Chapter 5

Stabilization using Industrial Waste Materials

5.1 General

In the previous chapter , the effect of NaOH concentration on heaving and other geotechnical properties of soil as well as the critical concentration of NaOH solution at which the maximum percentage of heaving, heaving pressure and deterioration in strength of the soil were investigated. This chapter explores the performance of the industrial waste-by-product in controlling the alkali-induced heaving and the possibility of improvement in the strength of alkali-interacted soil. Ground-granulated blast furnace slag (GGBFS) and alccofine (AF) are such industrial waste by-products that have been considered a means of addressing some of the challenges of enhancing the geotechnical properties of soil. These waste by-products possess cementitious and pozzolanic properties and have a great potential to control alkali-induced heaving (Vindula and Chavali, 2018; Vindula et al., 2019) as well as to stabilise the alkali-interacted soil to improve its geotechnical properties. Indeed, to the author's knowledge, control of heaving and stabilisation of alkali-interacted soil related studies using these industrial waste by-products are still scanty. Based on the current state of knowledge, the main aim of this chapter is to upscale the use of the different percentages of GGBFS and AF in the control of alkali-induced heaving and stabilization of alkali-interacted soil. The efficiency of the technique was evaluated in terms of heaving control and increase in unconfined compressive strength and shear strength parameter of alkali interacted soil. Apart from that, an electrokinetic enhanced bench-scale model study was also conducted to simulate the field application of GGBFS and AF to stabilise the alkali-interacted soil.

5.2 Specimen Preparation

The experimental work is focused on investigating the effect of GGBFS and AF on alkali-induced heaving behaviour of soil through oedometer test and strength behaviour of soil and alkali contaminated soil through unconfined compressive strength and unconsolidated undrained triaxial test. For heaving studies, the GGBFS and AF were mixed with dry soil samples in different percentages (w/w) to a uniform consistency. Water was then added while continuing the mixing process until a uniform, homogenous mixture was obtained. The mixture was then compacted to its maximum dry density in a consolidation ring in three layers. Porous stones were placed at the top and bottom of the specimens, which facilitate the movement of alkali solution to the sample. Then the sample was inundated with 16M NaOH solution selected on the basis of the heaving study in chapter 4 and allowed to heave under free loading conditions. The heaving was measured at the top using a dial gauge. The percentage heaving was expressed with respect to the original height of the soil sample.

To evaluate the strength of samples two methods have been followed. In the first method, the clean soil was mixed with varying percentages of GGBFS and AF and then 16M NaOH solution was added to their corresponding optimum moisture content. In the second method, the alkali interacted soil was mixed with varying percentages of GGBFS and AF individually and then water was added to their corresponding to optimum moisture content. The mixed sample was then compacted in three layers in the split mould to their maximum dry density. After the moulding process, the sample was extracted from the mould and placed in an airtight polythene bag as shown in Fig. 5.1. The sample was allowed to be cured for a specified period of curing in desiccators at room temperature. After completion of the curing period, the samples were tested to evaluate their strength after stabilizing with GGBFS and AF. Table 5.1 presents a summary of the main characteristics of tests conducted in this study.

Figure 5.1: Prepared sample in air tight polythene bag

Table 5.1: Summary of tests combinations with varying percentage of GGBFS and AF

S. No.	Soil Type	Curing Period (Days)	Test Conducted	Stabilizer Content
1	Uninteracted Soil	1,7,14,28	UCS	GGBFS (%) 1,5,10,20,30
2	Alkali interacted soil	1,7,14,28	Triaxial test	GGBFS (%) 20
3	Uninteracted Soil	1,7,14,28	UCS	AF (%) 5,10,15,20,25,30
4	Alkali interacted soil	1,7,14,28	Triaxial test	AF (%) 20

5.3 Experimental Results and Discussion

The results obtained from a series of geotechnical tests conducted on soils, alkali interacted soil with and without GGBFS and AF have been presented in this section. The effects of GGBFS and AF on the geotechnical properties of soils are studied thoroughly and discussed elaborately.

5.3.1 Particle Size Analysis

The particle size distribution of soil, alkali interacted soil, GGBFS and AF used in this study are shown in Fig 5.2.

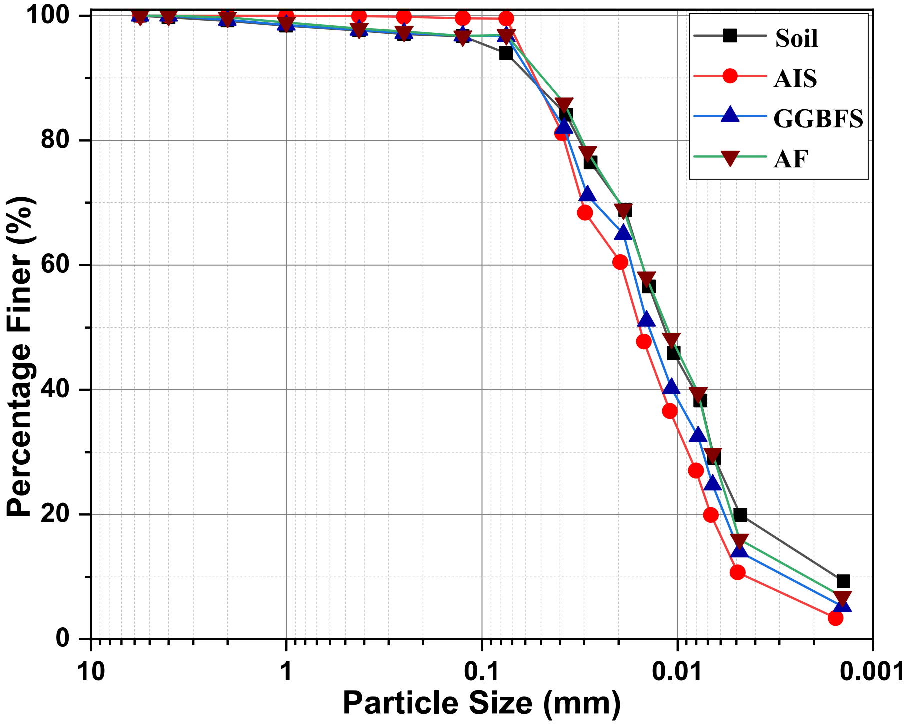


Figure 5.2: Particle size analysis of uninteracted soil, alkali interacted soil, GGBFS and AF

