Strength and Stiffness of a Geopolymer-treated Clayey Soil for Unpaved Roads

Huda S. Abdulwahed[a], Khalid. R. Mahmood [b], Ahmed H. AbdulKareem [c]

[a]*B.Sc., Department of Civil Engineering, University of Anbar, Ramadi, Anbar, Iraq. Email:* hud18e104@uoanbar.edu.iq

[b]*Assistant Professor (Ph.D.), Department of Civil Engineering, University of Anbar, Ramadi, Anbar, Iraq. Email:* kr_aljanabi@uoanbar.edu.iq

[c]*Assistant Professor (Ph.D.), Department of Civil Engineering, University of Anbar, Ramadi, Anbar, Iraq. Email:* ahm1973ed@uoanbar.edu.iq

ARTICLE INFO

ABSTRACT

This study is conducted to investigate the strength and stiffness of clayey soil stabilized with fly ash-based geopolymer for unpaved roads. Two sodium hydroxide concentrations of 6 and 8M and two alkali solution ratios of NaOH:Na2SiO3= 1 and 1.5 were considered. Other factors such as fly ash replacement ratio (by mass), curing period, and curing temperature were held constant at 15%, 48 hours, and 65 °C, respectively. The unconfined compressive strength (UCS) and ultrasonic pulse velocity (UPV) tests were performed to evaluate the mixtures. Outcomes of this study revealed that the strength of the clayey soil could be increased by up to 94%. Additionally, increasing sodium silicate content in the alkali solution increased the solution's activity and yielded higher strength and stiffness. This study confirms the effectiveness of the geopolymer binder for the improvement of soil strength and stiffness.

1. Introduction

Every highway network consists of a significant portion of unpaved roads. According to the Federal Highway Administration (FHWA) report 2016 (FHWA, 2016), about 31.6% of the total public road length in the United States, for example, is unpaved. In general, these roads carry low volume traffic and provide access to villages, farms, and other rural communities. However, traffic volumes on unpaved roads may increase during specific periods of the year (e.g., during the harvest season). Therefore, higher strength, stiffness, durability, and safety must be considered.

Traditionally, the locally available materials (e.g., soil and gravel) are utilized to construct the unpaved roads. Some soils are problematic, which requires the improvement of some of their properties. To improve the bearing capacity of these soils, treatments (such as soil stabilization) are applied. Ordinary Portland Cement (OPC) is a predominantly used stabilizer with different types of soils. However, incorporating large quantities of cement may have two negative impacts. The first is that it harms the durability of the resulting materials, as micro-cracks develop due to shrinkage resulting from heat released during hydration reaction (Adhikari, Khattak, & Adhikari, 2018). The second is regarding sustainability considerations. Producing large amounts of cement

---

produces significant quantities of greenhouse gases (namely, carbon dioxide (CO_2)). Specifically, the production of one ton of OPC emits about 0.85-1.0 ton of CO_2 (Davidovits, 2015). As a greener substitute for OPC, geopolymer binders have been incorporated to stabilize weak soils (Verdolotti, Iannace, Lavorgna, & Lamanna, 2008),(Cristelo, Glendinning, & Pinto, 2011),(Sukmak, Horpibulsuk, & Shen, 2013). Geopolymer binders are synthesized by activating alumino-silicate materials (e.g., fly ash (FA), metakaolin, and blast furnace slag) in an alkali solution. The alkali solution can be sodium hydroxide, sodium silicate, phosphoric acid, or others (Davidovits, 2017). The transformation of precursors (alumino-silicate materials) to a geopolymeric gel at ambient or slightly elevated temperatures is known as the *geopolymerization reaction* (Davidovits, 2017; Xu & Van Deventer, 2000). At the initial phases of this reaction, the alumino-silicate material is dissolved in the high PH solution, which becomes saturated with Si and Al species. Subsequently, gelation phase takes place by reorientation and accumulation of Si and Al species. This process continues until the forming complexes condense and harden, yielding a 3D alumino-silicate framework, i.e., geopolymer (Provis & Van Deventer, 2009; Xu & Van Deventer, 2000),(Farhan, Johari, & Demirboğa, 2020; Rao & Liu, 2015). The properties of the final product of geopolymerization are affected by several factors, such as alkali concentration and solution ratio, curing temperature and period, PH, liquid to solids ratio, etc.(Gasteiger, Frederick, & Streisel, 1992; Palomo, Grutzeck, & Blanco, 1999; Puertas, Martínez-Ramírez, Alonso, & Vázquez, 2000; Xu & Van Deventer, 2002).

