SCIENTIFIC PAPER
Published: September 29, 2025
https://doi.org/10.13167/2025.31.7

Effectiveness of geopolymer-treated soil plasticity characteristics: A road pavement material

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Received:
August 27, 2024

Revised:
June 19, 2025

Accepted:
July 15, 2025

Published:
September 29, 2025

Citation:
Turkan, S. D. et al.
Effectiveness of geopolymer-treated soil plasticity characteristics: A road pavement material.
Advances in Civil and Architectural Engineering,
2025, 16 (31), pp. 111-129.
https://doi.org/10.13167/2025.31.7

ADVANCES IN CIVIL AND ARCHITECTURAL ENGINEERING (ISSN 2975-3848)

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Abstract:
High- and low-expansivity are common in all expansive soils. Most roads are constructed on high- and low-plastic soils that can be enhanced by means of fly ash-based geopolymer, a “green cement”. This paper describes the effectiveness of fly ash-based geopolymer for construction of road subgrade through laboratory experimentation, considering free swell behaviour, shrinkage behaviour, unconfined compression test, California bearing ratio, and resilient modulus. The effectiveness and feasibility of the material were characterized in terms of reduction in swelling and shrinkage and improvement in strength behaviour of soil mass. The optimized fly ash and geopolymer mixes were noted at 25 %, as observed through the microstructural analysis of soil samples. Soil plasticity plays an important role, governing the strength of soil. Low-plastic soil shows high mechanical strength compared to high-plastic soil. Fly ash geopolymer-treated soil material was found to be more suitable for construction of the sub-grade or sub-base layer of flexible pavement, help to reduce conventional stabilizer, and lead to a sustainable solution.

Keywords:
green cement; high plastic; low plastic; fly ash; geopolymer; sustainable solution; road pavement

1 Introduction

Expansive soil is essentially clay soil with a higher concentration of clay minerals, low shear strength, considerable deformation under small force, and high swelling-shrinkage potential [1]. Consequently, in geotechnical engineering, this type of soil is classified as problematic [2]. Hence, such soils must be treated to avoid difficulties caused by their expansive characteristics. Chemical soil stabilisation is a more common, less expensive, and frequently used approach. Cement and/or lime are the most common conventional stabilisers (binders) used to create cementitious materials. Although both are intended to improve soil mechanical strength, cement-based stabilisers have greater strength than lime-based stabilisers [3]. However, cement manufacturing is becoming unsustainable due to the global production of greenhouse gases, such as carbon dioxide (CO_2), by the cement industry. Therefore, researchers and engineers are constantly searching for novel, sustainable, and cost-effective stabilizer alternatives to ordinary Portland cement. Moreover, industrial by-products, such as cement kiln dust, calcium carbide residue, granulated blast furnace slag, and fly ash, are of great concern for eco-friendly disposal. Such by-products can also be used as soil stabilizer materials, and their application in the geotechnical construction industry may lead to a sustainable solution. Various researchers [4-13] have successfully conducted studies on the application of these by-products in soil stabilisation. Of these, fly ash is of great concern for disposal, can be used in mass quantities, and has a high potential to form geopolymers [14-17]. The fly ash geopolymer material is described in the following sections. Geopolymer is an inorganic aluminosilicate material formed from the polycondensation of silica and alumina [18; 19].

Nowadays, the reuse of industrial by-products, such as alumina and silica, through alkaline activation stabilisers constitutes an attractive and effective alternative to traditional stabilisers [19-23]. The process of alkaline activation typically involves the dissolution of silica and alumina using a basic (high-pH) liquid and the formation of cementitious products. Based on the formation of cementitious products from various industrial by-products, three different models have been derived [21], as shown in Table 1.

Table 1. Alkaline activation models [21]

Model	Source materials	Reaction product
I	High calcium and silica-rich materials (class C fly ash, GGBS) $SiO_2 + CaO > 70$ %	Calcium Silicate Hydrate gel (C-A-S-H)
II	Low calcium (class F fly ash, metakaolin)	Alkaline aluminosilicate hydrate gel, i.e., geopolymer (N-A-S-H)
III	High calcium, silica, and alumina less than 20 % (GGBS + fly ash + OPC)	C-A-S-H gel and, N-A-S-H gel

Where:

- Model I - high-calcium and silica-rich materials are alkaline activated at high temperatures. The main reaction product is calcium silicate hydrate gel (CASH), which is similar to the product obtained after OPC pozzolanic reaction [24].
- Model II - the material is activated and enriched in silica and alumina and has a low calcium content. This model is known as a geopolymer or inorganic polymer. The working condition is aggressive to start the reaction or polymerisation due to the presence of highly alkaline media and high curing temperature. The main reaction product forms a three-dimensional structure of alumina and silica as a gel alkaline aluminosilicate hydrate (NASH) [18; 21; 25]. This gel is also called a geopolymer or inorganic polymer. This model has been used in several studies on soil stabilisation applications [3; 5-7; 26-30].
- Model III - comprises a combination of two models, consisting of the activation of fly ash and GGBS, where the reaction products of NASH and CASH gels are introduced.

This model requires ambient temperature and low-alkali conditions, which may assist in bringing the strength of treated soils to the economical boundary because elevated temperatures and high alkalinity are not practical for soils. This model has been used in the study of soil stabilisation applications [31-37].

Models II and III are both geopolymer models; however, there is debate in the literature on whether Model I can be classified as a geopolymer. Therefore, Model I was excluded from the current study. Compared to Model II, geopolymerisation through Model III (see Table 1) seems to be more appropriate for expansive stabilisation at ambient temperature and hence should be considered. However, Model III involves the combination of a pozzolanic material with other calcium-rich additives; therefore, before adopting Model III, it is necessary to understand the basic reaction mechanism of Model II in expansive soil stabilisation.

The concept of geopolymers was first introduced by Joseph Davidovits in 1976, who named them three-dimensional aluminosilicates as they formed by naturally occurring aluminosilicate materials [18]. The term geopolymer is also referred to in the literature as ‘soil cement’, ‘alkali activated materials’, ‘mineral polymer’, ‘inorganic polymer’, etc. For simplicity, the term ‘geopolymer’ is used throughout this paper. The geopolymer itself was demonstrated to be a suitable material for soil stabilisation, overcoming the issues faced by traditional stabilisers.

The efficiency of a fly ash-based geopolymer as a binder depends on several parameters, including the activator concentration and curing temperature. Practically, geopolymers for soil stabilisation are feasible at ambient temperatures because at higher temperatures, more alkaline conditions are required, which increases the cost of stabilisation. However, as per various previous studies, there is limited relevant research on the application of fly ash in geopolymers for the stabilization of expansive soil. Therefore, the main objective of this study was to understand the feasibility of fly ash-based geopolymers for expansive soil (high and low plastic) stabilisation through an experimental laboratory test program. In addition, studies on the characterisation of soil based on plasticity are rare, and no such studies have been found. The experimental investigation was carried out using unconfined compression strength, California bearing ratio, resilient modulus, and swelling-shrinkage behaviour.

2 Material and testing conditions

2.1 Expansive soil

The expansive soil was obtained from two locations near Raipur City. It was transported to the laboratory for classification and strength characterisation. To understand the effect of fly ash and geopolymer on the plasticity characteristics of the soil, it was classified into two categories according to the Unified Soil Classification System (USCS): high-plastic and low-plastic. High-plastic soil (HPS) (LL > 50) was collected from Amleshwar village, near Raipur City, Chhattisgarh, India. Low-plastic soil (LPS) (LL < 50) was collected from Dunda village, near Raipur City, Chhattisgarh, India.