5.3.2 Atterberg Limits

A series of liquid limit and plastic limit tests were carried out on the soil and alkali-interacted soil to assess the influence of the addition of percentages of GGBFS (1%, 5%, 10%, 20% and 30%) and AF (5%, 10%, 15%, 20%, 25% and 30%). Liquid limits of soil and soil samples with varying percentages of GGBFS and AF were determined by using the Casagrande apparatus. However, the liquid limit values of alkali interacted soil and alkali interacted soil admixed with varying percentages of GGBFS and AF were determined by using the cone penetration method due to the non-plastic behaviour of these samples. The variation in liquid limit and plastic limit value after the addition of GGBFS and AF are shown in Fig. 5.3 and Fig. 5.4 respectively.

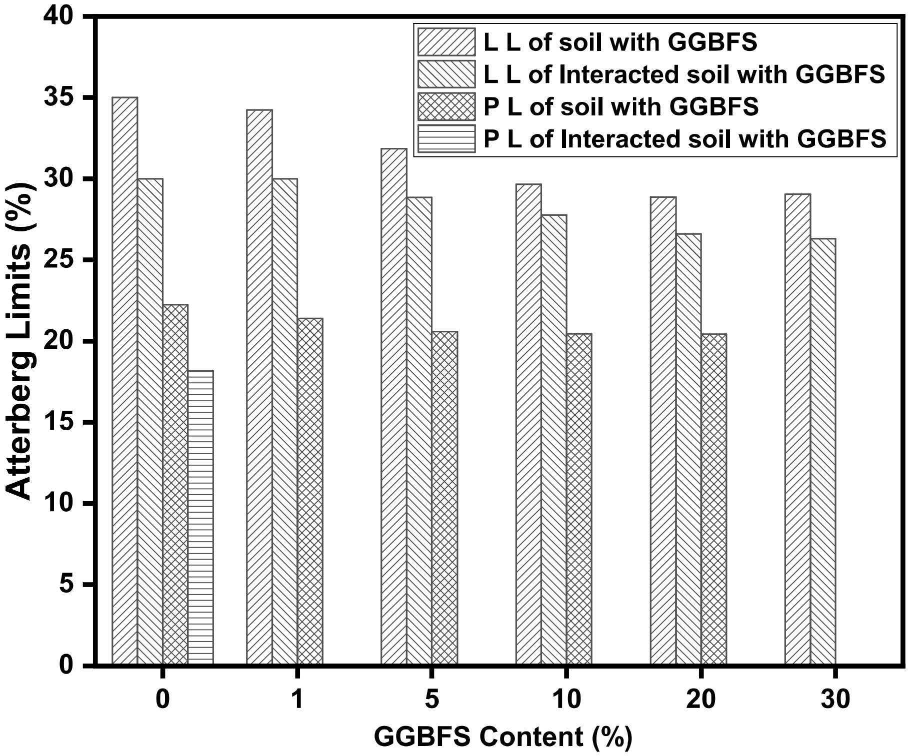


Figure 5.3: Atterberg limit with GGBFS

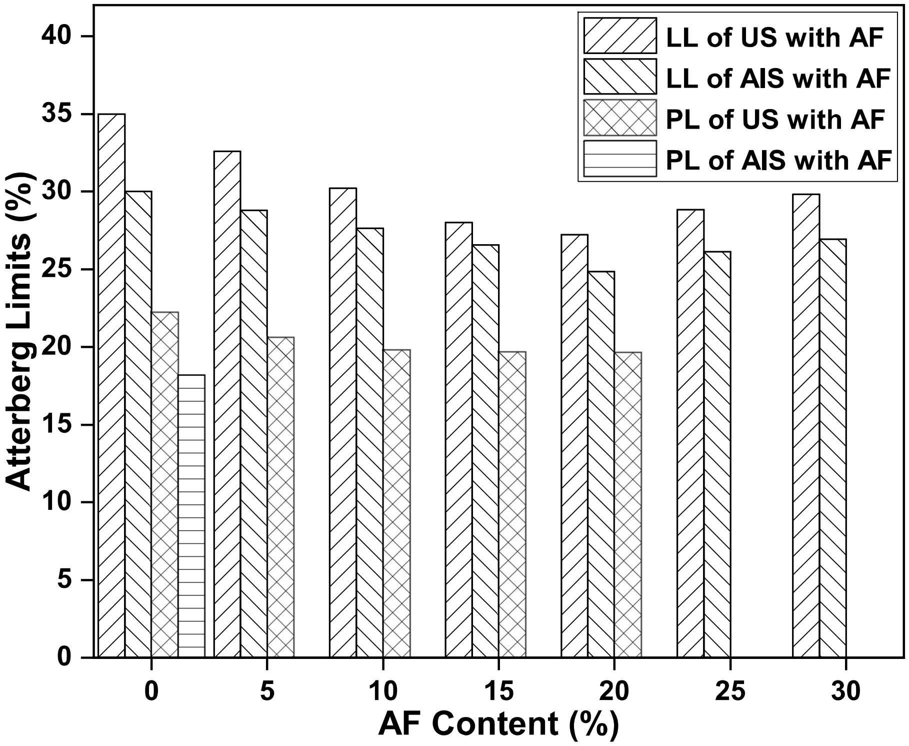


Figure 5.4: Atterberg limit with AF

From Fig. 5.3 It can be seen that liquid limit and plastic limit values decrease with the increase of GGBFS, similar observations were reported in the literature (Abdullah et al., 2017; Pathak et al., 2014; Yadu and Tripathi, 2013). It was observed that with increasing slag content the quantity of silt-sized particles in the mix increases while the number of clay-size particles decreases, resulting in a drop in liquid and plastic limits. It was also noticed that the plastic limit of alkali interacted soil admixed with GGBFS mix did not possible due to its non-plastic nature.