Fly ash is a by-product of coal combustion composed of fine particulate of light to dark grey color. The two primary chemical components of FA are SiO_3 and Al_2O_3, in addition to other oxides such as CaO, Fe_2O_3, MgO, and others. FA can be classified into Class F fly ash, or Class C fly ash based on CaO content (ASTM, 2010). As an alumino-silicate material, fly ash, low-calcium Class F in particular, has been preferably used in the synthesis of geopolymers because it is a widely-available industrial waste, and it may exhibit better properties than other precursors. For instance, alkali-activated fly ash paste would be more workable than a corresponding metakaolin paste if a quarter of the water is used to prepare the paste; hence, enhanced mechanical properties may be achieved (Provis & Van Deventer, 2009).

Recently, several researchers have considered the geopolymerization reaction to enhance the properties of problematic soils. In 2007, (Verdolotti et al., 2008) grouted a loose pozzolanic soil (i.e., a soil rich of silica and alumina) with different alkaline activators, namely, 10M NaOH solution and a slurry of solid $NaAlO_2$.+10M NaOH. The Results showed that the geopolymerization could be effectively used to consolidate loose pozzolanic soil as the NaOH-$NaAlO_2$ slurry activator yielded over 40 MPa compressive strength after 360 days of curing at 25 ℃. (Sukmak et al., 2013) examined the strength development of silty clay-geopolymer mixtures and found that the optimum NaOH:Na_2SiO_3 was about 1.4. (Ghadir & Ranjbar, 2018) stabilized a clayey soil with geopolymer and OPC, and observed that the dry curing conditions were favorable for geopolymer-stabilized clay. (Rios, Ramos, Fonseca, Cruz, & Rodrigues, 2016) considered a silty sand soil stabilized with FA-based geopolymer as low-cost road material. This study concluded that 10M NaOH yielded the highest compressive strength for all the studied mixtures. The study is useful because it also investigated the durability of mixtures, which is a crucial consideration in road applications. (Kwad, Abdulkareem, & Ahmed, 2020) assessed a geopolymer treated-sandy silt with high CaO content as a subgrade material at a range of FA replacement ratios (5 – 30%). This study demonstrated that about 22 MPa compressive strength of the treated soil could be attained by the activation of 20% fly ash+soil mixtures with 8M NaOH and 60:40 NaOH:Na_2SiO_3 at 28 curing days.

In this paper, the FA-geopolymer was used to stabilize a locally available clayey soil and investigate the resulting mixtures in terms of compressive strength, static elastic modulus, and dynamic elastic modulus. The compressive strength is a vital mechanical property of materials that indicates their ability to resist compressive stresses. In pavement design and analysis, it is used as material selection criteria and a parameter to predict some fundamental engineering properties of materials such as the elastic modulus and resilient modulus (C. Rao, Bhattacharya, Darter, Stanley, & Quintus, 2012). The unconfined compression test is a commonly used method to evaluate the compressive strength of untreated and treated cohesive soils. Typically, compacted soil cylinders are subjected to compressive axial load without lateral confinement; therefore, the test is relatively rapid and easy-to-perform. On the other hand, the dynamic elastic modulus from UPV tests provides an approximate estimation of the stiffness of materials at a very small strain range. The UPV tests are suggested by some researchers to examine the dynamic behavior of untreated and treated soils (Razouki & Ibrahim, 2019;

Rios et al., 2016; Stephenson, 1978). UPV tests are non-destructive and can be performed on a large number of specimens in a short time.

The evaluation of soil-geopolymer mixtures in this study was focused on the effect of NaOH molarity and NaOH:Na_2SiO_3 ratio (Sodium Hydroxide: Sodium Silicate, (SH:SS)). The findings will provide more significant information on the potentials of geopolymer as a greener soil stabilizer for unpaved roads.

