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Performance behavior of soil plasticity for fly ash-based geopolymer: a flexible pavement material

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Abstract

Soil plasticity plays a vital role in the strength gain of the material; high and low expansivity of soil is more common in nature for any expansive soils. Most of the 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 the construction of road subgrade through laboratory experimentation via free swell behavior, shrinkage behavior, unconfined compression test, California bearing ratio, and resilient modulus. The effectiveness and feasibility were shown by the material in terms of reduction in swelling and shrinkage, and improvement in the strength behavior of the soil mass. The optimized fly ash and geopolymer mixes were noted at 25%; this could be observed through the microstructure analysis of soil samples. The soil plasticity plays an important role in governing the strength of soil; low plastic soil has high mechanical strength compared to high plastic soil. Fly ash geopolymer-treated soil material is found to be more suitable for the construction of the subgrade or subbase layer of flexible pavement, and helps to reduce conventional stabilizers and leads to sustainable solutions.

Keywords Green cement, High plastic, Low plastic, Fly ash, Geopolymer, Sustainable solution, Road pavement

1 Introduction

Expansive soil is essentially clay soil with a larger concentration of clay minerals, low shear strength, considerable deformation under a small force, and high swelling-shrinkage potential [1]. As a result, in geotechnical engineering, this type of soil is mostly classified as problematic soil [2, 47]. Hence, such soils must be treated to avoid difficulties caused by their expansive character. Chemical soil stabilization is a more common, less expensive, and frequently used approach. Generally, cement and/or lime are the most common conventional stabilizers (binders) used to create cementitious materials. Despite the fact that both are intended to improve soil mechanical strength, cement-based stabilizers have more strength than lime-based stabilizers [3]. However,



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cement manufacturing is becoming unsustainable due to the cement industry's global production of greenhouse gases such as carbon dioxide (CO_2). Therefore, researchers and engineers are constantly looking for novel, sustainable, and cost-effective stabilizer alternatives to ordinary Portland cement. Also, industrial by-products such as cement kiln dust, calcium carbide residue, granulated blast furnace slag, fly ash, etc., are of great concern for disposal in an eco-friendly manner. This can also be a soil stabilizer material, and its application in the geotechnical construction industry may lead to a sustainable solution. However, during the last two years, several new eco-friendly materials have been emerged beside the geopolymer materials such as activated cement Kiln Dust, activated zeolite, bio cement, calcined shale [4–9]. The various researchers, such as [10–19, 53], have successfully conducted studies for the application of these by-products in soil stabilization. Out of which, fly ash has great concern about disposal and can be used in mass quantities; also, it has high potential to form geopolymer [9, 20–22]. The fly ash geopolymer material ingredients are explained in subsequent sections. Geopolymer is an inorganic aluminosilicate material formed from the polycondensation of silica and alumina [18, 19].

1.1 Alkaline activation or geopolymer

Nowadays, the reuse of such industrial by-products, which are rich in alumina and silica, through alkaline activation stabilizers constitutes an attractive and effective non-traditional stabilizer option as an alternative to traditional stabilizers [24–27]. The process of alkaline activation usually includes the dissolution of silica and alumina using 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 were derived by [21], as shown in Table 1.

Model I—In this model, high-calcium and silica-rich materials are alkaline-activated at high temperatures. The main reaction product formed is calcium silicate hydrate gel (CASH), similar to that obtained after the OPC pozzolanic reaction [28].

Model II—In this model, the material is activated and enriched in silica and alumina and low calcium content. This model is known as a geopolymer or inorganic polymer. The working conditions are aggressive to start the reaction or polymerization due to the presence of highly alkaline media and high curing temperature. The main reaction product formed a three-dimensional structure of alumina and silica as a gel alkaline aluminosilicate hydrate (NASH) [18, 21, 24]. This gel is also called geopolymer or inorganic polymer. This model has several studies in the literature for soil stabilization applications [3, 5–7, 25–34].

Model III—This model comprises the combination of two models, consisting of the activation of materials, fly ash and GGBS, where the reaction products NASH and CASH gels are introduced. This model requires an ambient temperature and low alkali

Table 1 Alkaline activation models [26]

Model	Source materials	Reaction product
I	High-calcium and silica-rich materials (class C fly ash, GGBS) $\text{SiO}_2 + \text{CaO} > 70\%$	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

conditions, which may assist in bringing the strength of treated soils to the economical boundary since elevated temperature and high alkalinity are not practical conditions for soils. This model has limited the study of soil stabilization application [35–41].

Models II and III are both geopolymeric models; however, there is debate in the literature on Model I as to whether this can be classified as a geopolymer or not. Therefore, Model I is excluded from the current study. As compared to Model II, the geopolymerization through Model III (see Table 1) seems to be more appropriate for soil stabilization at ambient temperature and hence should be considered. However, model III involves the combination of pozzolanic material with other calcium-rich additives, so it becomes again an unsustainable approach. So, before adopting model III, it is necessary to understand the basic reaction mechanism of model II in expansive soil stabilization.

1.1.1 Geopolymer (Model II)

The concept of geopolymer was first introduced by Joseph Davidovits in 1976 to name three-dimensional aluminosilicates that are formed by naturally occurring aluminosilicate materials [23]. The term ‘geopolymer’ is also named in much of the literature as ‘soil cement,’ ‘alkali-activated materials,’ ‘mineral polymer,’ ‘mineral polymer,’ ‘inorganic polymer,’ etc. For simplicity, the term ‘geopolymer’ will be used throughout the current research work. The geopolymer itself is demonstrated as a suitable material for soil stabilization that overcomes the issues faced by the traditional stabilizer.

The efficiency of a fly ash-based geopolymer as a binder is dependent on several parameters, including the activator concentration and curing temperature. Practically, geopolymer for soil stabilization is feasible at ambient temperature since at higher temperatures it needs more alkaline conditions, and this increases the cost of stabilization. However, as per various studies conducted in the past, there is limited relevant research on the application of fly ash for geopolymers for the stabilization of soil. Therefore, the main objective of this paper is to understand the feasibility of fly ash-based geopolymer for soil (high and low plastic) stabilization through an experimental laboratory testing program. Also, the study highlighting the characterization of soil based on plasticity is very rare, or no study at all was found.

The experimental investigation was carried out via unconfined compression strength, California bearing ratio, resilient modulus, and swelling-shrinkage behavior.

2 Material and testing conditions

2.1 Soil

The soil samples were collected from two different sites near Raipur city at a depth of 1 m and transported to the laboratory for classification and strength testing. After collection, the soil was air-dried for two days and then pulverized using a wooden mallet. To examine the influence of fly ash and geopolymer on the plasticity properties of soil, the samples were categorized based on the Unified Soil Classification System (USCS) into two groups: high-plastic soil (HPS) with a liquid limit (LL) greater than 50, and low-plastic soil (LPS) with a liquid limit (LL) less than 50.

2.2 Fly ash

In this research, fly ash was employed as a stabilizing material for soil improvement. The fly ash was sourced from the thermal power plant of the National Thermal Power

Corporation and the Steel Authority of India Limited (NSPCL), Bhilai, Chhattisgarh, India. India generates a significant amount of fly ash annually. As reported by the Central Electricity Authority, 2021 [42], New Delhi, the country produced about 232.56 million tons of fly ash, with Chhattisgarh accounting for the largest share of 40.25 million tons.

2.3 Alkaline activator

Fly ash material was activated in alkaline conditions by means of sodium hydroxide and sodium silicate. The sodium silicate (Na_2SiO_3) of alkaline-grade liquid form was collected from Shri Saibaba Chemicals, Gujarat, India. Whereas, sodium hydroxide (NaOH), originally in pellets, was collected from the local supplier. The chemical composition of liquid sodium silicate consists of $\text{Na}_2\text{O} = 14.35\%$ and $\text{SiO}_2 = 33.10\%$ with a specific gravity of 1.56 (provided by the supplier). In the current study, the two different concentrations of NaOH , i.e., 6 and 8 molar (M), were used for experimental testing from an economic and safety point of view. The NaOH solution was prepared one day before casting samples for the test by mixing NaOH flakes of 240 g for 6 M and 320 g for 8 M to make a one-liter solution. The $\text{Na}_2\text{SiO}_3/\text{NaOH}$ was selected as 1.5 as per the study conducted by Murmu et al. (2019) [13]. To enhance silicate gel formation and precipitation during geopolymerization, a liquid sodium silicate (Na_2SiO_3) solution was incorporated [43]. To promote silicate gelation and precipitation in geopolymerization, a liquid solution of Na_2SiO_3 was mixed [43].