The soil samples were collected from 1 m below the ground surface to avoid soil contamination. The soil was transported to a laboratory for testing; preliminarily, it was allowed to dry for two days and thoroughly ground using a wooden mallet.

2.2 Fly ash

In this study, fly ash was used as a stabilizer for the expansive soils. The soil and fly ash characteristics are presented in Table 2. Fly ash was collected from the thermal power plant of National Thermal Power Corporation and Steel Authority of India Limited (NSPCL), Bhilai, Chhattisgarh, India. According to the Central Electricity Authority (2021) [38] in New Delhi, India, the generation of fly ash in India was approximately 232,56 million tons, of which Chhattisgarh state generated 40,25 million tons, which is the highest in the country. The fly ash samples were collected in plastic bags and transported to the laboratory for different experiments.

Table 2. Physical and engineering properties of materials

Properties		High Plastic Soil	Low Plastic Soil	Fly ash
Color		Black	Gray	Light Gray
Specific gravity		2,61	2,65	1,44
Particle size distribution	Gravel (%)	---	---	---
	Sand (%)	30,45	32,10	-
	Silt (%)	28,73	55,13	73,22
	Clay (%)	39,40	12,77	26,78
Liquid Limit (%)		58,00	42,30	34,56
Plastic Limit (%)		25,00	20,16	NP
Plasticity Index (%)		33,00	22,14	-
Classification		CH	CL	Class F ([39])
Compaction	MDD (kN/m^3)	16,97	18,42	11,56
	OMC (%)	16,25	15,80	18,18
UCS (kN/m^2)		112,76	238,00	---
CBR (%)		Unsoaked = 5,60 Soaked = 1,80	Unsoaked = 18,50 Soaked = 4,80	---
Resilient Modulus (MPa)		47,00	55,00	---
Free Swell Ratio		4,80	4,00	---
Morphological Characteristics (SEM)		Irregular and flatty shape	Irregular and flatty shape	Spherical shape

2.3 Alkaline activator

Alkaline activators were used to activate the fly ash to stabilise the expansive soil. Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions were used for the activation of fly ash. Sodium hydroxide was originally in pellets and collected from a local supplier, while sodium silicate was in alkaline-grade liquid form and collected from Shri Saibaba Chemicals, Gujrat, India. Liquid sodium silicate consisted of Na_2O = 14,35 % and SiO_2 = 33,10 % of specific gravity 1,56 (provided by the supplier). Two different concentrations of NaOH, 6 and 8 M, were used for experimental testing from an economic and safety perspective. The NaOH solution was prepared one day before casting the samples for the test by mixing NaOH flakes of 240 g for 6 M and 320 g for 8 M to make a 1-L solution in water. In this study, the ratio of Na_2SiO_3 to NaOH was selected as 1,5; as per the study conducted by Murmu et al. (2019) [7]. To promote silicate gelation and precipitation during geopolymerisation, a liquid solution of Na_2SiO_3 was mixed [40]. To promote silicate gelation and precipitation during geopolymerisation, a liquid solution of Na_2SiO_3 was mixed [40].

2.4 Testing method

Specimens of expansive soil (HPS and LPS) were mixed with geopolymer components, i.e., fly ash, and activators, in different combinations to assess their respective impacts. Various proportions of fly ash (0; 10; 15; 20; 25; and 30 %) by weight of dry soil were used to conduct experiments. Fly ash is the main component expected to react with the activator [3] because it is rich in silica (62,39%) and alumina (24,47%). Therefore, to understand the effect of the activator on fly ash, the activator was mixed to achieve optimum moisture content (OMC). Additionally, untreated samples prepared only with expansive soil and water were used as references, allowing a comparison with the geopolymer-stabilised samples. Table 3 presents the mix proportions of fly ash-based geopolymer in terms of OMC and maximum dry unit weight (MDU) of expansive soil. The UCS, CBR, and resilient modulus samples were prepared using the respective MDU and OMC. For resilient modulus, the test was conducted according to the guidelines provided in AASHTO: T 307-99 (2012) [41], and the resilient modulus was calculated based on the average value for each cycle of each load sequence.

Table 3. Mix proportions of fly ash geopolymer

Type of soil	Samples ID	Fly ash-activator ratio (FAR)	MDU (kN/m^3)	OMC (%)	Na_2SiO_3/NaOH activator ratio	NaOH concentrations	Curing Days
HPS	HPS	---	16,97	16,25	---	---	---
	FA10	0,6	16,47	16,13	1,5	6 M and 8 M	0; 7; 14; 28; 56; and 128 days
	FA15	0,9	16,42	15,80			
	FA20	1,3	16,38	15,10			
	FA25	1,8	16,28	14,20			
	FA30	2,0	16,14	14,50			
LPS	LPS	---	18,42	15,80	---	---	---
	FA10	0,6	18,28	15,40	1,5	6 M and 8 M	0; 7; 14; 28; 56; and 128 days
	FA15	0,9	17,78	15,20			
	FA20	1,3	17,66	16,22			
	FA25	1,8	17,11	17,30			
	FA30	2,0	16,50	18,80			

3 Results and discussion

3.1 Free swell ratio and shrinkage

The free swell test was conducted on expansive soil and stabilised expansive soil for NaOH concentrations of 6 M and 8 M after a curing period of 28 days, and the results are presented in the form of a free swell ratio (FSR). Figure 1a) shows the FSRs for HPS and stabilised HPS, while Figure 1b) shows the FSRs for LPS and stabilised LPS. The swelling behaviour of soil is mainly based on the cation exchange capacity (CEC) of clay minerals present in the soil [42; 43]. A high swelling potential was observed in HPS owing to the higher content of clay minerals, as it showed a higher CEC because of its higher water adsorption potential and specific surface area.

It was noted from the obtained results that the clay mineralogy changed when a fly ash-based geopolymer was applied to the soil; as a result, the swelling properties of the soil diminished owing to a decrease in CEC. The X-ray diffraction (XRD) results also support the existence of high-clay minerals, as shown in Figures 13 and 14, with the substitution of a small quantity of fly ash, which disrupts the structure of clay minerals, resulting in a reduction in swelling behaviour. This may be due to the development of a new chemical with a lower affinity for water adsorption, as discovered and described by the XRD results. However, because of the low-clay minerals responsible for its swelling behaviour, LPS had a lower FSR than HPS.

