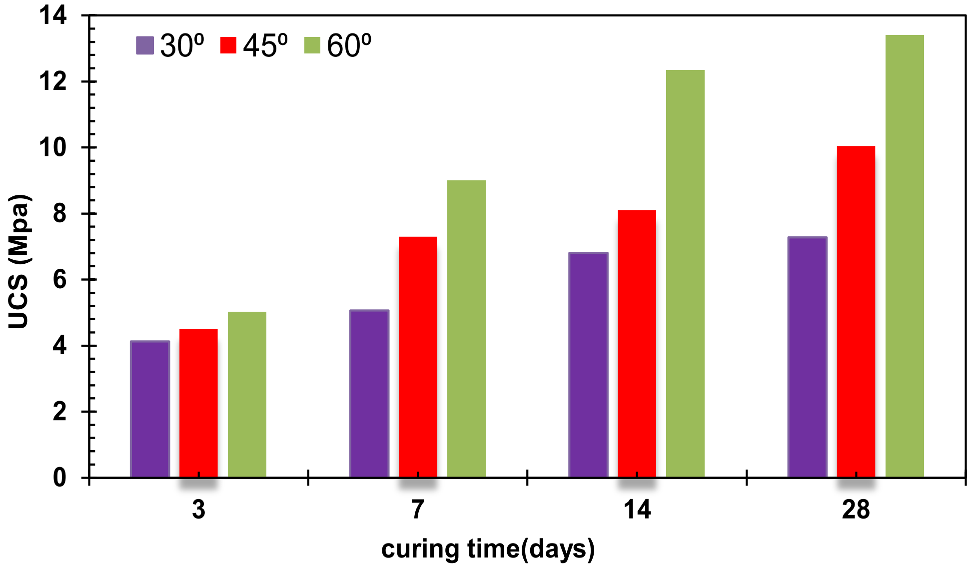

Figure 5. Effect of temperature on UCS of the river-sand geopolymer.

3.1.3. Effect of AA ratio of geopolymer

The type of activator, the ratio of SH: SS, immediately affect the UCS value of stabilized soil. The AA solution is prepared mixed from SH with SS. The solution of SH with 8 M concentration and the ratio of SH:SS 0, 0.75, and 1.5 % was used. Moreover, in this study, the AA ratio (SH:SS = 0:100) gives the highest UCS value at 28 days and 60 °C of curing as shown in Fig. 6. Soluble silica increases the condensation activity and promotes the growth of more silica in the polymeric chain, hence enhancing its strength characteristics [37, 38]. Increasing the activator content resulted in an increase in the leaching of silicon and aluminium from amorphous phase in river-sand geopolymer. The strength geopolymer materials prepared by SS was improved at room temperature [39].

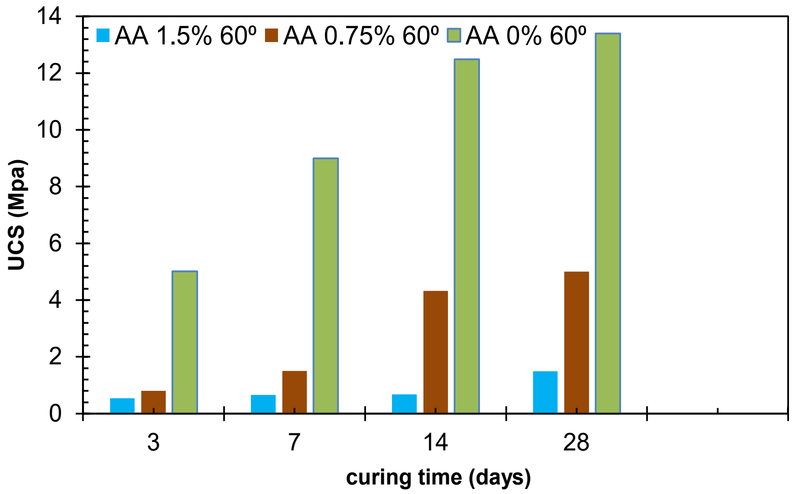

Figure 6. Effect of AA on UCS of the river-sand geopolymer.