2.4 Testing method

Soil specimens (HPS and LPS) were blended with geopolymer constituents, namely fly ash and alkaline activators, in varying combinations to evaluate their individual effects. Experimental tests were carried out using different fly ash proportions of 0%, 10%, 15%, 20%, 25%, and 30% by the dry weight of soil. Fly ash is the main component expected to react with the activator [3] due to high silica and alumina content. For simplicity, the amount of activator was mixed equally with the amount of optimum moisture content (OMC) to check the impact on the soil. Additionally, untreated samples prepared only with soil and water were also adapted to act as references, allowing comparison with the geopolymer-stabilized soil samples. Table 2 presents the mix proportion of fly ash-based geopolymer in terms of maximum dry unit weight (MDU) and OMC of soil.

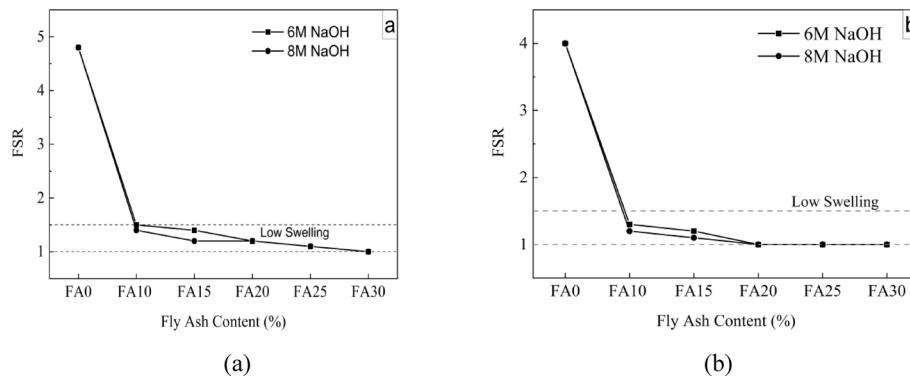
3 Results and discussion

3.1 Free swell ratio and shrinkage study

Free swell ratio—The free swell test was conducted on soil and stabilized soil for NaOH concentrations of 6 M and 8 M after a curing period of 28 days, and the results were presented in the form of a free swell ratio (FSR). Figure 1(a) shows the free swell ratio for HPS and stabilized HPS, while Fig. 1(b) shows the free swell ratio for LPS and stabilized LPS. The swelling behavior is generally understood through the cation exchange capacity (CEC) of clay minerals present in the soil [39, 40, 44]. The high swelling potential was observed in HPS due to higher content of clay minerals, due to high CEC thereof high water adsorption potential and specific surface area. It was noted from the obtained results that the clay mineralogy changes when a fly ash-based geopolymer is applied to soil; as a result, swelling properties of soil diminish owing to a drop in CEC. However,

Table 2 Mix proportion of fly Ash geopolymer

Type of soil	Samples ID	Fly ash-activator ratio (FAR)	MDU (kN/m ³)	OMC (%)	Na ₂ SiO ₃ /NaOH activator ratio	NaOH concentrations	Curing days
HPS	HPS	-	16.97	16.25	1.5	6 M and 8 M	0, 7, 14, 28, 56, and 128 days
	FA10	0.6	16.47	16.13			
	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	15.8	1.5	6 M and 8 M	0, 7, 14, 28, 56, and 128 days
	FA10	0.6	18.28	15.4			
	FA15	0.9	17.78	15.2			
	FA20	1.3	17.66	16.22			
	FA25	1.8	17.11	17.3			
	FA30	2.0	16.50	18.8			

**Fig. 1** Free Swell Ratio behavior: (a) HPS and (b) LPS

because of the low clay minerals responsible for swelling behavior, LPS has a lower FSR than HPS.

According to Sridharan & Prakash 2000 [46], soil having FSR less than 1 is classified as non-swelling soil, and in between 1 and 1.5 classified as low swelling potential [12, 41, 42]. As a result geopolymeric stabilized soil has limit the swelling potential of the soil, as shown in Fig. 1. It also observed that swelling of soil reduces for a change of NaOH concentration from 6 M to 8 M, owing to the higher concentration leading to more leaching of reaction product and lower swelling and water-holding capacity.

Shrinkage Behavior—The shrinkage study was conducted on a soil sample of 28 days of curing, as shown in Fig. 2. The HPS shows a shrinkage limit of quite a high 36.22% (Fig. 2(a)), and it decreases rapidly to 5.88% on stabilization with the addition of 10% fly ash. Whereas, LPS was 26.1% (Fig. 2(b)), which decreased to 4.5%. Further, it reduces with an increase in the increment of fly ash proportion in the soil. This may be due to the reduction in clay content and, therefore, water absorption capacity. Hence, after stabilization with a geopolymer based on fly ash, a substantial decrease in the swelling and shrinking behavior of HPS and LPS was found.

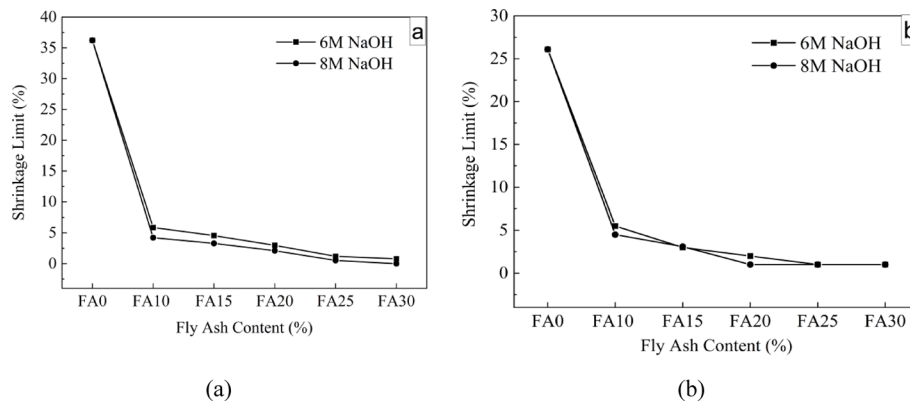


Fig. 2 Shrinkage Limit (a) HPS and (b) LPS

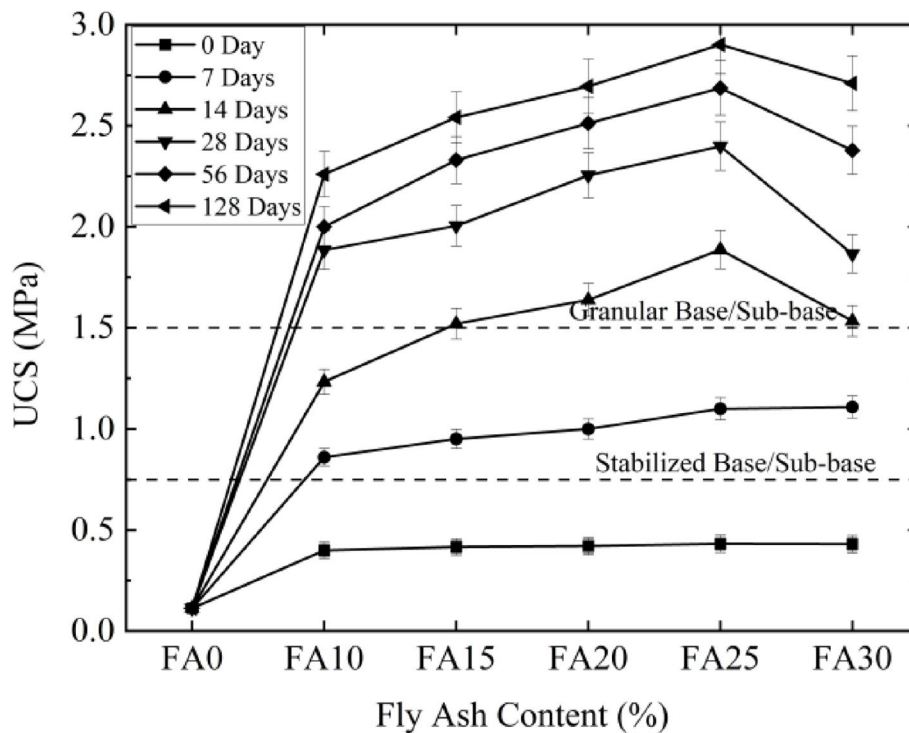


Fig. 3 Variation of UCS values for various proportions of fly ash at 6 M for HPS

3.2 Unconfined compression strength (UCS) test

The UCS test was conducted on HPS, LPS, and HPS/LPS-fly ash-based geopolymer. To maintain test result uniformity, the average UCS value of three samples was considered. A total of 363 samples of soil and stabilized soil with NaOH concentrations of 6 M and 8 M were cast and evaluated under unconfined compression test equipment.