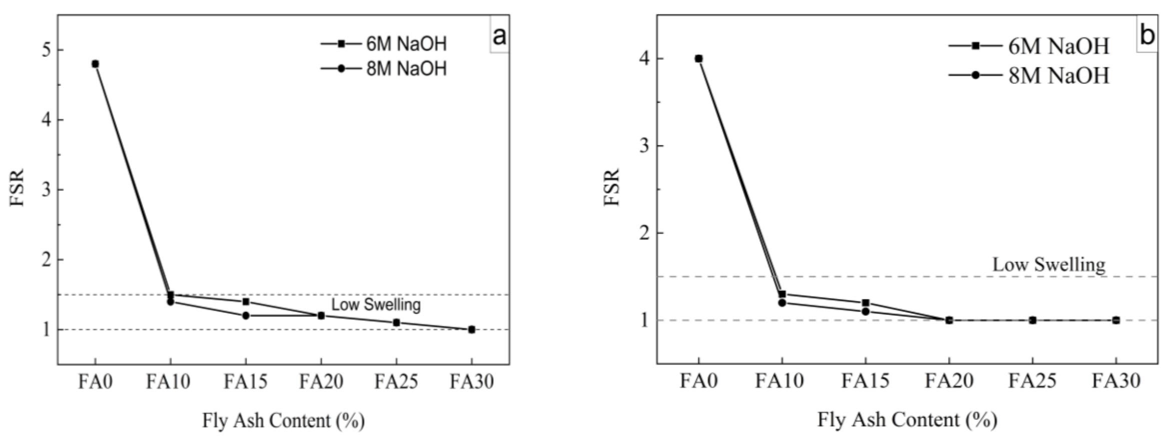


Figure 1. Free swell ratio behaviour: a) HPS; and b) LPS

According to Sridharan and Prakash (2000), soil with an FSR less than 1 is classified as non-swelling soil, and that between 1,0 and 1,5 is classified as having low swelling potential [12; 44; 45]. Because of the use of a geopolymer based on fly ash, expansive soil has a limited swelling potential, as shown in Figure 1. The swelling of the soil decreased with increasing NaOH concentration from 6 to 8 M owing to the higher concentration leading to more leaching of the reaction product and lower swelling and water-holding capacity.
The shrinkage study was conducted after 28 days of curing of the soil samples, as shown in Figure 2. The results show that the shrinkage limit of HPS was relatively high at 36,22 % (Figure 2a)), and it decreased drastically to 5,88 % upon stabilisation with the addition of 10,00 % fly ash. Meanwhile, LPS showed 26,10 % shrinkage (Figure 2b)), which decreased to 4,50 %. Furthermore, it decreased with increasing fly ash content in the soil. This reduction may be due to the reduction in clay content and therefore water absorption capacity. Thus, after stabilisation with a fly ash-based geopolymer, a substantial decrease in the swelling and shrinking behaviours of HPS and LPS was observed.

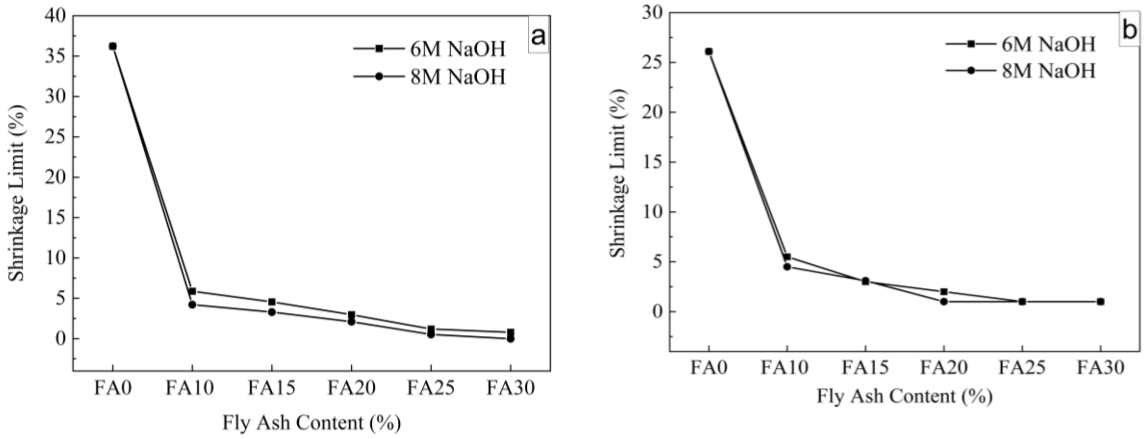


Figure 2. Shrinkage limit: a) HPS; and b) LPS

3.2 Unconfined compression strength test

The UCS test was performed on HPS and LPS and HPS/LPS-fly ash-based geopolymer. To maintain test result uniformity, the UCS findings are reported using the average UCS value of three samples. A total of 363 samples of expansive soil and stabilised expansive soil with NaOH concentrations of 6 M and 8 M were cast and evaluated using unconfined compression test equipment. The HPS and LPS mixtures with fly ash-based geopolymer were cast and evaluated for curing times of 0; 7; 14; 28; 56; and 128 days. Figures 3 and 4 illustrate the UCS value variations for HPS with varying fly ash content for 6 M and 8 M NaOH concentrations, respectively. With an increase in fly ash content, the UCS increased. The maximum increase in results was for a fly ash 25 % content, due to the presence of higher amounts of alumina and silica, which promoted the formation of the geopolymeric gel/matrix. Furthermore, up to 25 % of fly ash content, almost all fly ash particles participated in the formation of gel. However, at 30 % fly ash content, some unreacted or partially reacted fly ash particles acted as filler material, which led to decreased strength. A similar observation was made for LPS, as shown in Figures 5 and 6 for 6 M and 8 M NaOH concentrations, respectively.
In addition, varying UCS with increasing curing period was found, which shows that the UCS value increases with an increase in curing period, indicating that dense particle packing occurs owing to cementitious material formation with respect to time. The UCS value of 0 % FA (HPS) was 0,112 MPa without curing of soil samples. However, in the case of HPS, the UCS value for the 7-day curing periods for FA10% to FA30% samples were in the ranges of 0,860–1,198 MPa and 0,849-1,390 MPa for 6 M and 8 M NaOH, respectively, satisfying the minimum required strength (0,750 MPa) according to the guideline for stabilised sub-base layer at the end of the 28-days curing period given by the Indian Road Congress (IRC) 37-(2018). In the

case of LPS (Figures 5 and 6), the UCS value for the 7-day curing period for FA 10 % to FA 30 % samples was in the ranges of 0,778-1,008 MPa and 0,820–1,556 MPa for 6 M and 8 M NaOH, respectively. Furthermore, after 14-128 days of curing, the strength continuously increased because of the availability of more silicate and aluminate for geopolymer formation [6; 46]. Figures 5 and 6 also show the range of UCS values that satisfy the granular base/subbase requirement according to the guidelines of IRC: 37-2012.

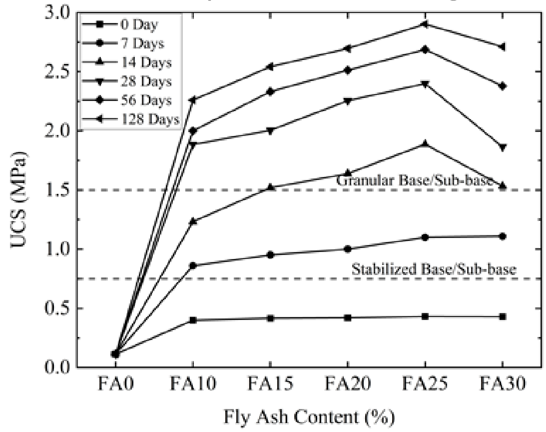


Figure 3. Variation of UCS values for various proportions of fly ash at 6 M for HPS

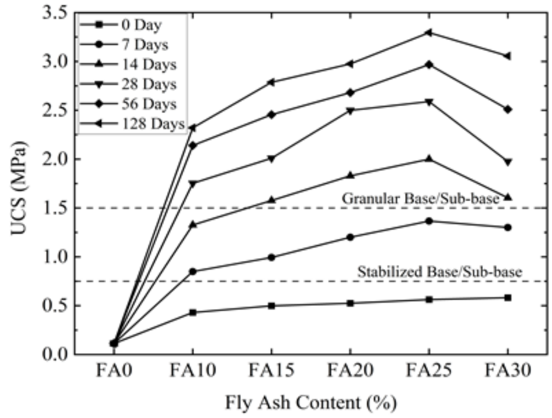


Figure 4. Variation of UCS values for various proportions of fly ash at 8 M for HPS