However, Fig. 5.4 reveal the effect of AF content on the liquid limit and plastic limit value of soil and alkali interacted soil. It can be seen that the liquid limit value and the plastic limit value of the soil and alkali interacted soil decrease with the upsurge of AF content up to 20%. Further increase in AF content increases the liquid limit and plastic limit. The decreasing trend of liquid limit and plastic limit is associated with the calcium ion which is the prominent mineral in AF leading to cation exchange and reduction in the double diffused layer. The presence of calcium ions makes the soils more friable and workable. The clay particles undergo flocculation to form aggregates which behave like particles of silt. The increasing trend in liquid limit and plastic limit of soil on the addition of 25% and 30% of AF is mainly due to the fact that the presence of extra AF that requires extra water for the formulation of flocculated fabric leads to an increase in liquid limit and plastic limit.

5.3.3 Specific Gravity

The effects of the addition of GGBFS on the specific gravity of soils and alkali interacted soil are presented in Fig. 5.5. It has been observed that an increase in the GGBFS content increases the specific gravity of soil-GGBFS and alkali interacted soil- GGBFS mixtures. The specific gravity of GGBFS is 2.85 which is greater than that of soil and alkali interacted soil having specific gravity 2.53 and 2.10 respectively. The specific gravity of the soil-GGBFS and alkali interacted soil- GGBFS mixture is found to be 2.68 and 2.60 respectively at 30% GGBFS content.

The variation in specific gravity on the addition of AF in the soils and alkali interacted soil is presented in Fig. 5.6. It is apparent from the figure that the specific gravity of specimen of soil and alkali interacted soil with AF increase with the increase in AF content. The specific gravity of AF is 2.87 which is greater than that of soil and alkali