2. Materials and Methodology

2.1 Soil

Soil was collected from a site near Ramadi city, Iraq. It was mechanically-pulverized before being used in the laboratory. Soil was classified as low plasticity clay (CL) according to the Unified Soil Classification System (USCS). Fig. 1 illustrates the grain size distribution of soil, as obtained from sieve and hydrometer analysis, according to ASTM D422 (ASTM, 2007a) and ASTM D1140 (ASTM, 2014). The modified Proctor test, detailed in ASTM D1557 (ASTM, 2003), was performed to obtain the maximum dry unit weight density (MDU) and optimum moisture content (OMC) of the untreated soil and soil-FA mixtures. The OMC and MDU of soil were 14% and 18.4 kN/m3, respectively, while for soil-FA mixtures, the OMC and MDU were 16.5% and 14 kN/m3, respectively. Tables 1 and 2 show the physical and chemical properties of soil, respectively. The chemical composition of soil and FA was obtained from X-Ray Fluorescence (XRF) analysis conducted at the Ministry of Science and Technology, Baghdad, Iraq.
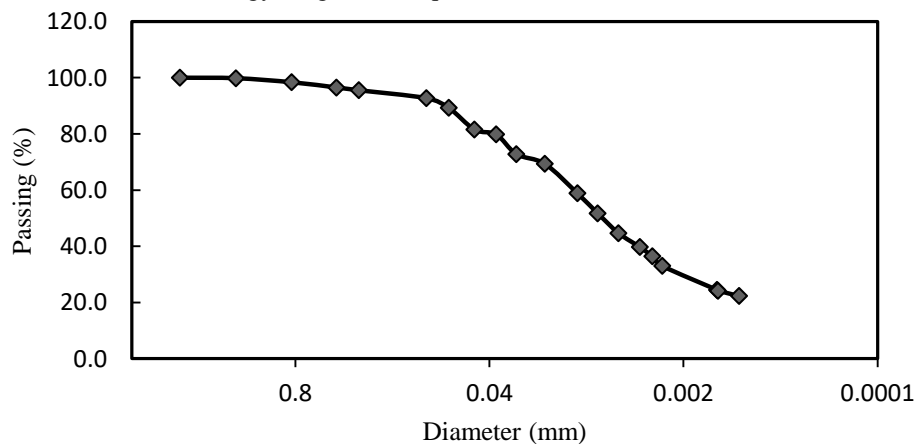

Fig. 1. Particle Size Distribution by Sieve and Hydrometer Analysis

2.2 Fly Ash

Fly ash was brought from a local vendor in Baghdad, Iraq. Table 2 lists the chemical composition of FA. Based on CaO content and according to ASTM C618 (ASTM, 2010), FA used in this study is classified as low calcium Class F Fly Ash.

Table 1: Physical Properties of Soil

Atterberg Limits				Compaction Characteristics		Soil Classification	
LL (%)	PL (%)	PI (%)	G_s[a]	MDU[b] (kN/m³)	OMC[c] (%)	AASHTO	USCS
46	23	23	2.7	18.4	14	A-7-6	CL

a: Specific Gravity   b: maximum dry unit weight   c: optimum moisture content

Table 2: Chemical Properties of Soil and Fly Ash

Oxide Composition	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	K_2O	SO_3	MnO
Soil (wt. %)	45.8	15.6	15.9	4.95	9.99	3.02	1.53	1.58	0.082
FA (wt. %)	51.6	36.55	0.35	3.6	1.91	1.18	3.77	0.107	0.017

2.3 Alkali Solution

Commercial-grade sodium hydroxide (NaOH) flakes of purity of 98% were used as the main activator for the synthesis of the geopolymer binder. Liquid sodium silicate (Na_2SiO_3) was also used with NaOH at predetermined ratios to provide more silicate content.

2.4 Alkali Solution Preparation

Alkali solution was prepared by dissolving NaOH flakes in distilled water at two molarities of 6M and 8M, at least 24 hours before use, because its reaction with water is exothermic such that a cool-down period is necessary. The resulting solution was thoroughly mixed with liquid Na_2SiO_3 for 7 to 10 minutes at two NaOH:Na_2SiO_3 (SH:SS) ratios, namely, 1 and 1.5. The solution was prepared at least 2 hours before being added to the dry materials. Metal tools were not used to mix and store the alkali solution as they may react, and consequent metal corrosion may occur, leading to a contaminated solution.
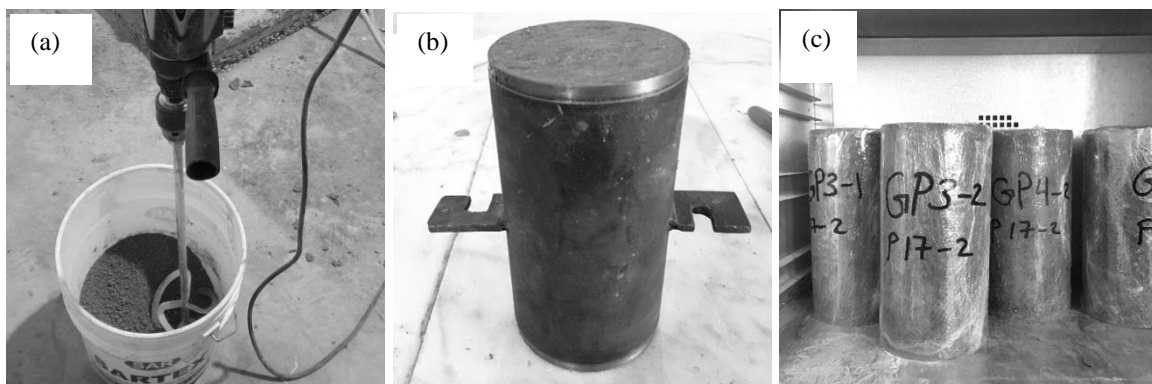
2.5 Specimen Preparation