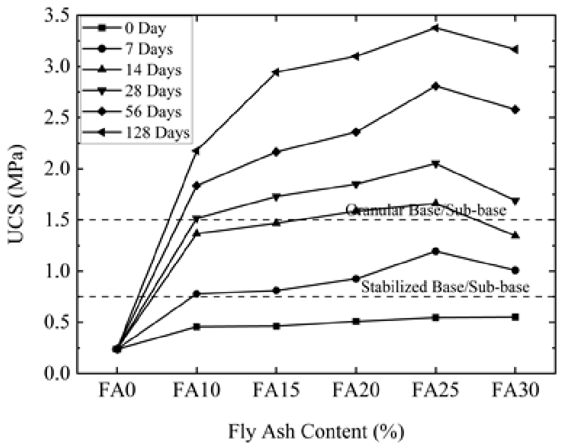


Figure 5. Variation of UCS values for various proportions of fly ash at 6 M for LPS

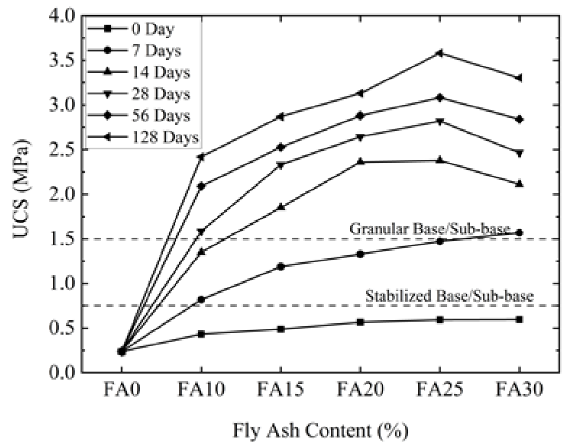


Figure 6. Variation of UCS values for various proportions of fly ash at 8 M for LPS

It was also observed that the plasticity of soil plays an important role in its strength gain. The strength of LPS was higher than that of HPS, possibly because HPS contains more clay minerals and clay content that do not allow the formation of geopolymeric gel in the full phase. Figure 7 depicts the influence of NaOH concentration on UCS for HPS with minimum strength requirements for the base and subbase, as per IRC 37; as the NaOH concentration increased from 6 M to 8 M, the UCS value increased with curing period. The increase in the UCS value may be due to an increase in the polymerisation rate with an increase in NaOH concentration; as a result, the amounts of Na+ and OH- ions were higher in 8 M than 6 M concentration, leading to more geopolymerisation [15]. Furthermore, the dissolution of fly ash was reduced at low NaOH concentrations compared to that at higher concentrations; as a result, the quantity of geopolymeric gel involved in occupying voids for the creation of a dense matrix was smaller. When fly ash reacts with NaOH, silicates, aluminates, and other minor ions are released. The number of ions released was determined by the concentration of NaOH and the leaching process time [40; 47]. In addition, when alkaline hydroxide was added, alumina silicate was generated as the primary reaction product, along with a small quantity of calcium silicate hydroxide (CSH) gel. At a constant ionic strength, aluminosilicate solubility increases with increasing hydroxide ion concentration [48]. Therefore, a higher NaOH concentration results in more leaching and the subsequent formation of the reaction product; as a result, the mixture will form a denser matrix and have higher strength [4; 49].

Figures 7 and 8 show the UCS values satisfying the minimum strength requirements for pavement layers of the stabilised base, sub-base, and granular base with varying percentages of fly ash and different curing periods for HPS and LPS, respectively. Figures 7a) and 8a) show the UCS values at 0 days of curing, which did not satisfy the minimum strength requirement for the stabilised base/sub-base. An increase in curing period to 7 days (Figures 7b) and 8b)) induced polymerisation in the samples, leading to strength enhancement and satisfying the minimum strength requirement of the stabilised base/sub-base. Furthermore, an increase in curing period from 14 to 128 days (Figures 7c–f) and 8c–f)) satisfied the minimum strength requirement of the granular base/sub-base. A higher strength performance was observed in LPS than in HPS, as LPS has a lower clay content and better packing of all soil fractions. This led to the formation of dense structures in the soil owing to the formation of a geopolymer gel.