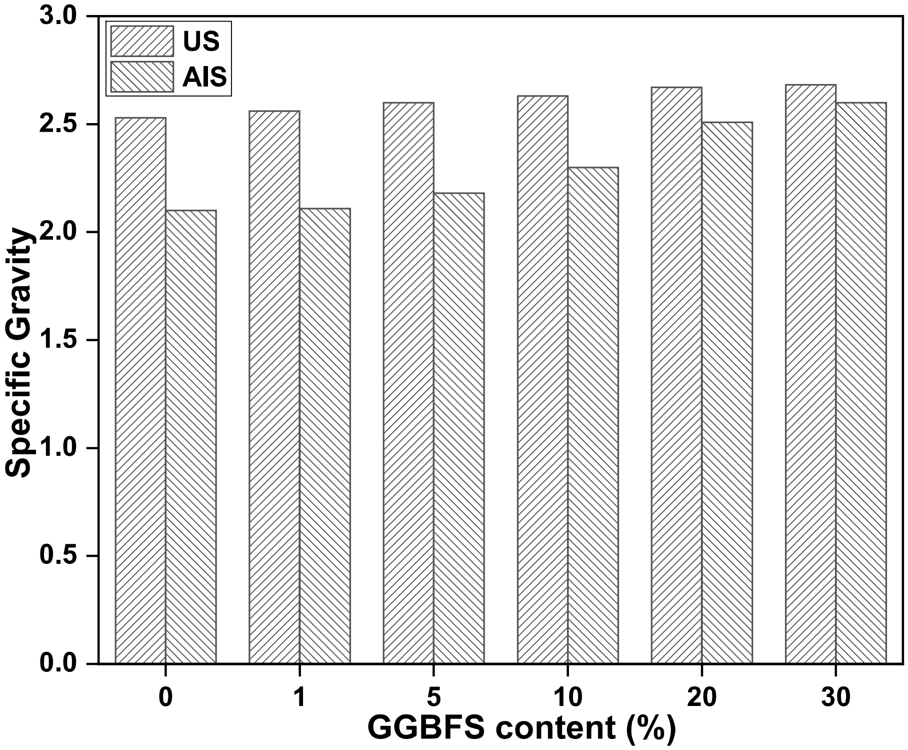


Figure 5.5: Specific gravity with GGBFS

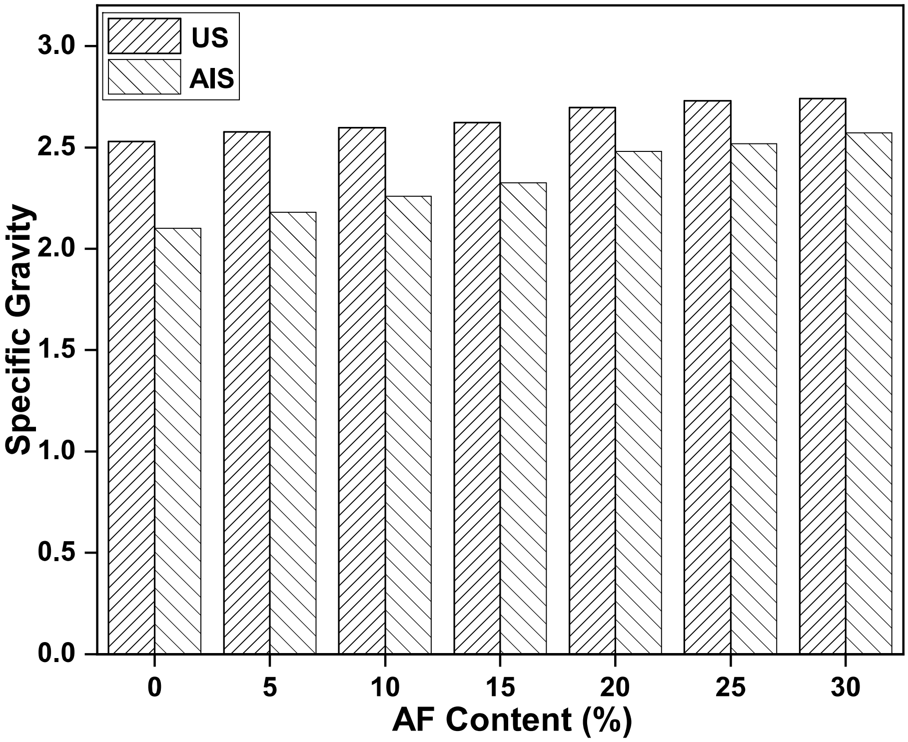


Figure 5.6: Specific gravity with AF

interacted soil having specific gravity 2.53 and 2.10 respectively. The specific gravity of the soil-AF and alkali interacted soil- AF mixture is found to be 2.73 and 2.57 respectively at 30% AF content. The increase in the specific gravity of soil and alkali interacted soil with GGBFS and AF is due to the replacement of soil with the same amount of GGBFS and AF having a specific gravity greater than that of soil.

5.3.4 Compaction Characteristics

A series of compaction tests were conducted to analyse the influence of the different percentages of GGBFS and AF on maximum dry density (MDD) and optimum moisture content (OMC) of soil and alkali interacted soil. The compaction characteristics not only depend upon the compaction effort and water content but also the quantity of admixture in soil. The relationship between MDD and OMC plays an important role in the geotechnical behaviour of the mixture. The variation in these parameters affects the strength, swelling and compressibility of the mixture. The compaction curves of soil-GGBFS and alkali interacted soil-GGBFS mixture are shown in Fig. 5.7 and Fig. 5.8 respectively. The variation of the MDD and OMC for different soil–GGBFS and alkali interacted soil-GGBFS mixtures are shown in Fig. 5.9. The figures show that the MDD of soil increases from 1.66 g/cc to 1.8 g/cc and the MDD of alkali interacted soil increases from 1.72 g/cc to 1.88 g/cc respectively with the addition of different percentages of GGBFS content in the soil, whereas OMC of soil decreases from 16.42% to 15.19% and the OMC of alkali interacted soil decreases from 20.11% to 16.78% respectively. The increase in MDD with increasing GGBFS content is due to an increase in the specific gravity of soil on GGBFS addition which fills the voids in the stabilized soil samples which is also supported by several other studies in the past (Awang et al., 2011; Yadu and Tripathi, 2013). Moreover, the addition of GGBFS increases the silt content in the soil, which reduces its water holding capacity, due to which OMC decreases (Kumar Sharma and Sivapullaiah, 2012). However, the variation in OMC and MDD of soil and alkali interacted soil on the addition of AF are presented in Fig. 5.10 and 5.11 respectively. It can be inferred from the figures that the MDD of the soil increases from 1.66 g/cc to 1.81 g/cc and the MDD of alkali interacted soil increases from 1.72 g/cc to 1.82 g/cc respectively with the inclusion of AF up to 20%. Further addition of AF reduces the MDD of soil and alkali interacted soil to 1.67 g/cc and 1.69 g/cc respectively. The OMC of soil and alkali interacted soil