The HPS and LPS mixtures with fly ash-based geopolymer were subjected to curing times of 0, 7, 14, 28, 56, and 128 days and tested. Figures 3 and 4 illustrate UCS value variations for HPS with varying fly ash content for NaOH concentrations of 6 M and 8 M, respectively. It was observed that the UCS value improved with the increase in fly ash content, reaching its peak at 25% fly ash. This enhancement is attributed to the higher alumina and silica content, which facilitates the development of a geopolymeric

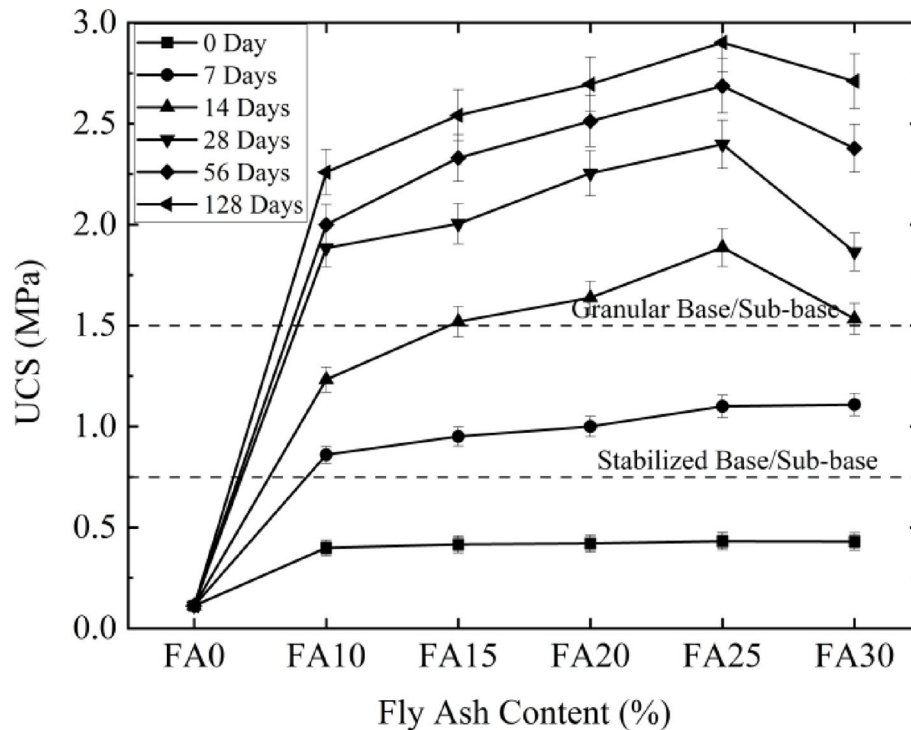


Fig. 4 Variation of UCS values for various proportions of fly ash at 8 M for HPS

gel/matrix. Up to 25% replacement, nearly all fly ash particles actively contributed to gel formation. However, at 30% fly ash content, some particles remained unreacted or only partially reacted, functioning as filler material, which could result in a reduction in strength. A similar observation was made for LPS, as shown in Figs. 5 and 6 for 6 M and 8 M NaOH concentrations, respectively.

Also, various UCS with increasing curing periods have been found that show UCS value increases with an increase in curing periods, indicating that dense particle packing takes place due to the formation of cementitious binding material with time. The UCS value for HPS (0% FA) was noted as 0.112 MPa without curing of soil samples. However, for the 7-day curing periods for FA10% to FA30% containing soil samples was in the range of 0.860–1.198 MPa and 0.849–1.390 MPa for NaOH concentration of 6 M and 8 M, respectively, that satisfies the minimum required strength (0.750 MPa) according to the Indian Road Congress (IRC) 37-(2018) the stabilized sub-base layer at the end of the 28-day curing period. In the case of LPS (Figs. 5 and 6), the UCS value for FA10% to 30% at a 7-day curing period soil samples was in the range of 0.778–1.008 MPa and 0.820–1.556 MPa for 6 M and 8 M NaOH, respectively. Furthermore, for 14 to 128 days of curing, the strength continuously increased because of the availability of more silicate and aluminate for geopolymer formation [6, 43]. Figures 5 and 6 also show the range of UCS values that satisfy the granular base/subbase requirement according to IRC: 37-2012 [49].

It has also been seen that the plasticity of soil plays an important role in the strength gain of soil. The LPS has higher strength compared to the HPS; the possible reason is that the HPS contains higher clay minerals and clay content that does not allow the formation of geopolymeric gel into the full phase.

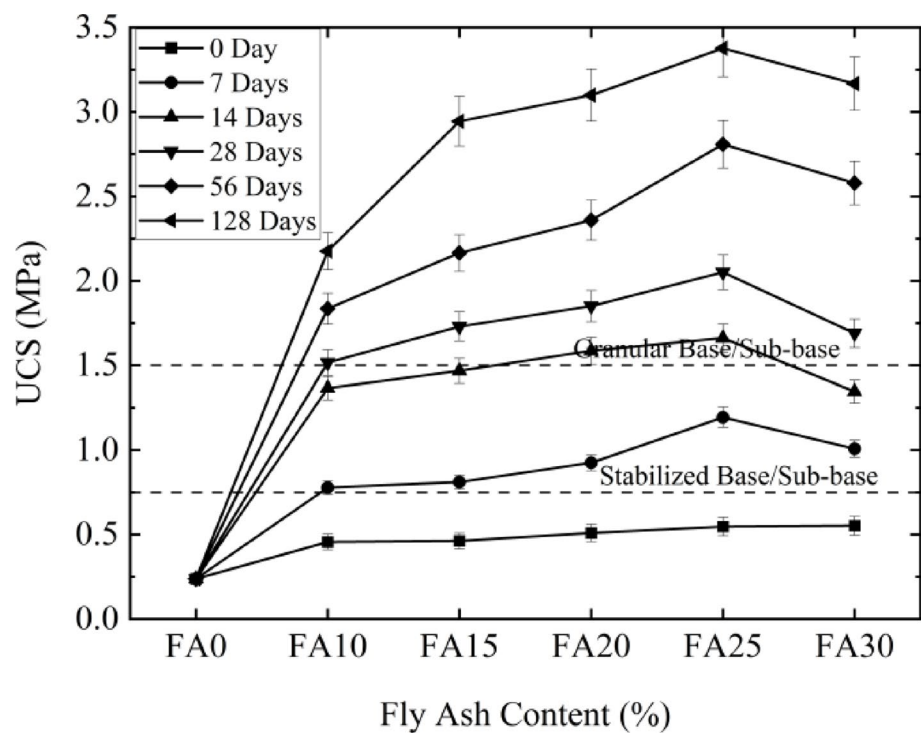


Fig. 5 Variation of UCS values for various proportions of fly ash at 6 M for LPS

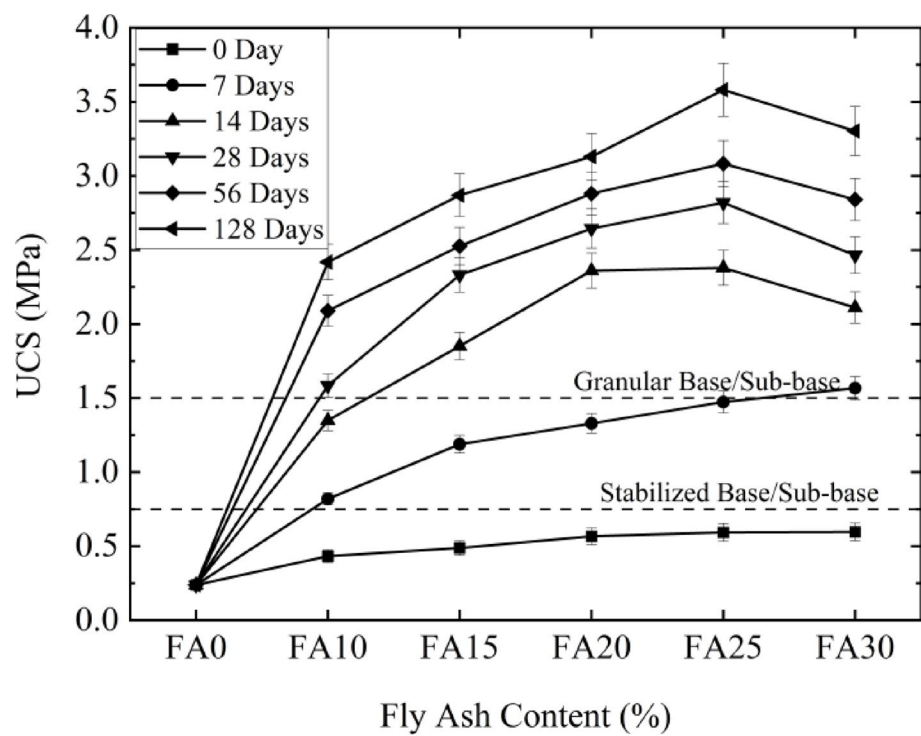


Fig. 6 Variation of UCS values for various proportions of fly ash at 8 M for LPS

Figure 7 depicts the influence of NaOH concentration on UCS for HPS with minimum strength requirements for base and subbase as per IRC 37; it has been noticed that when the NaOH concentration increases from 6 M to 8 M, the UCS value increases with regard to the curing periods. The rise in UCS value can be attributed to the higher rate of polymerization with increasing NaOH concentration. At 8 M, the availability of Na^+ and OH^- ions is greater compared to 6 M, which enhances the extent of geopolymerization [21]. Furthermore, the dissolving of fly ash was reduced at low NaOH concentrations compared to higher concentrations; as a result, the quantity of geopolymeric gel involved in occupying voids for the creation of a dense matrix would be smaller. When fly ash reacts with NaOH, silicates, aluminates, and other minor ions are released. The number of ions released is determined by the concentration of NaOH and the time of the leaching process [38, 45]. In addition, when alkaline hydroxide was added, alumina silicate was generated as the primary reaction product, along with a tiny quantity of calcium silicate hydroxide (CSH) gel. At constant ionic strength, aluminosilicate solubility rises with increasing hydroxide ion concentration [50, 51]. Therefore, higher NaOH