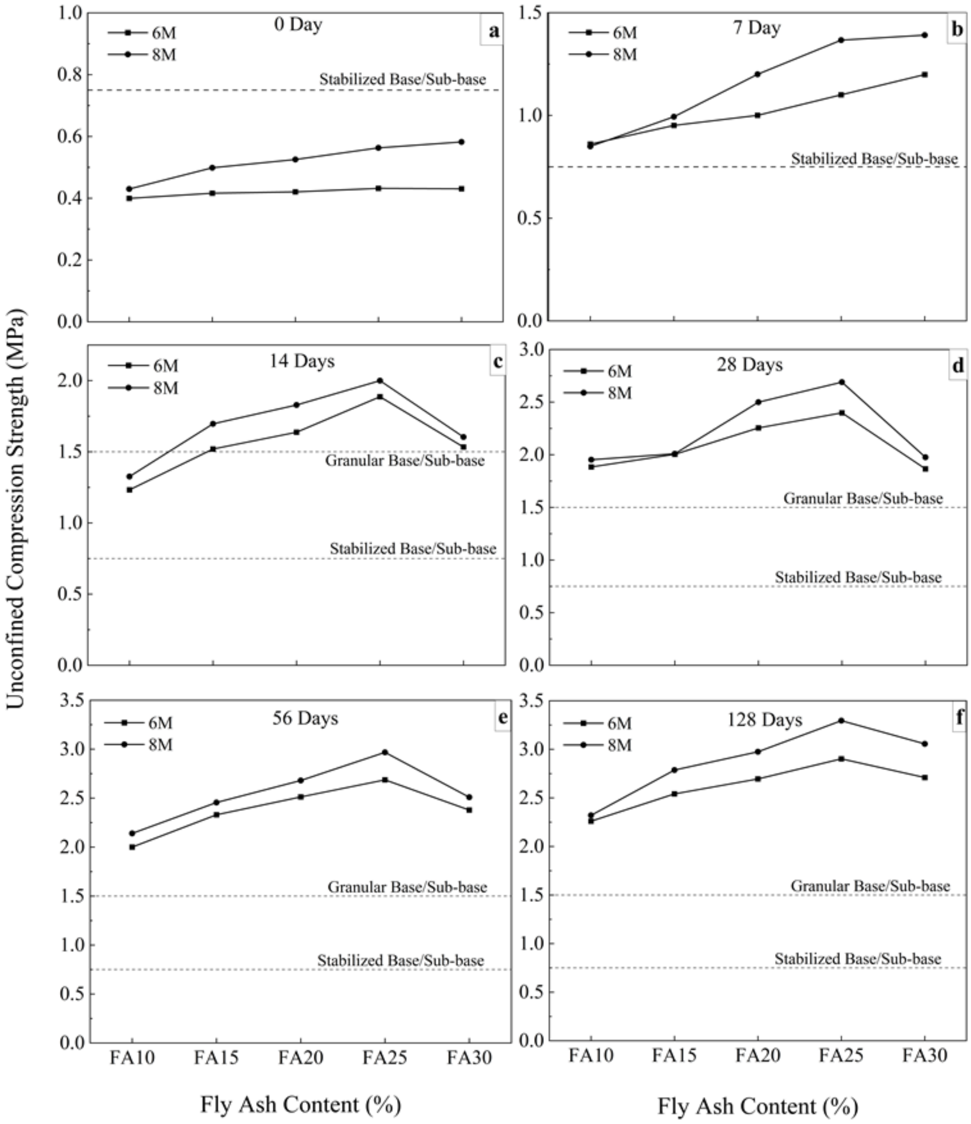


Figure 7. NaOH concentration influence on UCS values of HPS

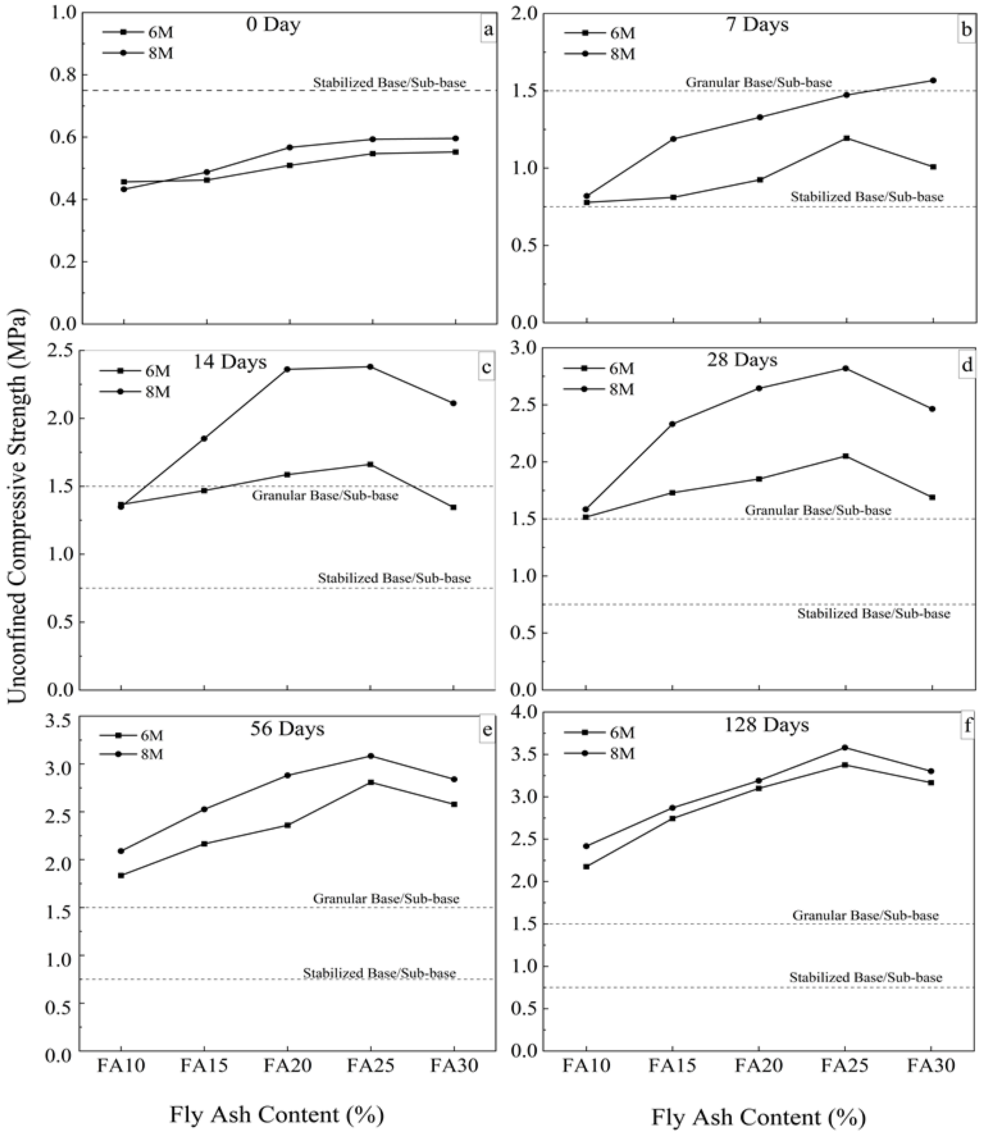


Figure 8. NaOH concentration influence on UCS of LPS

3.3 California Bearing Ratio (CBR)

Figures 9 and 10 illustrate the fluctuations in the CBR values of HPS and LPS with fly ash contents for unsoaked and 28-day cured samples of 6 M and 8 M NaOH, respectively. The CBR value for HPS in the unsoaked condition was found to be 5,6 % (Figure 9), and in the soaked condition, it was 1,8 %. Under the unsoaked condition, an increase in fly ash content led to an enhancement in CBR values because blends provide greater resistance owing to better packing of different-sized soil fractions, and fly ash behaves as a coarser material owing to floc formation. Under the soaked condition, i.e., 28 days of curing (4 days soaking +24 days curing), the soil samples exhibited a rapid increase in CBR values. When compared to untreated HPS, unsoaked CBR with fly ash contents of 10 % to 30 % increased from 114 % to 400 % and from 186 % to 529 % for 6 M and 8 M, respectively, whereas soaked CBR increased from 787 % to 1519 % and from 900 % to 1757 % for 6 M and 8 M, respectively.

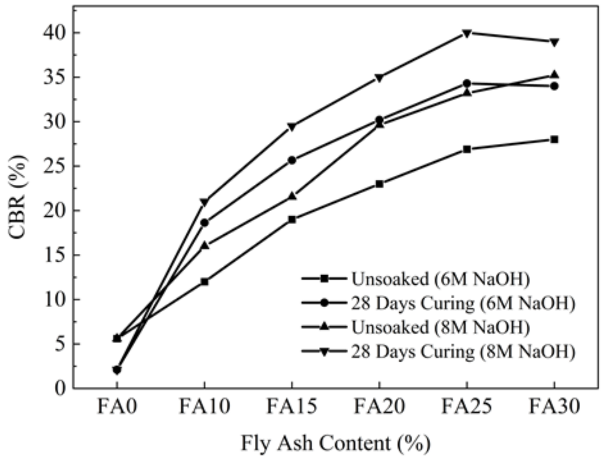


Figure 9. CBR values for HPS

In Figure 10, for LPS, the unsoaked CBR was 18,5 %, and the soaked CBR was 4,8 %, which is relatively higher than in HPS owing to the lower clay content and more sand fractions. The unsoaked CBR values increased continuously with increasing fly ash content. However, percentage increments in the CBR values for fly ash contents of 10-30 % were 3-44 % and 9-52 % for 6 M and 8 M NaOH concentrations, respectively. When soaked, CBR values increased from 421-670 % and from 487-775 % for 6 M and 8 M NaOH concentrations, respectively. This increase in CBR values was attributed to the dense microstructure of the soil particles owing to gel formation [6; 16]. During curing, fly ash may form more geopolymer gel from accessible silica, alumina, and calcium, resulting in less moisture attraction in the soil [8; 50]. Furthermore, fly ash may be favourable for the long-term development of cementitious products by filling larger pores, lowering porosity, and boosting mechanical performance. Moreover, owing to aluminate and silicate product leaching, the 8 M NaOH soil samples had higher CBR values than the 6 M samples. Owing to the partial participation of fly ash in the production of the dense matrix, the CBR value after 25 % FA concentration reduced for both 6 M and 8 M NaOH.