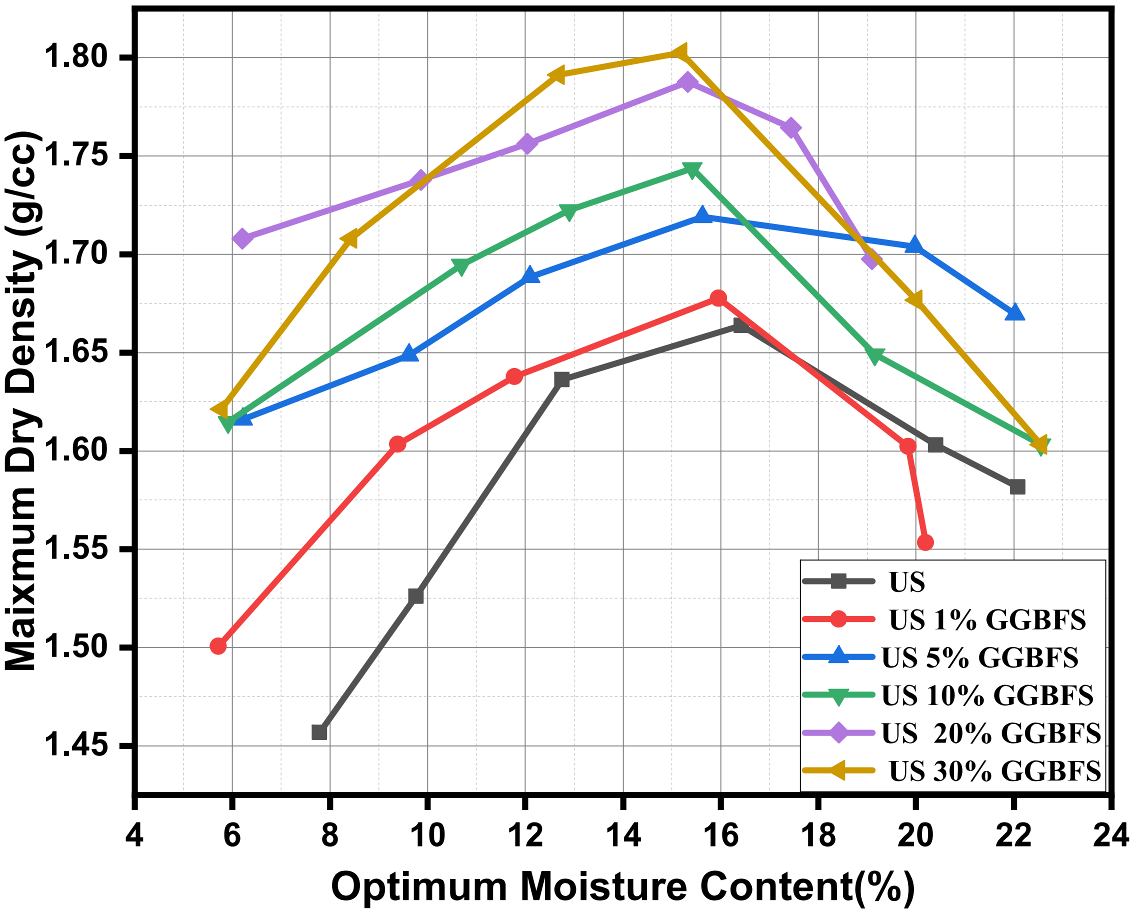


Figure 5.7: Compaction characteristics of uninteracted soil with GGBFS

decreases from 16.42% to 15.49% and 20.11% to 17.38% on the addition of AF up to 20% respectively. After that, the addition of AF increases the OMC of soil and alkali interacted soil. The change in the MDD and OMC for different soil–AF and alkali interacted soil -AF mixtures are shown in Fig. 5.12. The calcium content of AF reacted with the soil and alkali interacted soil which results the occurrence of base exchange aggregation and flocculation of soil particles leading to an increase in MDD of the mixture. The increase in MDD of AF mixed soil specimens may also be attributed to the ultra-fine nature of AF particles which fill the void spaces in the soils. The addition of AF also reduces the thickness of the diffused double layer of water around the soil particles and consequently increases the density of the soil. The AF content beyond an 20%, the MDD of soil and alkali interacted soil decreased. This decrease in MDD was attributed to the poor gradation of the mix beyond an AF content of 20%. Contrary to MDD, up to 20% addition of AF into the soil and alkali interacted soil, a decrement in the OMC from