To prepare specimens for the UPV and UCS tests, a proper amount of oven-dried soil was manually mixed for about 3 minutes with 15% FA replacement of the total mass. Next, the alkali solution was added and thoroughly mixed for about 10 minutes by using a mechanical mixer to obtain a homogenous mixture. The alkali solution was denser than water, so the amount of alkali solution added was the same amount of the OMC of soil-FA mixture obtained from the modified proctor test plus an additional amount. The additional amount was equivalent to the difference in density of water and alkali solution. This procedure was used because trial mixing at exactly the OMC yielded specimens dry to the optimum.

The mixture was compacted in a 100 mm diameter cylindrical mold that has an aspect ratio of 2:1. Compaction was carried out according to ASTM D1557 using a mechanical compactor. The number of compaction layers was kept five while the number of blows was modified to accomplish the same compaction energy of the modified proctor test. Mixing, molding, and demolding were performed as quickly as possible, typically within approximately 30 minutes, to eliminate moisture loss and exposure of the specimen to the atmosphere. Four mixtures, a minimum of two replicates each, were compacted and labeled, as presented in Table 4.

Table 4: Proportioning of Mixtures

Label	Fly Ash Replacement (%)	NaOH Molarity	SH:SS Ratio
GP1	15	6	1
GP2	15	6	1.5
GP3	15	8	1
GP4	15	8	1.5

Fig. 2. Specimen Preparation; a) Mixing b) Molding c) Curing

Immediately after demolding, the specimens were carefully wrapped with a cling film and placed in the drying oven for curing. Specimens were cured at $65°C$ for 48 hours and then given a 24 hours rest period before testing. The preparation process is displayed in Fig. 2.

2.6 Ultrasonic Pulse Velocity (UPV) Test

The ultrasonic pulse test was conducted according to ASTM C597-09 (ASTM, 2009) to estimate the dynamic modulus of elasticity of the treated soil specimens. The test is a quick and non-destructive test, so it was performed prior to the UCS tests using the same specimens.

After calibrating the apparatus, grease was applied at the top and bottom of the specimen surface as a coupling agent, then the transmitter and receiver transducers were placed oppositely and pressed firmly against the surface of the specimen. An ultrasonic compressive pulse (P-wave) was generated, transmitted through the specimen, and finally, the transit time (in μsec) was recorded from the display screen (See Fig. 3). Height, diameter, and weight of each specimen were also measured to calculate their density.

Dynamic elastic modulus was calculated by the following equation (ASTM, 2009):

$$E = \frac{\rho(1+\mu)(1-2\mu)}{(1-\mu)}V^2 \ .... (1)$$

Where:
- E: Dynamic elastic modulus (MPa)
- ρ: Density (kg/m^3)
- μ: Poisson's ratio (assumed 0.3 in this study)
- V: P-wave velocity (km/sec)

Poisson's ratio was assumed 0.3 as an average of typical values of Poisson's ratio of clay and concrete, i.e., soil-geopolymer mixtures were regarded as weak concrete.
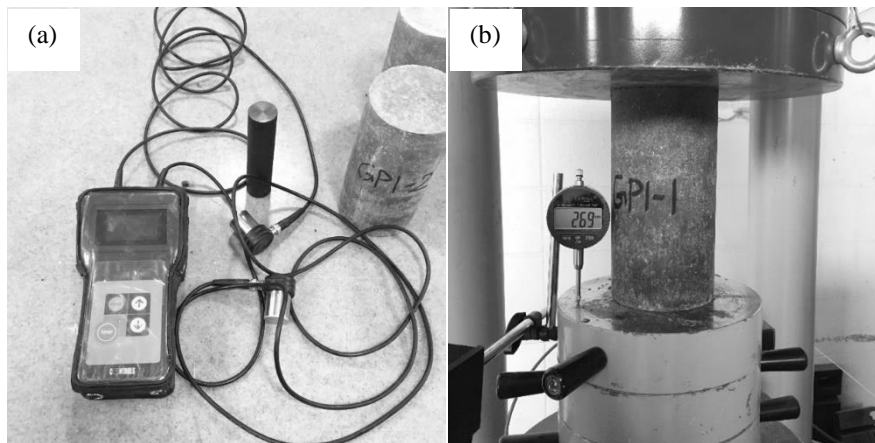