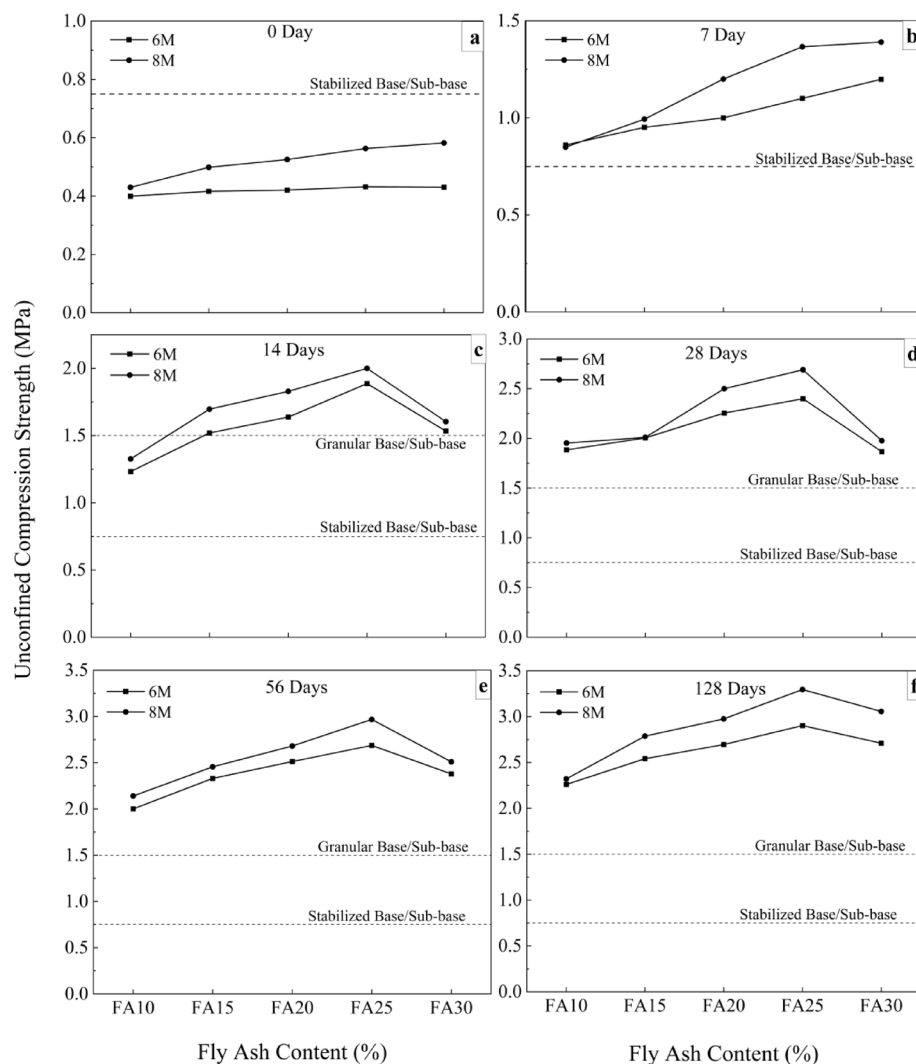


Fig. 7 NaOH Concentration influence on UCS values of HPS

concentration, more leaching, and subsequent formation of the reaction product; as a result, the mixture will form a denser matrix and have higher strength [10, 52].

Figures 7 and 8 show the UCS values satisfying the minimum requirement of strength for pavement layers of stabilized base, sub-base, and granular base with varying percentages of fly ash and different curing periods for HPS and LPS, respectively. Figure 7(a) and Fig. 8(a) show UCS values at the 0-day curing period that did not satisfy the minimum strength requirement for the stabilized base/sub-base. With an extended curing period of 7 days (Fig. 7(b) and Fig. 8(b)), polymerization within the samples enhanced strength, meeting the minimum strength criteria for stabilized base/sub-base layers. Furthermore, prolonging the curing period from 14 to 128 days (Fig. 7(c to f) and Fig. 8(c to f)) fulfilled the minimum strength requirements for granular base/sub-base layers. LPS exhibited higher strength performance than HPS, owing to its lower clay content and improved particle packing, which facilitated the development of denser soil structures through geopolymer gel formation.