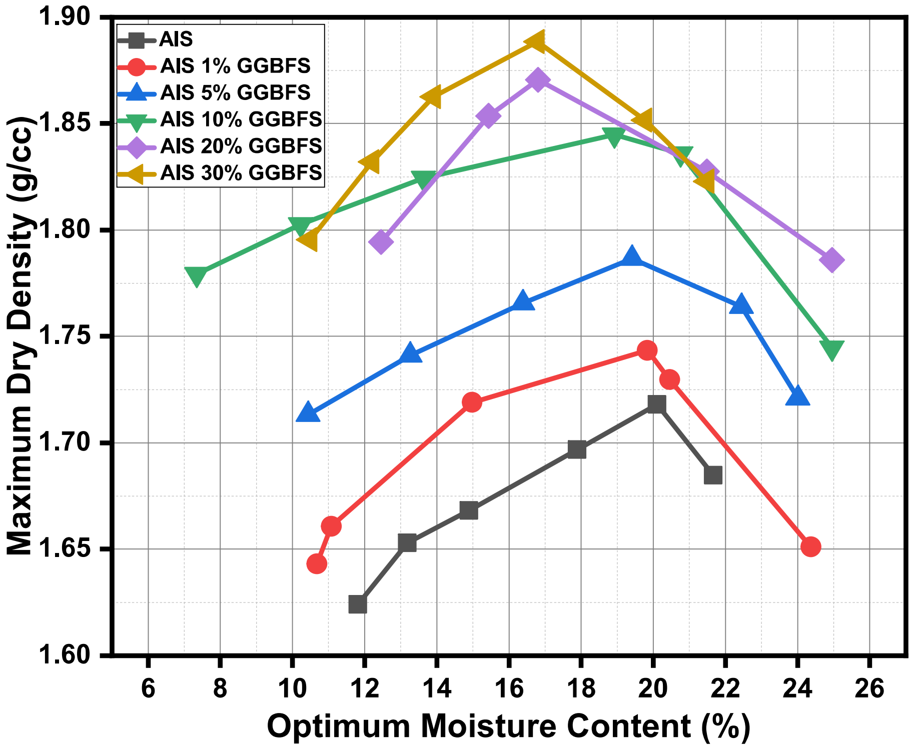


Figure 5.8: Compaction characteristics of alkali interacted soil with GGBFS

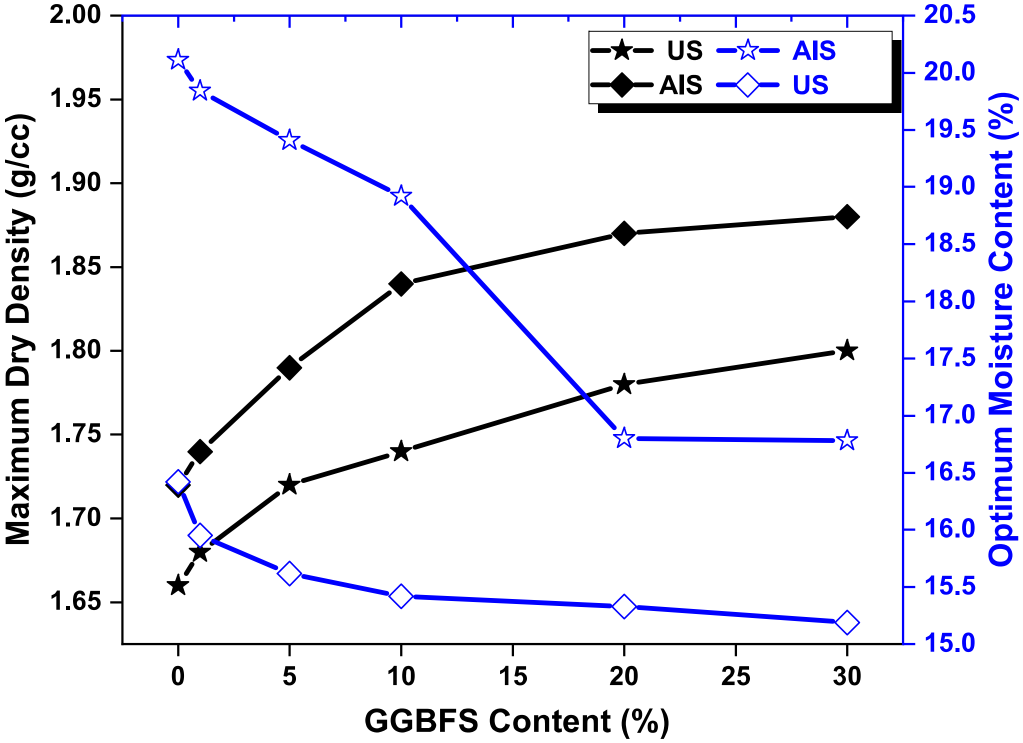


Figure 5.9: Compaction characteristics of alkali interacted soil with GGBFS

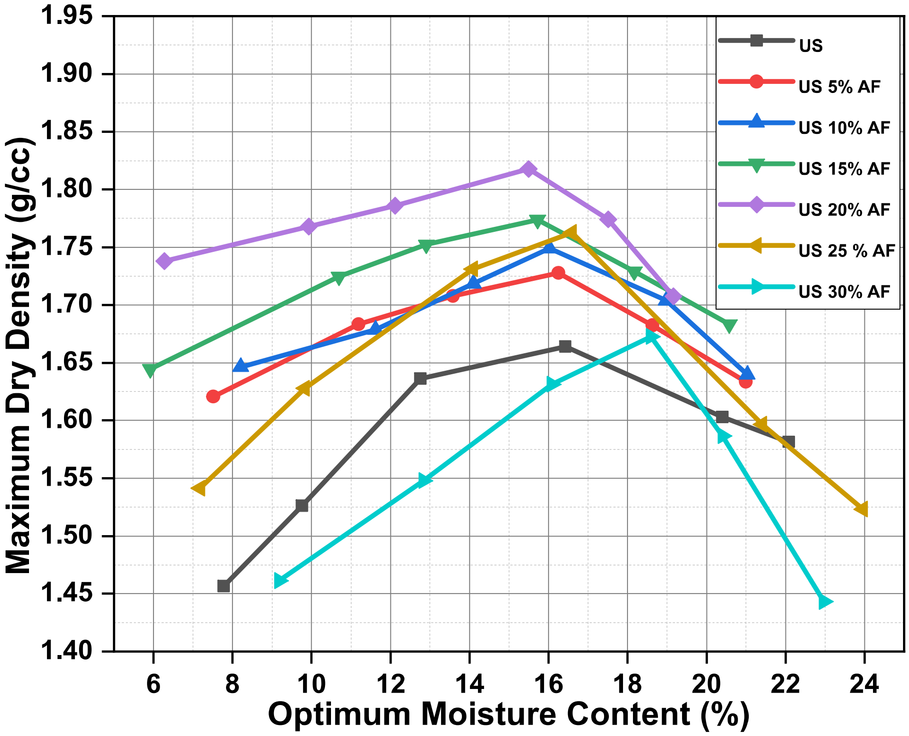


Figure 5.10: Compaction characteristics of soil with AF

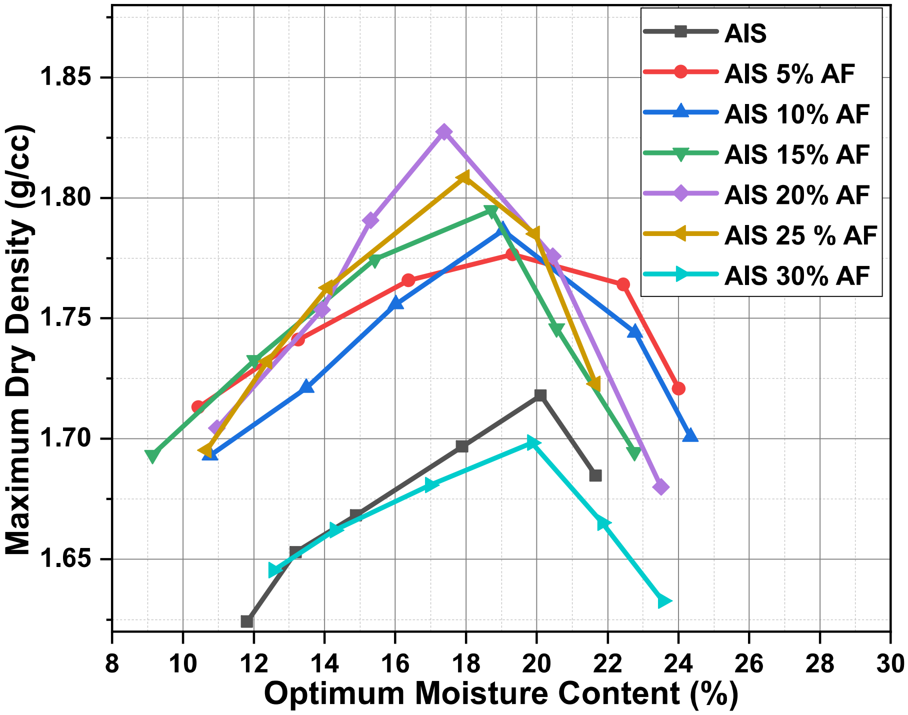


Figure 5.11: Compaction characteristics of alkali interacted soil with AF

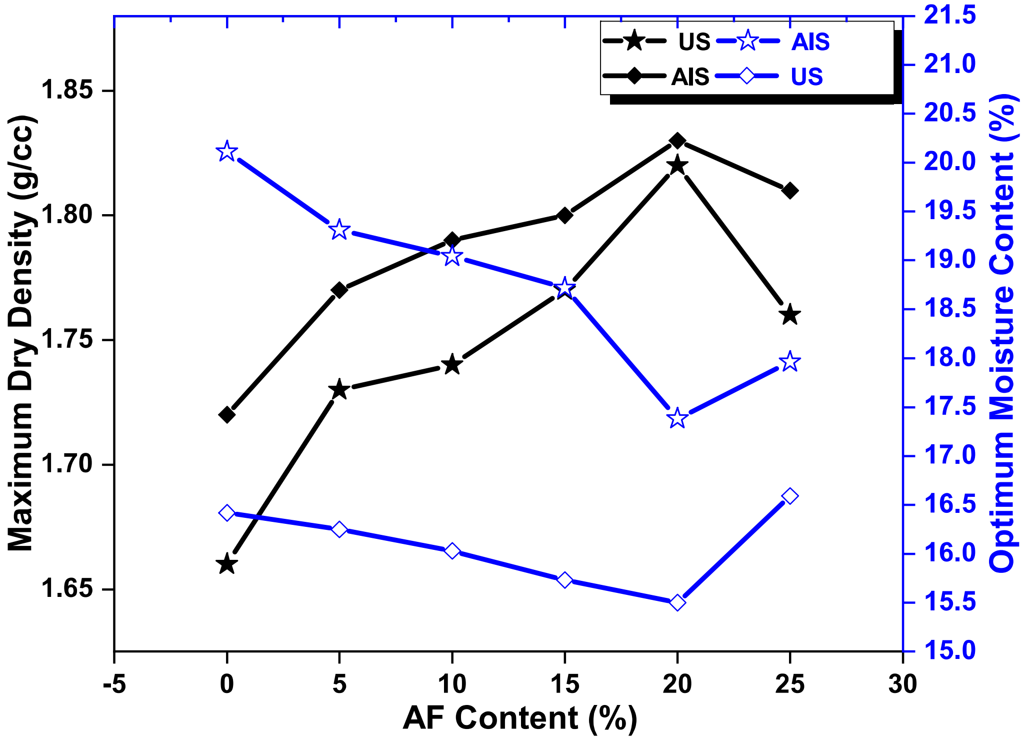


Figure 5.12: Variation of MDD and OMC with AF

16.42% to 15.49% and 20.10% to 17.38% were observed for soil-AF and alkali interacted soil-AF mixtures respectively. The reduction in OMC of soil specimens on the addition of AF is due to its unique chemistry and ultrafine particle size of AF. The addition of AF decreases the voids between the soil particle, which reduces the space for retaining water. Further incorporation of 25% and 30% of AF to the soil and alkali interacted soil increases the OMC