Fig. 3. Testing Systems; a) UPV Test, b) UCS Test

2.7 Unconfined Compressive Strength (UCS) Test

The UCS test was performed according to ASTM D1633 (ASTM, 2007b) to evaluate the compressive strength of soil-geopolymer specimens. Once the ultrasonic test was completed, each soil specimen was placed on the center of the bearing plate of the compression machine. In an effort to obtain an approximate elastic modulus of the samples, a 0.01 mm dial gauge was also mounted on the plate. The test was performed at the stress-controlled mode at a rate of 0.5 kN/sec. Failure load, as well as load and displacement at each 1 kN load increment (or decrement after failure), were recorded to obtain the ultimate strength and plot the stress-strain relationship of specimens under study.

3. Results and Discussion

3.1 Dynamic Elastic Modulus

The transit distance, i.e., the height of the specimen, was divided by transit time recorded from the UPV test to obtain the pulse velocity, and then calculate the dynamic modulus. Fig. 4 shows the results of the dynamic elastic modulus. It can be seen that increasing molarity from 6 to 8M at 1 SH:SS led to a decrease in the dynamic modulus by approximately 7%. The decrease is more pronounced at 1.5 SH:SS. This may signify a denser microstructure yielded from 6M NaOH activation and can be justified by the fact that ultrasound waves travel faster through solid media than air (Hoskins, Matrin, & Thrush, 2020). A denser specimen means fewer air voids, thus, larger pulse velocity, which, according to Eq.1, means higher dynamic modulus.

On the other hand, the dynamic modulus was decreased by decreasing sodium silicate content in the alkali activator (SH:SS increased from 1 to 1.5). This can be attributed to the increased silica content that assists in the formation of the geopolymeric gel (Fernández-Jiménez & Palomo, 2005; Srinivasan & Sivakumar, 2013; Xu & Van Deventer, 2000).
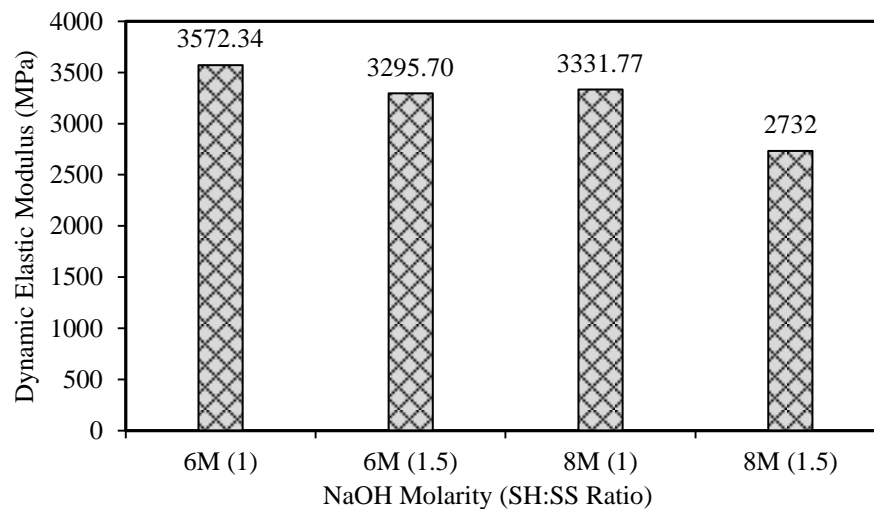

Fig. 4. Dynamic Modulus Results from UPV Test

3.2 Unconfined Compressive Strength

The unconfined compressive strength of the control mix (soil) plus soil-geopolymer mixes investigated are illustrated in Fig. 5. A significant improvement in the compressive strength of soil due to the incorporation of geopolymer binder was observed. It can be seen that the compressive strength of soil raised by 94% at 8M (1SH:SS) alkali activation of FA-soil mixture. This mixture exhibited the highest compressive strength compared to the other mixtures. Higher molarity means higher alkali ions concentration, which enhances the solubility of alumino-silicate species and accelerates strength development (Gasteiger et al., 1992; Srinivasan & Sivakumar, 2013). Fig. 5 also indicates that decreasing Na_2SiO_3 had an adverse impact on the strength of the mixtures, which agrees with the results of dynamic modulus.