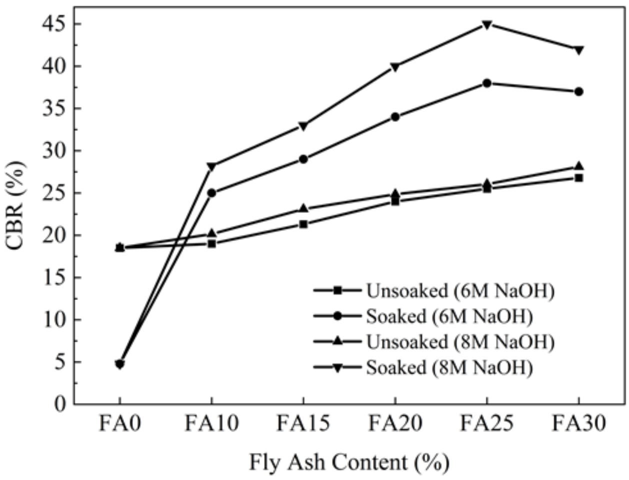


Figure 10. CBR Values for LPS

According to IRC 37 [51], the minimum criteria for CBR for stabilised expansive soil for subgrade and subbase are no less than 10 %. It was discovered that by applying geopolymer to the HPS and LPS, CBR values improved by more than 10 %, meeting the standards for subbase and subgrade.

3.4 Resilient Modulus (M_R)

Resilient Modulus (M_R) is a fundamental material property used to characterise unbound pavement materials (AASHTO T 307-99 (2012)). As per the guideline of AASHTO: T 307-99 (2012), the M_R values of stabilized HPS and LPS were determine. Figures 11 and 12 show the variations in M_R for HPS and LPS with different proportions of fly ash, respectively. The resulting behaviour indicates a pattern similar to that observed in the CBR tests. The M_R values of fly ash-based geopolymer-stabilised HPS for 6 M NaOH were 143-165 MPa and for 8 M NaOH, they were 169-181 MPa, which are much higher than that of virgin HPS (47 MPa) (Figure 11). The stabilized LPS was found in the range of 148,00-149,98 MPa and 178,05-198,00 MPa for 6 M and 8 M NaOH concentrations, respectively, while untreated LPS showed 55 MPa (Figure 12).

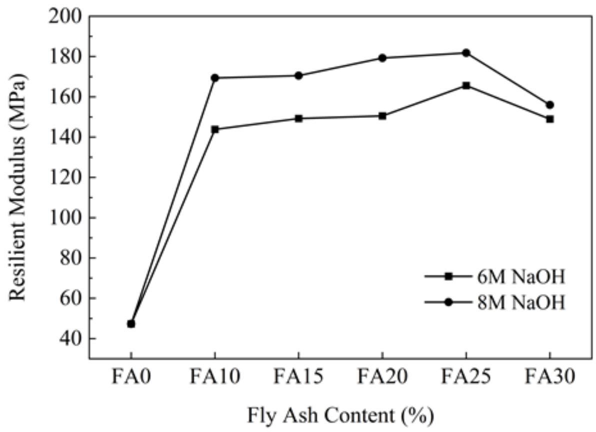


Figure 11. Resilient Modulus for HPS

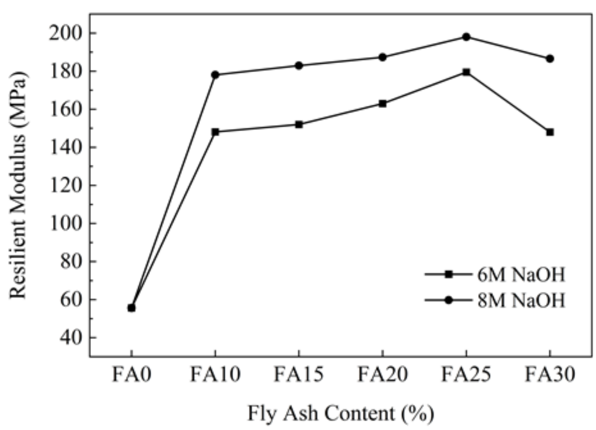


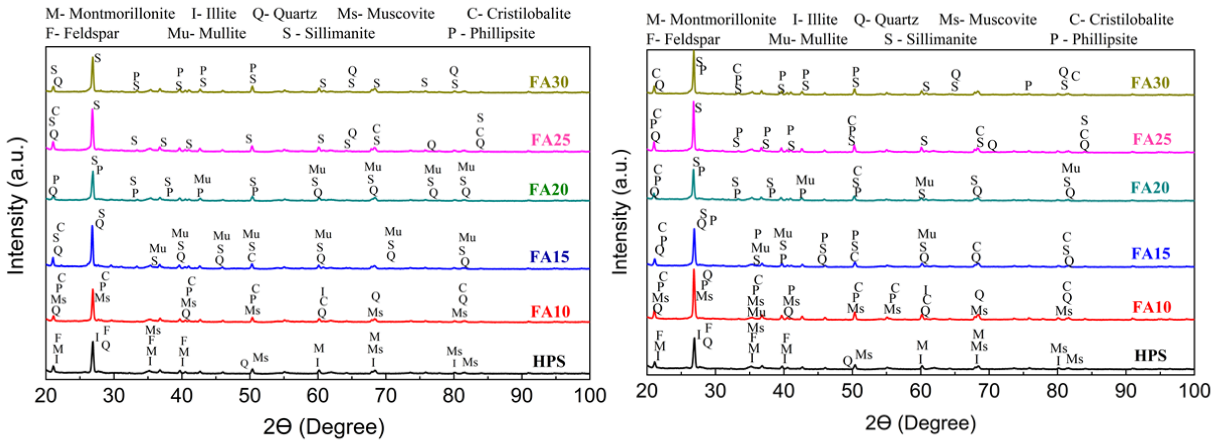
Figure 12. Resilient Modulus for LPS

3.5 Microstructural study

XRD, Scanning Electronic Microscopy (SEM), and Energy-Dispersive X-ray Spectroscopy (EDX) were used to conduct microstructural analyses on fly ash-based geopolymer specimens. This is a sophisticated instrument for tracking the production of gels and matrices over time. All soil samples tested for microstructural analysis were cured for 28 days at 6 M or 8 M NaOH concentrations for various proportions of fly ash contents.