of the mix to 18.59% and 19.85% respectively. Such an increase in OMC is mainly due to the ultra-fine nature of AF results in more surface area. The additional water required for the lubrication of a large specific surface area of AF may increase OMC to achieve MDD.

5.3.5 Heaving Analysis

The effect of different concentrations of NaOH on the heaving behaviour of soil was analysed in chapter 4. It was observed that the maximum heaving has occurred in soil due to 16M NaOH solution. In this section assessment of heaving on the inundation of 16M NaOH solution to the soil mixed with varying percentages of GGBFS and AF was studied. The effect of different mix proportions of GGBFS and AF on the heaving of soil statically compacted with water and inundated with 16M NaOH solution are shown in Fig. 5.13 and Fig. 5.14 respectively.

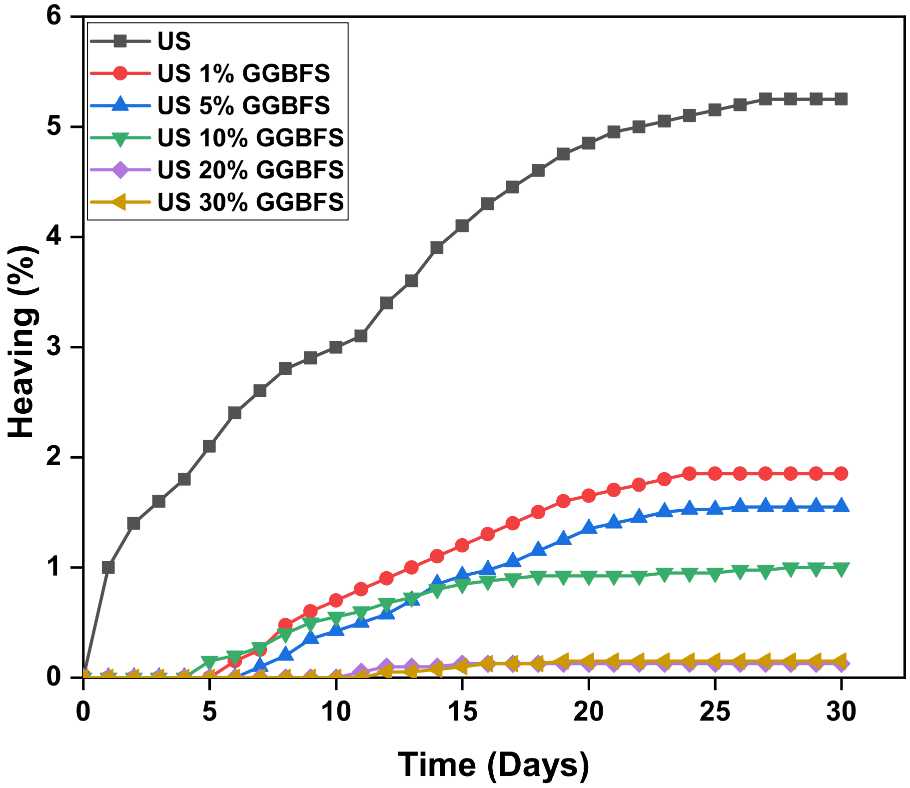


Figure 5.13: Heave in soil inundated with 16 M sodium hydroxide solution and stabilises with different percentages of GGBFS