3.2. Stress-strain curve

The experiment involved testing stabilized soil-geopolymer specimens containing an AA ratio (SH:SS = 0:100) from SS only, and other specimens containing an AA (SH:SS = 43:57, 60:40) at 8 M concentration of SH. The specimens were kept to mature for 48 hours and were subjected to curing temperatures of 30, 45, and 60 °C. After that, they were left in the oven until the time of the test at 3, 7, 14, and 28 days. The stress-strain relationship between the specimens is shown in Fig. 7. The results showed that as curing time and temperature increased, the stress increased, and the strain decreased as the results displays in [40, 41]. The stress-strain curve of the river-sand geopolymer specimens showed a clear peak stress, followed by a gradual decrease in strain. This indicates inherent brittleness under shearing. In comparison, shear failure occurred in specimens (S-AA 0) at a relatively lower strain compared to the specimens of (S-AA 0.75) and (S-AA 1.5) at all curing temperatures in different ages of the test. This is because the addition of SS improves the strength between soil particles, provides a uniform distribution, and reduces the average pore size. The decrease in the percentage of SS in the AA solution negatively affects the strength of the geopolymer.

3.3. Microstructure Characteristic

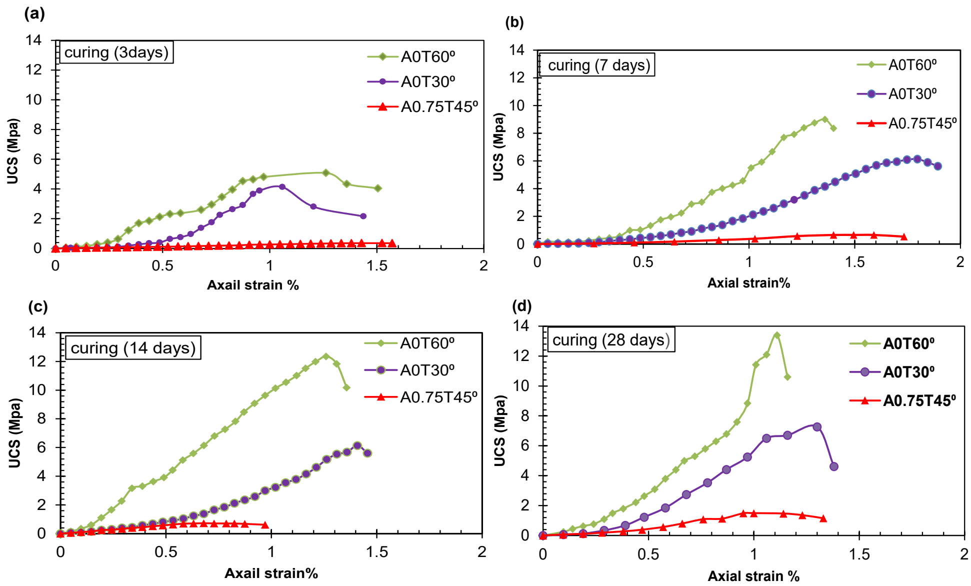

Figure 7. Stress-strain curve for the specimen with test time of: (a) 3 days; (b) 7days; (c) 14 days; (d) 28 days.

A SEM investigation was conducted on river-sand geopolymer specimens with two different AA ratios: 100:0 (0 %) and 60:40 (1.5 %). All specimens were allowed to be cured for 28 days before conducting the SEM test. The geopolymer mixtures were polymerized for 48 hours at 60 °C. Fig. 8 displays the SEM images of river-sand geopolymer. The SEM test was conducted on samples identical to those used for the UCS test. The chosen activated solution ratio filled the pores of the loose river sand and created thick formations. Furthermore, a noticeable alteration took place in the composition of sandy soil because of the introduction of an AA and the polymerization process, causing partial dissolving of aluminosilicate and activation of sand particles effectively. The stabilized sand particles were tightly connected by a geopolymer connection within a highly cross-linked 3D network, forming a solid crystalline composite. This aligns with the substantial improvements in soil stability. The polymerization process occurred due to the addition of an activator solution (SS) to the alkaline nature of selected river sand, which resulted in the formation of sodium aluminium silicate hydrate (N-A-S-H) gel in conjunction with the partial dissolution of activated soil sand with an AA ratio of 0 more than the specimens of AA = 1.5. The results match the findings of the studies on the effect of the geopolymer on the microstructure of the improved soil as a binder [22, 24].