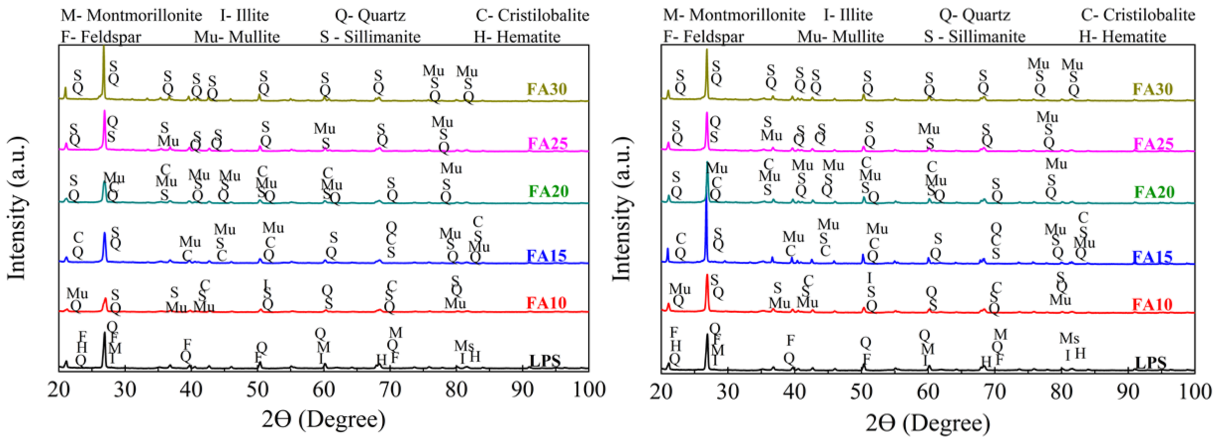
3.5.1 X-ray diffraction analysis (XRD)

XRD is the most extensively used approach for identifying soil minerals and studying their crystal structures in fine soils. After 28 days of curing, the XRD patterns of the different fly ash-based geopolymer compositions combined with expansive soil (HPS and LPS) are shown in Figures 13 and 14. Expansive soil has a high content of clay minerals, such as montmorillonite (M), illite (I), and other minerals, such as quartz (Q), muscovite (Ms), and feldspar (F). Thus, HPS with a geopolymer based on fly ash greatly affected the diffraction pattern; novel reflection patterns were also observed; notably, sillimanite (S), phillipsite (P), mullite (Mu), cristobalite (C), and hematite (H) around approximately 2Ɵ= 21,11°; 26,89°; 33,39°; 40,51°; 42,65°; 45,98°; 50,35°; 60,12°; 64,36°; 68,33°;75,80°; and 80,03° (Figure 13). For LPS, reflection peaks were observed at 2Ɵ = 21,22°; 27,07°; 35,49°;39,87°; 42,75°; 50,50°; 60,38°; 68,53°; 75,97°; 81,70°; and 82° (Figure 14). These minerals were crystalline phases identified in the gel generated by the active dissolution of sodium aluminosilicate compounds with pozzolanic particles [12; 35; 52].



a) b)

Figure 13. XRD results for HPS: a) 6 M NaOH; and b) 8 M NaOH



a) b)

Figure 14. XRD Results for LPS: a) 6 M NaOH; and b) 8 M NaOH

Furthermore, some of the peaks were not traced in stabilised soil compared to the original HPS and LPS, which showed a change in the layered structure of the clay mineralogy [35]. The low-intensity peaks of stabilised soils indicate the participation of soil in the geopolymerisation process [28]. The number of new peaks detected at a higher concentration of NaOH indicates more leaching of alumina silicate gel as a result of the higher strength. The swelling behaviour of the soil was mainly controlled by clay minerals (montmorillonite and illite), which were not detected in the stabilised soil being less prone to swelling and shrinkage.

3.5.2 Scanning electronic microscopy and energy-dispersive X-ray spectroscopy (EDX)

A microstructural study was conducted after 28 days of curing the stabilised soil sample through SEM and EDX tests. The sample was collected after performing the UCS test on 1-cm cubes with a smooth surface to obtain high-resolution SEM images. SEM images and EDX spectra of the stabilised HPS and LPS are shown in Figures 15 and 16, respectively. The microstructural variations in HPS and LPS for fly ash contents of 10 %; 15 %; 20 %; 25 %; and 30 % are shown in Figures 15a-e) and 16a-e), respectively. From the images, it can be seen that a majority of the fly ash particles dissolved in the alkaline solution and leached alumina and silica to form the geopolymer. However, some fly ash particles remained unreacted or were partially reacted, as shown in Figures 15e) and 16e).

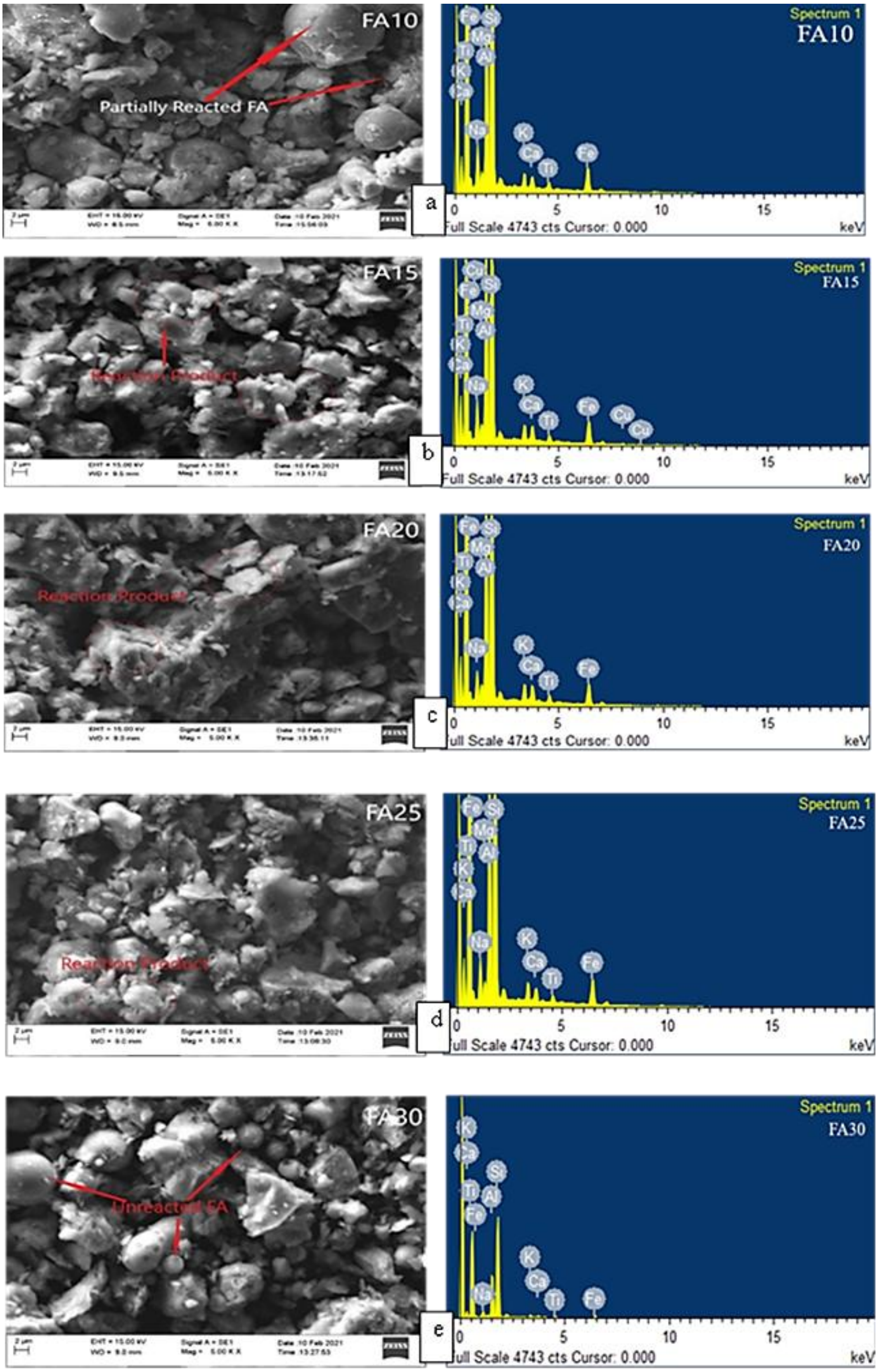


Figure 15. SEM and EDX Spectra for: a) HPS+FA10; b) HPS+FA15; c) HPS+FA20; d) HPS+FA25; and e) HPS+FA30