The compressive strength results showed the same trend of dynamic elastic modulus results, except for GP1 (6M, 1SH:SS). Cautiously interpreted, this contradiction may be due to a non-homogeneous microstructure such that the dynamic wave in the ultrasonic pulse velocity test had traveled through a path denser than other paths in the same specimen.
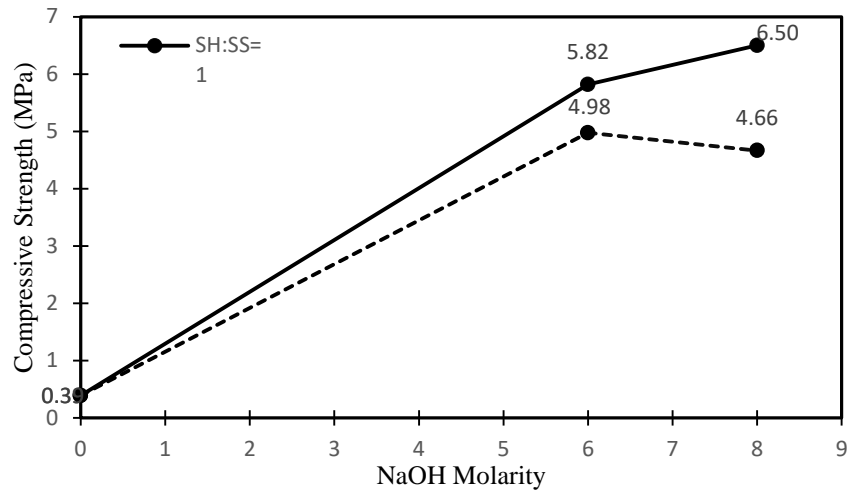
Fig. 5. Compressive Strength Test Results

3.3 Static Elastic Modulus

The stress-strain curves of the four mixtures (see Fig. 6) were plotted using the load and deformation readings from the UCS test. The initial static elastic modulus of each mixture was obtained by determining the slope of the linear portion of each curve. Table 5 lists the results of the static elastic modulus. It can be seen that the static elastic modulus follows the same tendency of compressive strength. Noteworthy, the stress-strain variation of the mixtures investigated remains linear up to approximately 40-65% of the peak stress. Since the test was stress-controlled at a relatively high loading rate compared to the anticipated strength of the mixtures, loading the specimens beyond peak stress caused a sudden damage to the specimen, so it was not possible to further examine the post-peak behavior of the mixtures. However, by viewing the stress-strain curves and visually inspecting the specimens at failure, it is observed that the failure of soil-geopolymer specimens is semi-brittle with the development of cracks along the axis of loading, as shown in Fig. 6.
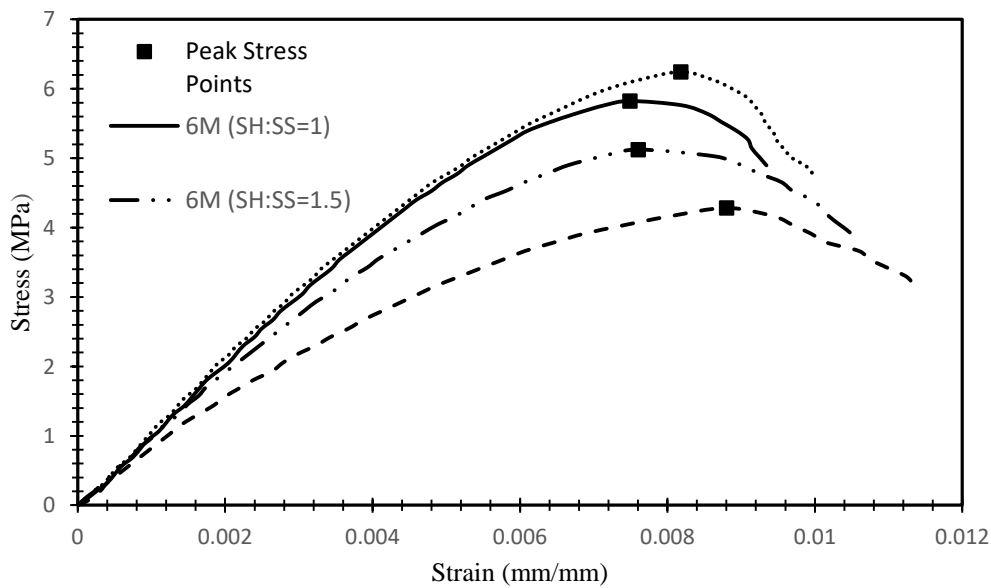