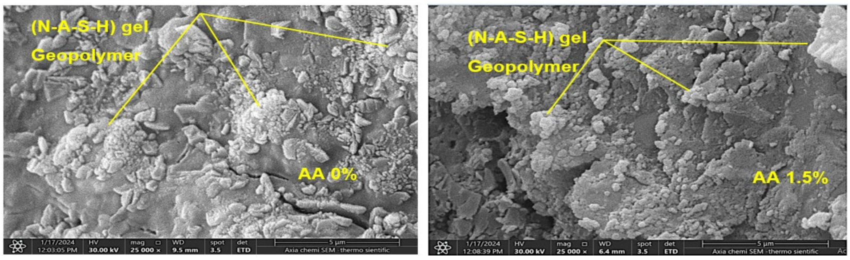

Figure 8. SEM images (9.5 X: 5 un) of geopolymer (a) AA 0 % (SH:SS = 0:100), (b) AA 1.5 % (SH:SS = 43:57), at 60° and 28 days. Sodium aluminate silicate hydrate gel (N-A-S-H).

4. Conclusion

The study investigated the significance of using geopolymer based on river sand soil (granular soil) merely without the addition of any fine pozzolanic materials such as FA, volcanic ash, etc.

Sandy soil stabilization by geopolymer showed a promising eco-friendly, economically viable, and sustainable alternative to OPC and lime.

The geopolymer could enhance the mechanical properties of soil, where the strength of river-sand geopolymer, measured as UCS, significantly increased with the AA = 0 (SH:SS = 0:100) ratio (high concentration of activator solution (SS)).

The highest value of UCS (13.42MPa) was at AA ratio = 0, 60 °C, and 28 days curing time. This result might be attributed to the existence of soluble silica that enhanced the condensation activity and developed more silica in the polymeric chain, which improved the strength property of the soil matrix.

Furthermore, under UCS, the dominant stress-strain reaction for geopolymer-based river sand soil was brittle yield, with stress peaking before sudden failure. When the geopolymer stress ratio increases, the response becomes stiffer. The SEM images revealed a homogeneous, denser, and very stiff structure.

The geopolymer gel improved the soil particles. The images indicated that the pores in the texture surrounding the geopolymer gel were evenly distributed and that the geopolymer behaved as a binder among the soil particles.