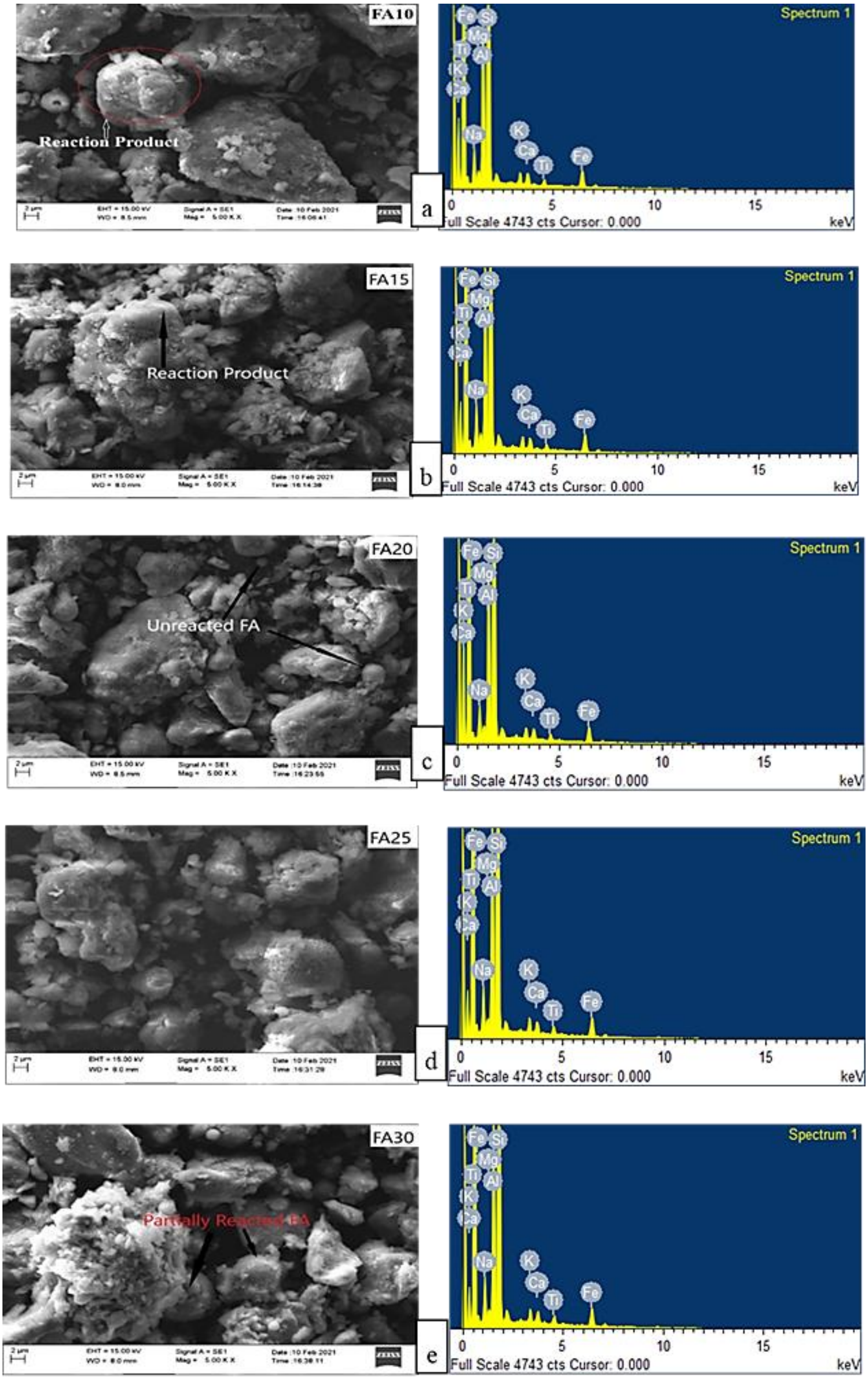


Figure 16. SEM and EDX Spectra for: a) LPS+FA10; b) LPS+FA15; c) LPS+FA20; d) LPS+FA25; and e) LPS+FA30

Along with SEM, the EDX spectra of the stabilised HPS and LPS were obtained for the detection of chemical compounds. This revealed that the geopolymer gel formed owing to the active dissolution of silica and alumina ions, which leached the NASH and CASH. Thus, a dense and compact microstructure of HPS and LPS was formed because of these two reaction products (NASH and CASH). However, higher amounts of CASH were observed in LPS than in HPS, as per the EDX spectra.

4 Benefits of application of fly ash-based geopolymer

Due to the excessive use of natural resources in the development of civil engineering infrastructure, such as pavements and building foundations, there is a scarcity of natural materials in particulate construction areas. Thus, forceful treatment of locally available soil is one of the ways to save natural resources as well as the cost of construction. In addition, the treatment of soil with available industrial waste products provides a more sustainable solution to environmental issues. As stated in the introduction, cement and lime are common stabilisers used for soil treatment. In comparison with these traditional stabilisers, the following are some of the benefits of using non-traditional stabilisers.

The use of fly ash-based geopolymers for the treatment of soil is a very good alternative to cement and lime. It is worth noting that replacing 15-50 % of cement usage worldwide with supplementary fly ash-based geopolymer would lead to a decrease of 250-800 million tons of CO_2 emissions [53].

Thus, the environmental problems caused by the disposal of fly ash into landfills can be solved. Because this by-product is utilised as a construction material, it improves the poor properties of soil, supports sustainable construction, and helps preserve the environment.

The experimental results indicate that the application of fly ash-based geopolymer can successfully stabilize concrete through its in-situ existence in soil. Hence, there are no environmental impacts from the excavation and transportation of expansive soil. Considering the quantity of material and transportation used in the soil stabilisation process, the energy consumption and CO_2 emissions are relatively lower with this non-traditional soil stabiliser compared to traditional soil stabilisers.

Furthermore, the overall material requirements were reduced by improving the high-strength properties of local soil. This can reduce the overall cost of construction and related costs, such as the excavation of soil, borrowed stabilised soil, and transportation. The study by Turkane and Chouksey (2022) [54] showed a reduction in overall cost of a project of up to 11 %, which shows the effectiveness of the material in road pavement construction.

Because of the limited money available to build and maintain civil infrastructure, it is necessary to develop a cost-effective approach for constructing civil substructures.

5 Conclusions

The swelling and shrinkage behaviours of stabilised expansive soil were reduced by 79,17 %; 83,77 %; 75,00 %; and 96,17 % compared with untreated HPS and LPS, respectively.

The strength parameters (UCS, CBR, and MR) of the expansive soil treated with fly ash-based geopolymer were greatly improved. Continuous strength improvement was observed up to a fly ash content of 25,00 % for all curing periods. The 8 M NaOH concentration exhibited the highest strength performance compared to the 6 M NaOH concentration.

The strength of the soil increased as the NaOH concentration rose from 6-8 M. In addition, LPS showed a higher strength than HPS because of its clay content and mineralogy. After 7 days of curing, the strength improvement using fly ash-based geopolymer-stabilised expansive soil was larger than the minimum strength necessary for the sub-base course of road pavement under IRC: 37-2012.

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