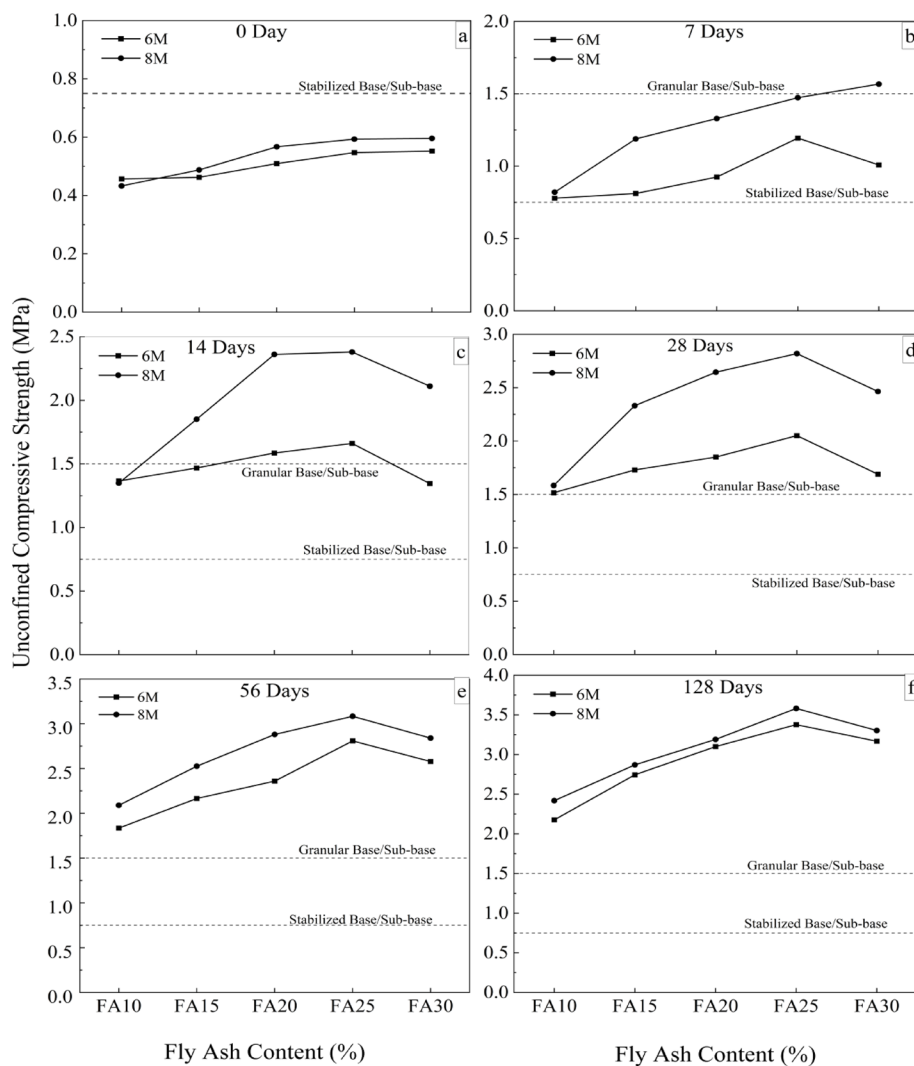


Fig. 8 NaOH Concentration Influence on UCS of LPS

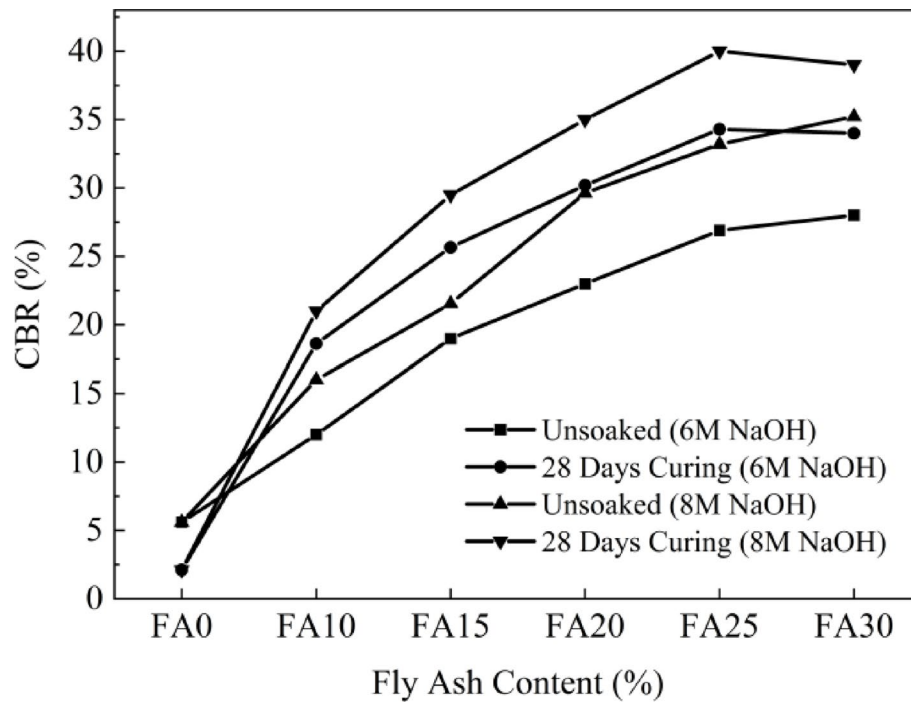


Fig. 9 CBR values for HPS

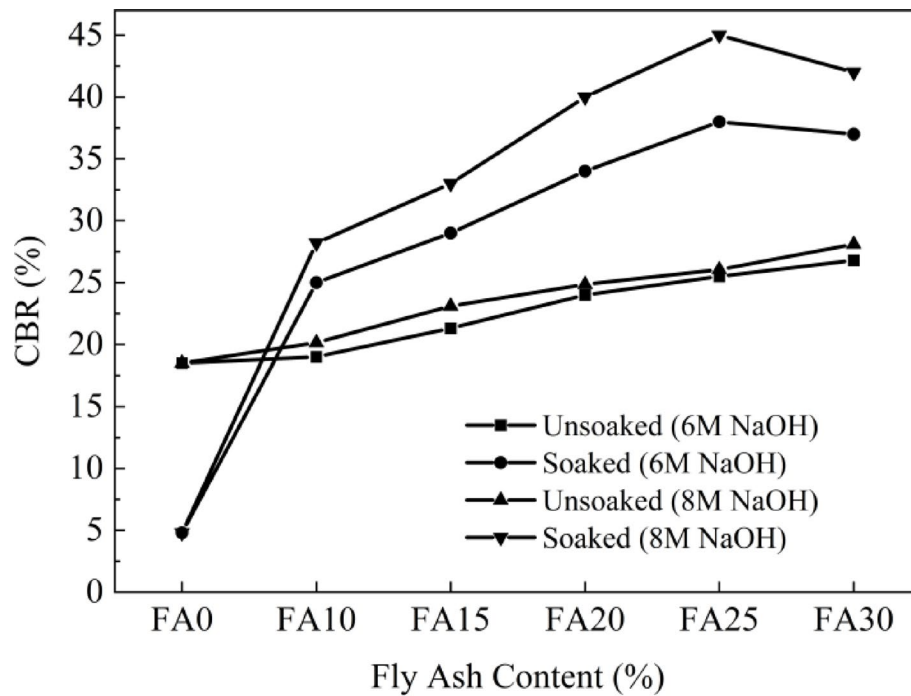


Fig. 10 CBR values for LPS

3.3 California bearing ratio (CBR)

Figures 9 and 10 illustrate the fluctuation of 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 unsoaked condition was found to be 5.6% (Fig. 9), and in the

soaked condition, it was 1.8%. Under unsoaked conditions, increasing the fly ash content improves the CBR values, as the soil–fly ash blends offer higher resistance due to improved packing of differently sized soil particles, with fly ash acting as a coarser material because of floc formation. In contrast, under soaked conditions (28 days curing, including 4 days of soaking and 24 days of curing), the soil samples show a sharp rise in CBR values. Compared to untreated HPS, the unsoaked CBR increases by 114% to 400% and 186% to 529% for 6 M and 8 M concentrations, respectively, while the soaked CBR rises by 787% to 1519% and 900% to 1757% for 6 M and 8 M, respectively.

In Fig. 10 for LPS, the unsoaked CBR was 18.5%, and the soaked CBR was 4.8%, which is relatively higher than in HPS due to lower clay content and more sand fractions. The unsoaked CBR values continuously increase with increasing fly ash content. However, percentage increments in the CBR values for fly ash content of 10% to 30% were 3 to 44% and 9 to 52% for 6 M and 8 M NaOH concentrations, respectively. While soaked, CBR values increased from 421 to 670% and 487–775% for 6 M and 8 M NaOH concentrations, respectively. This increase in CBR values was attributed to the dense microstructure of soil particles due 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, 48]. Furthermore, fly ash may be favorable to the long-term development of cementitious products by filling larger pores, lowering porosity, and boosting mechanical performance. Moreover, due to aluminate and silicate product leaching, 8 M NaOH concentrated soil samples had a higher CBR value than 6 M NaOH concentrated soil samples. Due to the partial participation of fly ash in the production of dense matrix, the CBR value after 25% FA concentration was reduced by both 6 M and 8 M NaOH.

According to IRC 37, the minimum criteria for CBR for stabilized soil for subgrade and subbase should not be 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 the subbase and subgrade.

3.4 Resilient modulus (M_R)

Resilient modulus (M_R) is defined as a fundamental material property for characterization of unbound pavement materials (AASHTO T 307–99 (2012)) [54]. According to AASHTO: T 307–99 (2012), the M_R of stabilized HPS and LPS was determined. Figures 11 and 12 show the variation of resilient modulus (M_R) for HPS and LPS with various fly ash contents, respectively. The resulting behavior indicates a similar pattern to that noted in CBR tests. The M_R value of fly ash-based geopolymer stabilized HPS for 6 M NaOH was 143 to 165 MPa and for 8 M NaOH, 169 to 181 MPa, which was much higher than virgin HPS (47 MPa) (Fig. 11). The stabilized LPS was found in the range of 148 to 149.98 MPa and 178.05 to 198 MPa for 6 M and 8 M NaOH concentrations, respectively, compared to untreated LPS (55 MPa) (Fig. 12).

Anisotropy significantly influences the strength enhancement from geopolymer-bonding, as the arrangement of material structure and particle alignment dictates the distribution of nanoparticles and bonding efficiency. This leads to non-uniform strength gains, with the most substantial improvements typically occurring along the axis of polymer reinforcement, while transverse directions exhibit weaker enhancements. Properly