References

1. Elipe, M.G.M., López-Querol, S. Aeolian sands: Characterization, options of improvement and possible employment in construction – The State-of-the-art. Construction and Building Materials. 2014. 73. Pp. 728–739. DOI: 10.1016/j.conbuildmat.2014.10.008
2. Flodin, N., Broms, B. Historical development of civil engineering in soft clay. Soft Clay Engineering. Elsevier. Amsterdam, 1981. Pp. 27–133.
3. Sherwood, P. Soil Stabilization with Cement and Lime. Transport Research Laboratory, 1993. 153 p.
4. Huat, B.B.K., Prasad, A., Kazemian, S., Anggraini, V. Ground Improvement Techniques. CRC Press. London, 2019. 316 p. DOI: 10.1201/9780429507656
5. Karkush, M.O., Yassin, S. Using sustainable material in improvement the geotechnical properties of soft clayey soil. Journal of Engineering Science and Technology. 2020. 15(4). 2208–2222.
6. Dhowian, A.W. Laboratory simulation of field preloading on Jizan sabkha soil. Journal of King Saud University – Engineering Sciences. 2017. 29(1). Pp.12–21. DOI: 10.1016/j.jksues.2015.09.001
7. Al-Amoudi, O.S.B. Characterization and chemical stabilization of Al-Qurayyah sabkha soil. Journal of Materials in Civil Engineering. 2002. 14(6). Pp. 478–484. DOI: 10.1061/(ASCE)0899-1561(2002)14:6(478)
8. Al-Homidy, A.A., Dahim, M.H., Abd El Aal, A.K. Improvement of geotechnical properties of sabkha soil utilizing cement kiln dust. Journal of Rock Mechanics and Geotechnical Engineering. 2017. 9(4). Pp.749–760. DOI: 10.1016/j.jrmge.2016.11.012
9. Khedari, J., Watsanasathaporn, P., Hirunlabh, J. Development of fibre-based soil–cement block with low thermal conductivity. Cement and Concrete Composites. 2005. 27(1). Pp.111–116. DOI: 10.1016/j.cemconcomp.2004.02.042
10. Provis, J.L., Van Deventer, J.S.J. Alkali Activated Materials: State-of-the-Art Report, RILEM TC 224-AAM. Springer. Dordrecht, 2013. XIV, 388 p. DOI: 10.1007/978-94-007-7672-2
11. Garcia-Lodeiro, I., Palomo, A., Fernández-Jiménez, A. An overview of the chemistry of alkali-activated cement-based binders. Handbook of Alkali-Activated Cements, Mortars and Concretes. Woodhead Publishing, 2015. Pp.19–47. DOI: 10.1533/9781782422884.1.19
12. Hamzah, H.N., Al Bakri Abdullah, M.M., Heah, C.Y., Arif Zainol, M.R.R., Kamarudin, H. Review of soil stabilization techniques: Geopolymerization method one of the new technique. Key Engineering Materials. 2015. 660. Pp. 298–304. DOI: 10.4028/www.scientific.net/KEM.660.298
13. Davidovits, J. Geopolymer Chemistry and Applications. 2nd edn. Geopolymer Institute, 2008. 585 p.
14. Provis, J.L. Activating solution chemistry for geopolymers. Geopolymers: Structures, Processing, Properties and Industrial Applications. Woodhead Publishing, 2009. Pp. 50–71. DOI: 10.1533/9781845696382.1.50
15. Papadopoulos, A.M., Giama, E. Environmental performance evaluation of thermal insulation materials and its impact on the building. Build Environ. 2007. 42(5). Pp. 2178–2187. DOI: 10.1016/j.buildenv.2006.04.012
16. Cristelo, N., Glendinning, S., Fernandes, L., Pinto, A.T. Effects of alkaline-activated fly ash and Portland cement on soft soil stabilisation. Acta Geotechnica. 2013. 8. Pp. 395–405. DOI: 10.1007/s11440-012-0200-9
17. Adhikari, B., Khattak, M.J., Adhikari, S. Mechanical and durability characteristics of flyash-based soil-geopolymer mixtures for pavement base and subbase layers. International Journal of Pavement Engineering. 2021. 22(9). Pp. 1193–1212. DOI: 10.1080/10298436.2019.1668562
18. Alimi, M., Ghorbani, A. Mechanical and compressibility characteristics of a soft clay stabilized by slag-based mixtures and geopolymers. Applied Clay Science. 2020. 184. Article no. 105390. DOI: 10.1016/j.clay.2019.105390
19. Bhavita Chowdary, V., Ramanamurty, V., Pillai, R.J. Experimental evaluation of strength and durability characteristics of geopolymer stabilised soft soil for deep mixing applications. Innovative Infrastructure Solutions. 2021. 6. Article no. 40. DOI: 10.1007/s41062-020-00407-7
20. Rios, S., Ramos, C., Viana da Fonseca, A., Cruz, N., Rodrigues, C. Mechanical and durability properties of a soil stabilised with an alkali-activated cement. European Journal of Environmental and Civil Engineering. 2019. 23(2). Pp. 245–267. DOI: 10.1080/19648189.2016.1275987
21. Hai-yan, Y., Juan, Z., Jiu-jun, Y., Yong-qiang, L. Research on the mechanical properties and mechanism of alkali-activated saline soil composite materials. Ferroelectrics. 2018. 529(1). Pp. 49–58. DOI: 10.1080/00150193.2018.1448195
22. Ameen, S.K., Abdulkareem, A.H., Mahmood, N.S. Shear strength behavior of organic soils treated with fly ash and fly ash-based geopolymer. Journal of the Mechanical Behavior of Materials. 2023. 32(1). Article no. 20220264. DOI: 10.1515/jmbm-2022-0264
23. Abdulwahed, H.S., Aljanabi, K.R., Abdulkareem, A.H. Optimization of equivalent modulus of RAP-geopolymer-soil mixtures using response surface methodology. Journal of King Saud University – Engineering Sciences. 2024. 36(6). Pp. 375–384. DOI: 10.1016/j.jksues.2022.06.005