Fig. 6. Typical Stress-Strain Curves for the Four Mixtures

Table 5: Static Elastic Modulus from Compressive Strength Test

Label	Mixture	Elastic Modulus (MPa)	Linear Up to (%) of Peak Stress
GP1	6M (1)	1013.4	63
GP2	6M (1.5)	870.42	46
GP3	8M (1)	1031.3	54
GP4	8M (1.5)	772.59	41

4. Conclusions and Recommendations

This study was carried out to evaluate the impact of FA-based geopolymer binder on the strength and stiffness of clayey soil, focusing on the effect of alkali solution concentration (i.e., NaOH molarity) and proportion (i.e., NaOH: Na_2SiO_3 ratio). Based on data obtained, the following inferences and recommendations are drawn:

- The compressive strength of soil increased by up to 94% with the inclusion of alkali-activated fly ash.
- Increasing NaOH molarity had a positive impact on the strength and stiffness of soil-geopolymer mixtures. However, further increment should be investigated to determine the optimum molarity for this type of soil.
- Increasing NaOH content over the Na_2SiO_3 in the alkali solution had a detrimental effect on the strength of the resulting mixture.
- The failure mode of soil-geopolymer mixtures was semi-brittle, although post-peak behavior of soil-geopolymer mixtures could not be examined.
- Since the soil-geopolymer mixtures are proposed as unpaved road material, it is recommended to assess the durability characteristics of theses mixtures as it is of particular importance for road pavements.

References

Adhikari, S., Khattak, M. J., & Adhikari, B. (2018). Mechanical characteristics of Soil-RAP-Geopolymer mixtures for road base and subbase layers. *International Journal of Pavement Engineering*, *0*(0), 1–14. https://doi.org/10.1080/10298436.2018.1492131

ASTM. (2003). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3(2,700 kN-m/m3)). *ASTM International*, *3*, 1–10. https://doi.org/10.1520/D1557-09.1

ASTM. (2007a). Standard Test Method for Particle-Size Analysis of Soils. *ASTM International*, *63*(Reapproved 2007), 1–8. https://doi.org/10.1520/D0422-63R07E02.2

ASTM. (2007b). Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders 1. *ASTM International*. https://doi.org/10.1520/D1633-00R07.the

ASTM. (2009). Standard Specification for Pulse Velocity Through Concrete. *ASTM International*, (Note 2), 6–9. https://doi.org/10.1520/C0597-09.2

ASTM. (2010). Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use. *ASTM International*, (C), 3–6. https://doi.org/10.1520/C0618

ASTM. (2014). Standard Test Methods for Determining the Amount of Material Finer than 75-μm (No. 200) Sieve in Soils by Washing. *ASTM International*.

C. Rao, L. T.-G., Bhattacharya, B., Darter, M. I., Stanley, M., & Quintus, H. L. Von. (2012). *Estimation of Key PCC , Base , Subbase , and Pavement Engineering Properties from Routine Tests and Physical Characteristics*.

Cristelo, N., Glendinning, S., & Pinto, A. T. (2011). Deep soft soil improvement by alkaline activation. *Proceedings of the Institution of Civil Engineers: Ground Improvement*, *164*(2), 73–82. https://doi.org/10.1680/grim.900032

Davidovits, J. (2015). False Values on CO2 Emission for Geopolymer Cement / Concrete published in Scientific Papers. *Geopolymer Institute Library*, (January 2015), 1–9.

Davidovits, J. (2017). Geopolymers: Ceramic-like inorganic polymers. *Journal of Ceramic Science and*

Technology, *8*(3), 335–350. https://doi.org/10.4416/JCST2017-00038

Farhan, K. Z., Johari, M. A. M., & Demirboğa, R. (2020). Assessment of important parameters involved in the synthesis of geopolymer composites: A review. *Construction and Building Materials*, *264*. https://doi.org/10.1016/j.conbuildmat.2020.120276

Fernández-Jiménez, A., & Palomo, A. (2005). Composition and microstructure of alkali activated fly ash binder: Effect of the activator. *Cement and Concrete Research*, *35*(10), 1984–1992. https://doi.org/10.1016/j.cemconres.2005.03.003

FHWA. (2016). *Public Road Length - 2015 Miles By Type of Surface and Ownership / Functional System National Summary* (Vol. 2015).