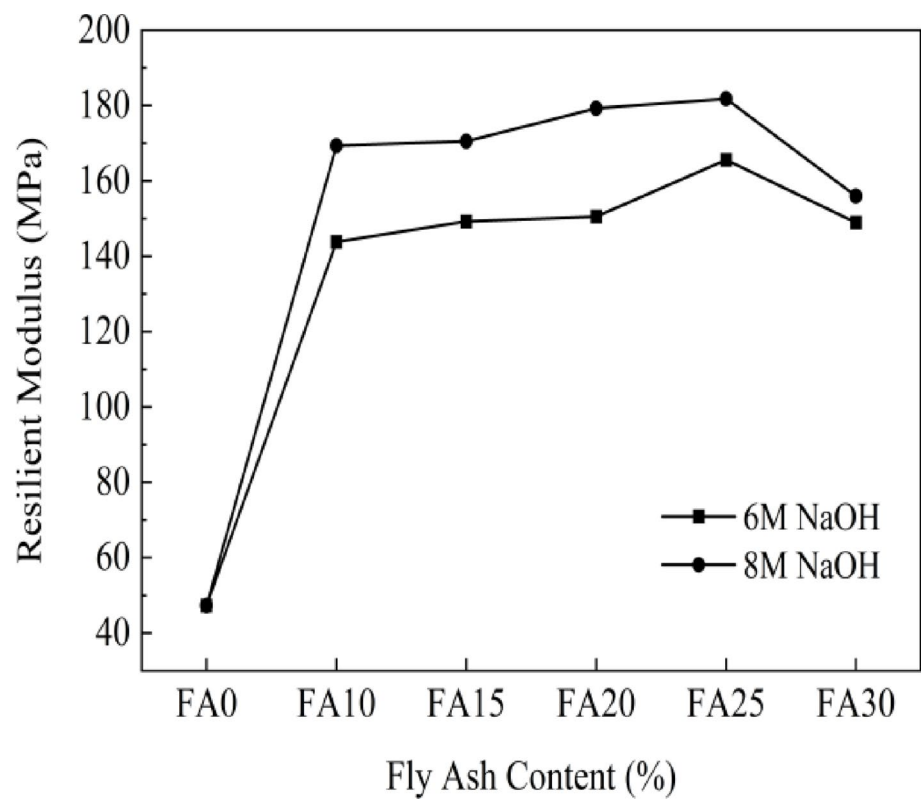


Fig. 11 Resilient modulus for HPS

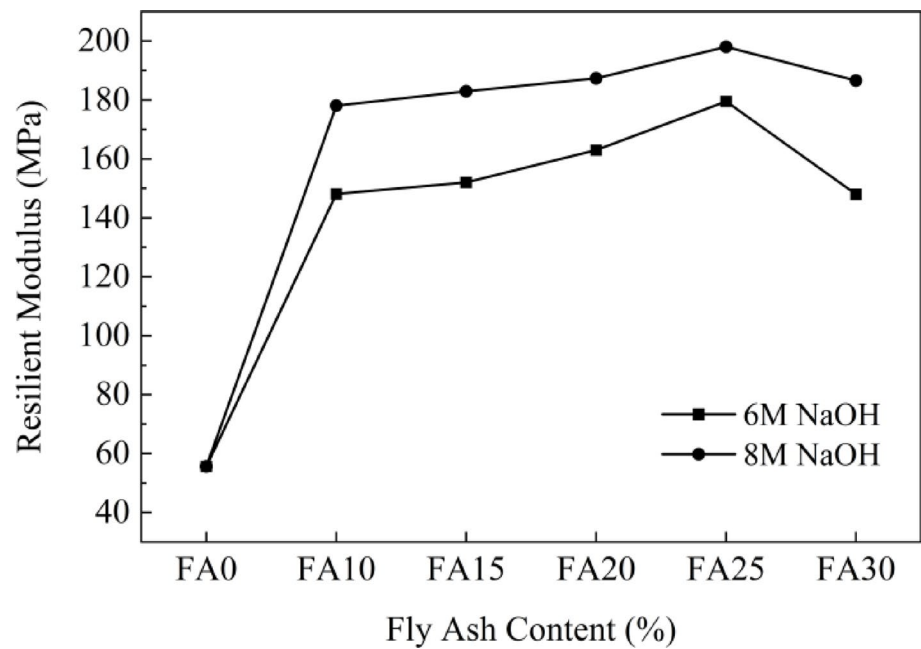


Fig. 12 Resilient modulus for LPS

addressing anisotropy is essential for optimizing the performance of nano-modified soils in geotechnical applications [55, 56].

3.5 Microstructural study

Microstructural studies of soil samples of fly ash-based geopolymer-treated were performed using X-Ray Diffraction Analysis (XRD), Scanning Electronic Microscope (SEM), and Energy-dispersive X-ray Spectroscopy (EDX). This is an advanced tool for chemical change and monitoring gel or matrix synthesis over time. Following 28 days of curing for 6 M and 8 M NaOH concentrations for varying fractions of fly ash contents, all soil samples were examined microstructurally.

3.5.1 XRD

The XRD technique is widely used approach in fine soils for identifying soil minerals and understading internal crystal structure. After 28 days of curing, the XRD patterns for the different fly ash-based geopolymer compositions combined with expansive soil (HPS and LPS) are shown in Figs. 13 and 14. The 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) roughly around $2\Theta = 21.11^\circ, 26.89^\circ, 33.39^\circ, 40.51^\circ, 42.65^\circ, 45.98^\circ, 50.35^\circ, 60.12^\circ, 64.36^\circ, 68.33^\circ, 75.80^\circ, \text{ and } 80.03^\circ$ (Fig. 13). While, for LPS, reflection peaks at $2\Theta = 21.22^\circ, 27.07^\circ, 35.49^\circ, 39.87^\circ, 42.75^\circ, 50.50^\circ, 60.38^\circ, 68.53^\circ, 75.97^\circ, 81.70^\circ, \text{ and } 82^\circ$ (Fig. 14). These minerals are crystalline phases and generated by dissolution of sodium aluminosilicate compounds with fly ash particles [18, 19, 39, 57].

Furthermore, some of the peaks were not traced in stabilized soil compared to the original HPS and LPS, which shows a change in the layered structure of clay mineralogy [39]. The low-intensity peaks of stabilized soils showed the participation of soil in the process of geopolymerization [32]. The number of new peaks detected in a higher concentration of NaOH shows the higher amount of leaching of alumina silicate gel, resulting high strength. This can also be observed in terms of reduction in swelling behavior of soil mainly controlled by clay minerals (montmorillonite and illite), as it was not detected in the stabilized soil, showing less proneness towards swelling and shrinkage.

3.5.2 SEM and EDX

The microstructural study was carried out after 28 days of curing of the stabilized soil sample by conducting SEM and EDX tests. The sample was collected after performing the UCS test on around one cm smooth surface cubes to get high-resolution SEM pictures. The SEM images and EDX spectrum of stabilized HPS and LPS are shown in Figs. 15 and 16, respectively. The microstructural variation of HPS and LPS for fly ash content of 10%, 15%, 20%, 25%, and 30% was observed in Fig. 15 (a) to (e) and Fig. 16 (a) to (e), respectively. The observation noted from the images is that a higher content of fly ash particles had dissolved in an alkaline solution and leached alumina and silica that form geopolymer. However, a few of the fly ash particles remain unreacted or partially reacted, as observed in Fig. 15(e) and Fig. 16(e).