24. Al-Rkaby, A.H.J., Katea, A. Improvement the Strength Characteristics of Loose Sandy Soil Using Sustainable Geopolymer. Math Stat Eng Appl. 2023. 72(1). Pp. 660–667. DOI: 10.17762/msea.v72i1.1975
25. Nabizadeh Mashizi, M., Bagheripour, M.H., Jafari, M.M., Yaghoubi, E. Mechanical and Microstructural Properties of a Stabilized Sand Using Geopolymer Made of Wastes and a Natural Pozzolan. Sustainability. 2023. 15(4). Article no. 2966. DOI: 10.3390/su15042966
26. D2487-17 A. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International. West Conshohocken, PA, 2017. 10 p. DOI: 10.1520/D2487-17
27. D422-07. Standard Test Method for Particle-Size Analysis of Soils. West Conshohocken, PA, 2007. 8 p.
28. D698-12. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort. ASTM International. West Conshohocken, PA, 2007. 13 p.
29. Iowa Statewide Urban Design and Specifications. Chapter 6: Geotechnical. URL: https://www.iowasudas.org/wp-content/uploads/sites/15/2022/12/Chapter_06-2022.pdf (date of application: 10.02.2026).
30. D2166-06 A. Standard Test Method for Unconfined Compression Strength of Cohesive Soil. ASTM Standards. West Conshohocken, PA, 2006. 6 p.
31. Yu, J., Chen, Y.-H., Chen, G., Wang, L. Experimental study of the feasibility of using anhydrous sodium metasilicate as a geopolymer activator for soil stabilization. Engineering Geology. 2020. 264. Article no. 105316. DOI: 10.1016/j.enggeo.2019.105316
32. Abdullah, H.H., Shahin, M.A., Sarker, P. Use of Fly-Ash Geopolymer Incorporating Ground Granulated Slag for Stabilisation of Kaolin Clay Cured at Ambient Temperature. Geotechnical and Geological Engineering. 2019. 37. Pp. 721–740. DOI: 10.1007/s10706-018-0644-2
33. Dungca, J.R., Codilla II, E.E.T. Fly-ash-based geopolymer as stabilizer for silty sand embankment materials. International Journal of GEOMATE. 2018. 14(46). Pp. 143–149. DOI: 10.21660/2018.46.7181
34. Leong, H.Y., Ong, D.E.L., Sanjayan, J.G., Nazari, A. Strength development of soil–fly ash geopolymer: Assessment of soil, fly ash, alkali activators, and water. Journal of Materials in Civil Engineering. 2018. 30(8). Article no. 4018171. DOI: 10.1061/(asce)mt.1943-5533.0002363
35. Tian, X., Xu, W., Song, S., Rao, F., Xia, L. Effects of curing temperature on the compressive strength and microstructure of copper tailing-based geopolymers. Chemosphere. 2020. 253. Article no. 126754. DOI: 10.1016/j.chemosphere.2020.126754
36. Lopes, A., Lopes, S., Pinto, I. Influence of Curing Temperature on the Strength of a Metakaolin-Based Geopolymer. Materials (Basel). 2023. 16(23). Article no. 7460. DOI: 10.3390/ma16237460
37. Duan, P., Yan, C., Zhou, W. Compressive strength and microstructure of fly ash based geopolymer blended with silica fume under thermal cycle. Cement and Concrete Composites. 2017. 78. Pp. 108–119. DOI: 10.1016/j.cemconcomp.2017.01.009
38. Rangan, B.V., Hardjito, D., Wallah, S.E., Sumajouw, D.M. Studies on fly ash-based geopolymer concrete. Proceedings of the world congress geopolymer, Saint Quentin, 2005. Pp. 133–137.
39. Alrefaei, Y., Wang, Y.S., Dai, J.G. The effectiveness of different superplasticizers in ambient cured one-part alkali activated pastes. Cement and Concrete Composites. 2019. 97. Pp. 166–174. DOI: 10.1016/j.cemconcomp.2018.12.027
40. ASTM D1633-00. Standard test methods for compressive strength of molded soil-cement cylinders. ASTM International. West Conshohocken, PA, 2007. 4 p.
41. Association BS. Mortar and concrete – Test method for splitting tensile strength of cylindrical specimens. NBR, 1983.

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