Gasteiger, H. A., Frederick, W. J., & Streisel, R. C. (1992). Solubility of Aluminosilicates in Alkaline Solutions and a Thermodynamic Equilibrium Model. *Industrial and Engineering Chemistry Research*, *31*(4), 1183–1190. https://doi.org/10.1021/ie00004a031

Ghadir, P., & Ranjbar, N. (2018). Clayey soil stabilization using geopolymer and Portland cement. *Construction and Building Materials*, *188*, 361–371. https://doi.org/10.1016/j.conbuildmat.2018.07.207

Hoskins, P. R., Matrin, K., & Thrush, A. (2020). Diagnostic Ultrasound: Physics and Equipment. In *Ultrasound in Medicine & Biology* (Vol. 46). https://doi.org/10.1016/j.ultrasmedbio.2019.12.006

Kwad, N. F., Abdulkareem, A. H., & Ahmed, T. M. (2020). The Effect of Fly Ash Based Geopolymer on the Strength of Problematic Subgrade Soil with High CaO Content. *Lecture Notes in Civil Engineering*, *76*(June), 539–551. https://doi.org/10.1007/978-3-030-48679-2_51

Palomo, A., Grutzeck, M. W., & Blanco, M. T. (1999). Alkali-activated fly ashes: A cement for the future. *Cement and Concrete Research*, *29*(8), 1323–1329. https://doi.org/10.1016/S0008-8846(98)00243-9

Provis, J. L., & Van Deventer, J. S. J. (2009). *Geopolymers Structure, processing, properties and industrial applications*. Woodhead Publishing Limited.

Puertas, F., Martínez-Ramírez, S., Alonso, S., & Vázquez, T. (2000). Alkali-activated fly ash/slag cements. Strength behaviour and hydration products. *Cement and Concrete Research*, *30*(10), 1625–1632. https://doi.org/10.1016/S0008-8846(00)00298-2

Rao, F., & Liu, Q. (2015). Geopolymerization and its potential application in mine tailings consolidation: A review. *Mineral Processing and Extractive Metallurgy Review*, *36*(6), 399–409. https://doi.org/10.1080/08827508.2015.1055625

Razouki, S. S., & Ibrahim, A. N. (2019). Improving the resilient modulus of a gypsum sand roadbed soil by increased compaction. *International Journal of Pavement Engineering*, *20*(4), 432–438. https://doi.org/10.1080/10298436.2017.1309190

Rios, S., Ramos, C., Fonseca, A. V. Da, Cruz, N., & Rodrigues, C. (2016). Colombian Soil Stabilized with Geopolymers for Low Cost Roads. *Procedia Engineering*, *143*(Ictg), 1392–1400. https://doi.org/10.1016/j.proeng.2016.06.164

Srinivasan, K., & Sivakumar, A. (2013). Geopolymer Binders: A Need for Future Concrete Construction. *ISRN Polymer Science*, *2013*, 1–8. https://doi.org/10.1155/2013/509185

Stephenson, R. W. (1978). Ultrasonic Testing for Determining Dynannic Soil Moduli. *ASTM International*.

Sukmak, P., Horpibulsuk, S., & Shen, S. L. (2013). Strength development in clay-fly ash geopolymer. *Construction and Building Materials*, *40*, 566–574. https://doi.org/10.1016/j.conbuildmat.2012.11.015

Verdolotti, L., Iannace, S., Lavorgna, M., & Lamanna, R. (2008). Geopolymerization reaction to consolidate incoherent pozzolanic soil. *Journal of Materials Science*, *43*(3), 865–873. https://doi.org/10.1007/s10853-007-2201-x

Xu, H., & Van Deventer, J. S. J. (2000). The geopolymerisation of alumino-silicate minerals. *International Journal of Mineral Processing*, *59*(3), 247–266. https://doi.org/10.1016/S0301-7516(99)00074-5

Xu, H., & Van Deventer, J. S. J. (2002). Geopolymerisation of multiple minerals. *Minerals Engineering*, *15*(12), 1131–1139. https://doi.org/10.1016/S0892-6875(02)00255-8