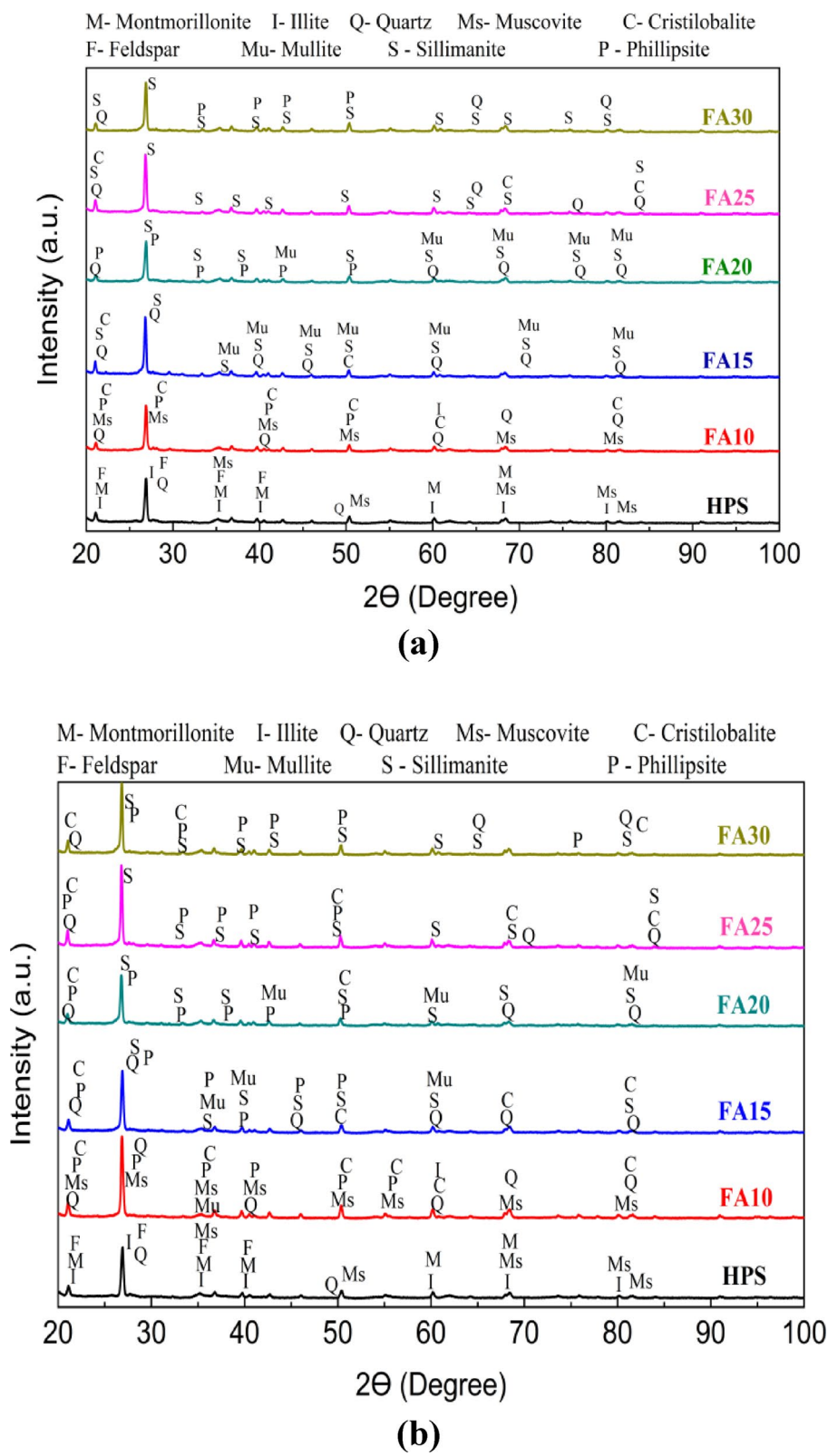


Fig. 13 XRD results for HPS (a) 6 M NaOH & (b) 8 M NaOH

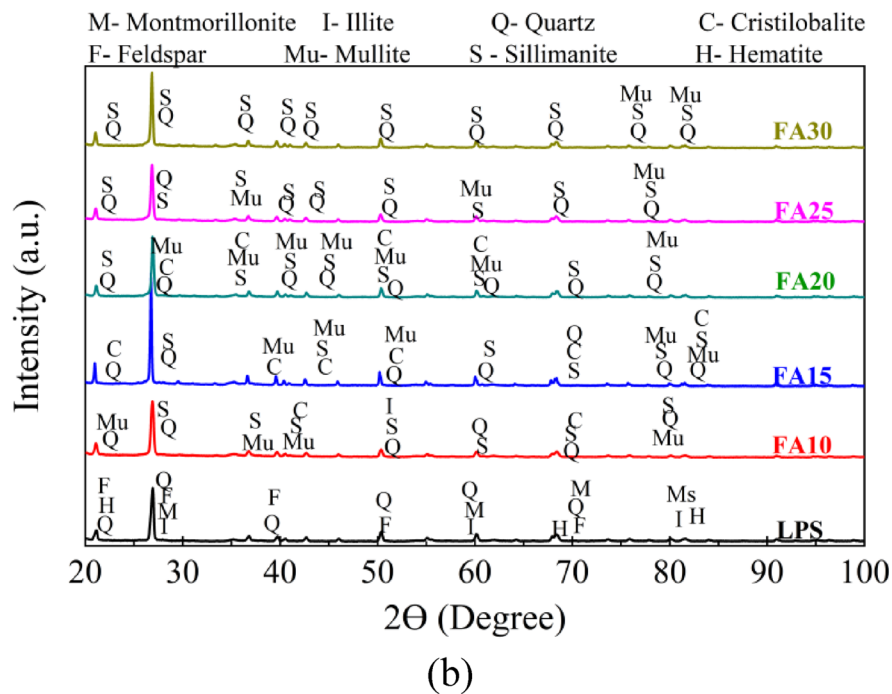
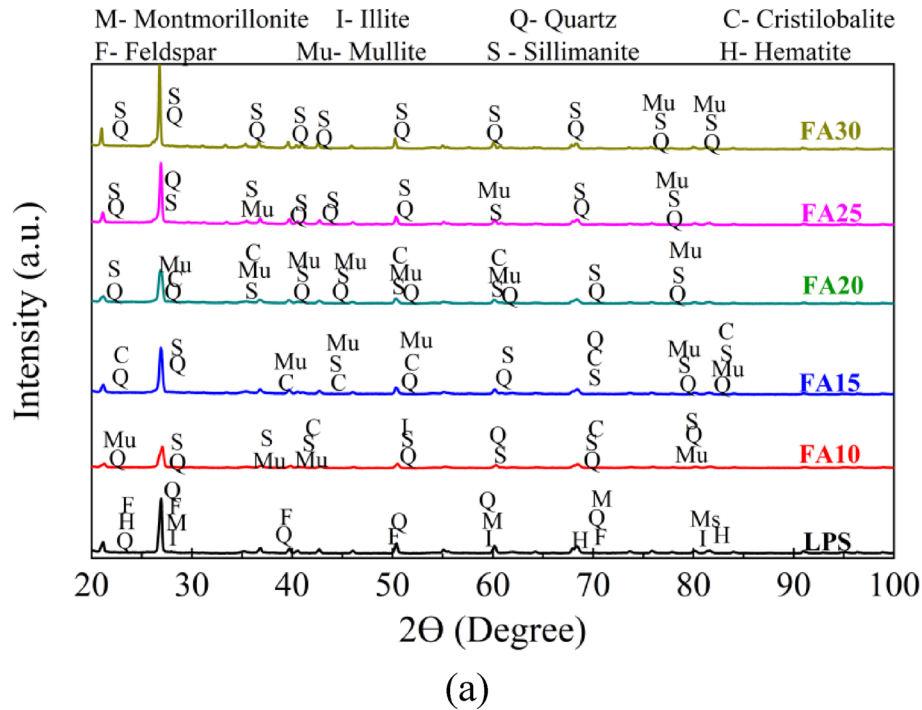


Fig. 14 XRD results for LPS (a) 6 M NaOH & (b) 8 M NaOH

Along with SEM, the EDX spectra for stabilized HPS and LPS were performed for the detection of chemical compound measurement. This reveals that a geopolymer gel formed due to the active dissolution of silica and alumina ions that leach sodium aluminate hydrate gel (NASH) and calcium aluminosilicate hydrate (CASH). Hence, due to NASH and CASH reaction products, the dense and compact microstructure of HPS and

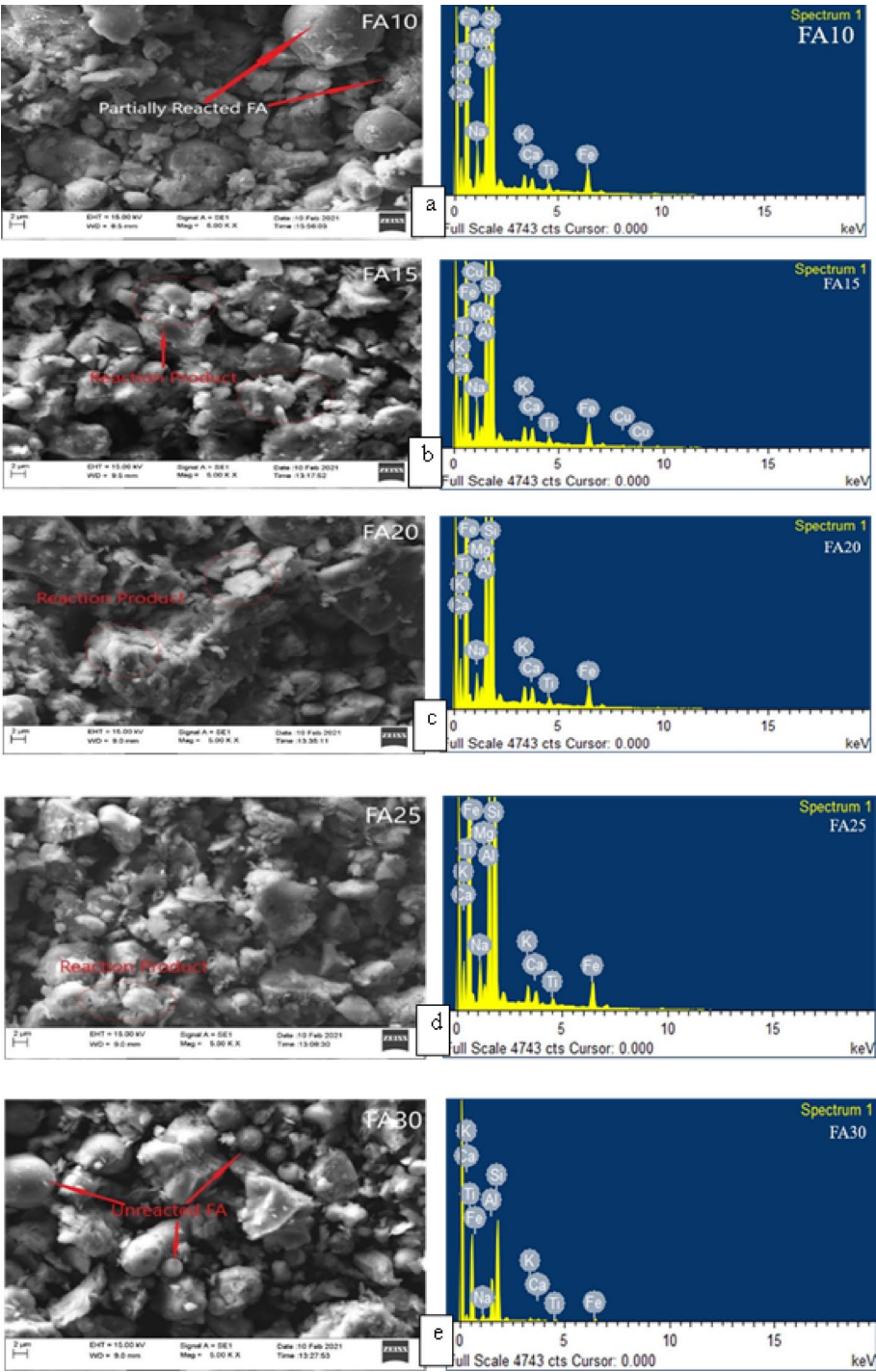


Fig. 15 SEM and EDX Spectra for (a) HPS + FA10, (b) HPS + FA15, (c) HPS + FA20, (d) HPS + FA25, and (e) HPS + FA30

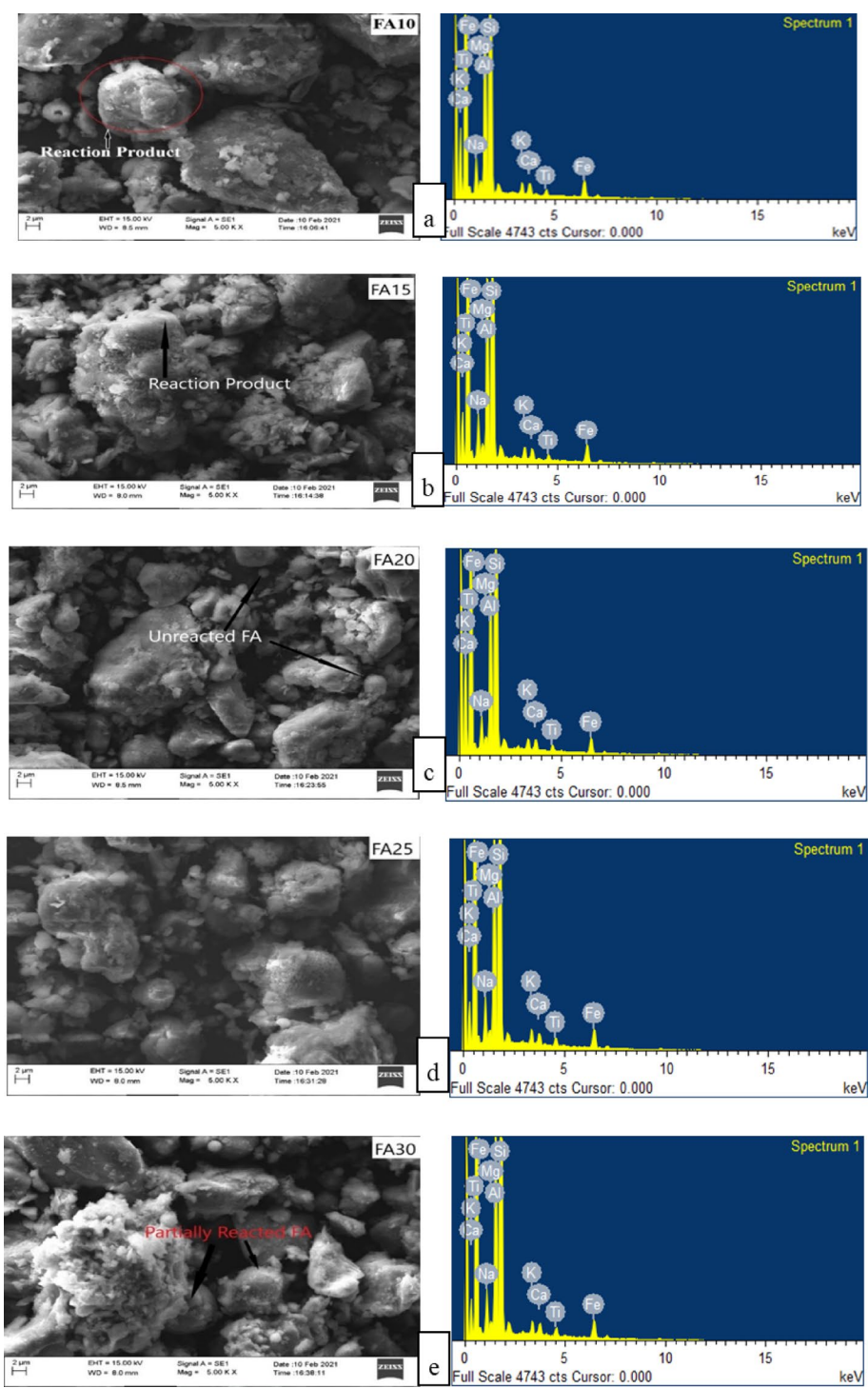


Fig. 16 SEM and EDX Spectra for (a) LPS + FA10, (b) LPS + FA15, (c) LPS + FA20, (d) LPS + FA25, and (e) LPS + FA30

LPS formation takes place. However, larger amounts of CASH were noted in the LPS compared to HPS as per the EDX spectra.

4 Benefits of fly ash-based geopolimer

Due to the excessive use of natural resources in the development of civil engineering infrastructures, such as pavements and building foundations. The scarcity of natural material in the particulate construction area means that forceful treatment of locally available soil is one of the ways to save the natural resources, as well as the cost of construction. Also, 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 the common stabilizers used for soil treatment. In comparison with these traditional stabilizers, the following are some of the benefits of the usage of non-traditional stabilizers.

1. Fly ash-based geopolimer serves as an excellent alternative to cement or lime for soil treatment. Notably, substituting 15% and 50% of global cement consumption with fly ash-based geopolimer could reduce CO₂ emissions by approximately 250 million tons and 800 million tons, respectively [58].
2. The environmental issues associated with disposing of fly ash in landfills can be mitigated. By using this by-product as a construction material—for example, to enhance the properties of weak soils—it promotes sustainable construction and contributes to environmental conservation.
3. The experimental results demonstrate that fly ash-based geopolimer can effectively stabilize soil in situ, eliminating the need for excavation and transportation and thereby minimizing environmental impacts. Given the reduced material usage and transportation requirements, energy consumption and CO₂ emissions are significantly lower with this non-traditional soil stabilization method compared to conventional stabilizers.
4. Because of the limited money available to build and maintain civil infrastructure, it is necessary to consider developing a cost-effective approach to constructing civil substructures.

Safety in Chemical Handling – Especially NaOH- While the use of high-concentration chemicals like sodium hydroxide (NaOH) can be managed under controlled laboratory conditions, special precautions are essential when using even lower concentrations in field applications. Appropriate safety protocols must be strictly followed. Key measures include the use of personal protective equipment (PPE) such as chemical-resistant gloves, full-face shields, and splash-proof goggles. For storage, HDPE-lined or stainless-steel containers should be used, and the material must be kept in cool, well-ventilated areas, away from acids and moisture. During preparation, NaOH pellets should always be added to water—never the reverse—to control the intense exothermic reaction. Additionally, adequate ventilation or fume extraction systems should be in place, and proper spill response and first aid procedures must be established and followed.

5 Conclusions

1. The swelling and shrinkage behavior of stabilized soil was reduced by 79.17% and 83.77% for HPS and 75% and 96.17% for LPS, respectively, compared to untreated HPS and LPS.
2. The strength parameters (UCS, CBR, and MR) of soil treated with fly ash-based geopolymer are greatly improved. Continuous strength improvement was observed up to a fly ash content of 25% for all curing periods. The 8 M NaOH concentration showed the highest strength performance compared to the 6 M NaOH concentration.
3. The strength of the soil increases as the NaOH concentration rises from 6 M to 8 M. Also, LPS has higher strength than HPS, perhaps because of the clay content and mineralogy.
4. After 7 days of curing, the strength improvement using fly ash-based geopolymer stabilized soil was greater than the minimum strength necessary for the sub-base course of road pavement under IRC: 37–2012.

Author contributions

Sagar D. Turkane: Conceptualization; Writing—review and editing; Avinash V. Navale: Methodology; Formal analysis and investigation; Resources; Hari Naga Prasad Chenna: Formal analysis and investigation.

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Data availability

All data generated or analysed during this study are included in this article.

Declarations

Ethics approval

The authors declare that this manuscript has not been submitted to more than one publication for simultaneous consideration. The submitted work is original and has not been published previously, in whole or in part, in any form or language. Any related prior work by the authors represents a distinct study, and the current manuscript constitutes a substantial expansion of that work, where applicable.

Consent to participate

All authors confirm that they have participated in the work reported in this manuscript and have contributed significantly to its development. Each author has read and approved the final version of the manuscript prior to submission. Since the study did not involve human participants or animal subjects.

Consent for publication

All authors give their consent for the publication of this manuscript titled “Performance Behavior of Soil Plasticity for Fly Ash-Based Geopolymer: A Flexible Pavement Material” and approve its submission to the journal. The authors confirm that the content represents their original work and agree to the publication of all data, figures, and results contained within the paper.

Competing interests

The authors declare no competing interests.

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