The maximum heaving of about 5.55% in soil with 16M NaOH solution was mainly attributed to the dissolution of minerals structure of soil and formation of new minerals. The maximum reduction in heaving was observed from 5.55% to 0.13% and 0.23% with a mix proportion of 20% of GGBFS and AF respectively. This reduction in heaving may be due to the replacement of soil with the GGBFS and AF. The large reduction in heaving is due to a reduction in the mineralogical transformation along with the formation of a significant component of the binder phase. The reduction in heaving on the addition of GGBFS and AF is also attributed to the cementitious properties possessed by these materials. The reaction between these materials with alkali solution leads to the formation of calcium aluminium silicate hydrate gels (CASH) after the rupture of the aluminosilicate clay nucleus and these materials with subsequent combination with cations in the alkali solution. These materials act as a binding medium between the soil

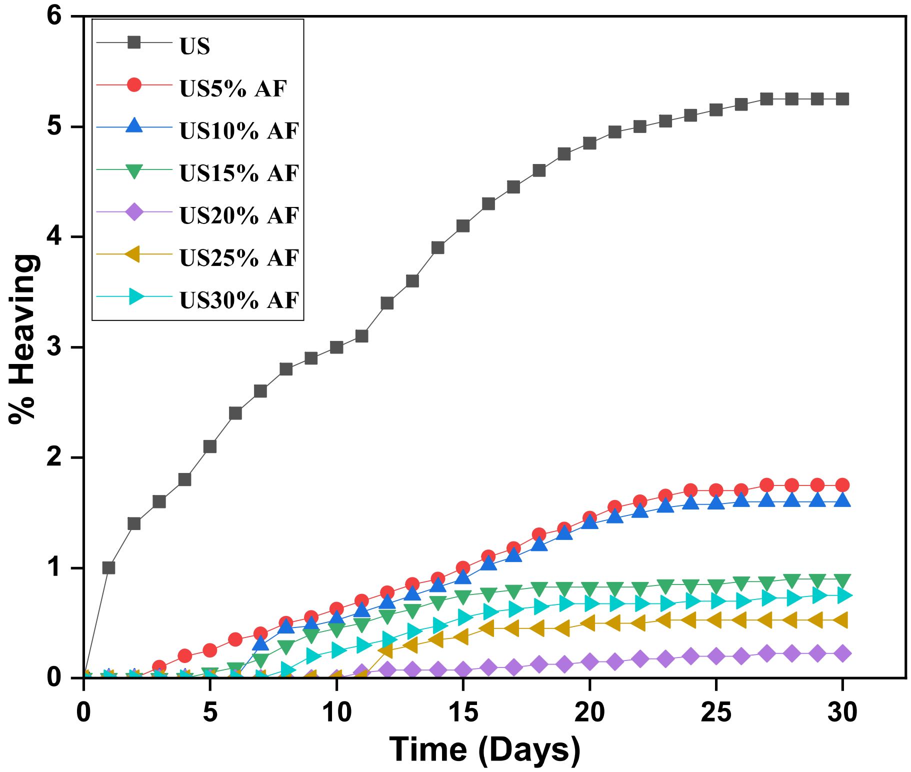


Figure 5.14: . Heave in soil inundated with 16 M sodium hydroxide solution and stabilises with different percentage of AF

due to geo-polymerisation after alkali interaction which arrests the heaving in soil caused due to inundation of 16M NaOH solution.

5.3.6 Unconfined Compressive Strength

The structural deterioration of soil after alkali interaction was discussed in chapter 4. In this section, a series of unconfined compressive strength tests have been carried out to analyse the stabilizing effect of GGBFS and AF on soil and alkali-interacted soil. The variation of unconfined compressive strength of soil and alkali interacted soil with GGBFS and AF content and curing period are shown in Fig. 5.15, Fig.5.16, Fig.5.17 and Fig.5.18 respectively. An increase in the unconfined compressive strength of soil and alkali interacted soil with the increase in GGBFS and AF content is clearly seen from these figures. An increasing trend in unconfined compressive strength is also observed with the curing period. The main cause for the curing of the specimen was to give sufficient time to achieve more pozzolanic reaction of GGBFS and AF with soils and alkali interacted soil. The unconfined compressive strength of soil is increased from 141kPa to 7265.65 kPa with 20% GGBFS and 7553.86 kPa with 30% GGBFS after 28 days curing period respectively. The unconfined compressive strength of alkali interacted soil is increased from 103 kPa to 2111.04 kPa with 20% GGBFS and 2247.12 kPa with 30% GGBFS after 28 day curing period respectively. The rate of increase in UCS with GGBFS addition was significantly high up to 20% GGBFS content, after which the rate of increase in UCS declined. However, in the case of soil-AF mixture and alkali interacted soil-AF mixture the unconfined compressive strength of soil increases up to 20% inclusion of AF as shown in Fig.5.17 and the unconfined compressive strength of alkali interacted soil increases up to 25% inclusion of AF as shown in Fig.5.18. Furthermore, incorporation of AF reduces the unconfined compressive strength of soil and alkali interacted soil. A similar trend is also noticed for other curing periods. The unconfined compressive strength of soil is increased from 141kPa to 6456.64 kPa with 20% AF and then decreases to 4153.86 kPa with 25% AF and 2832.73 kPa with 30% AF after 28 day curing period respectively. The unconfined compressive strength of alkali interacted soil is increased from 103kPa to 2656.09 kPa with 25% AF and then decreases 1778.48 kPa with 30% AF after 28 day curing period respectively.

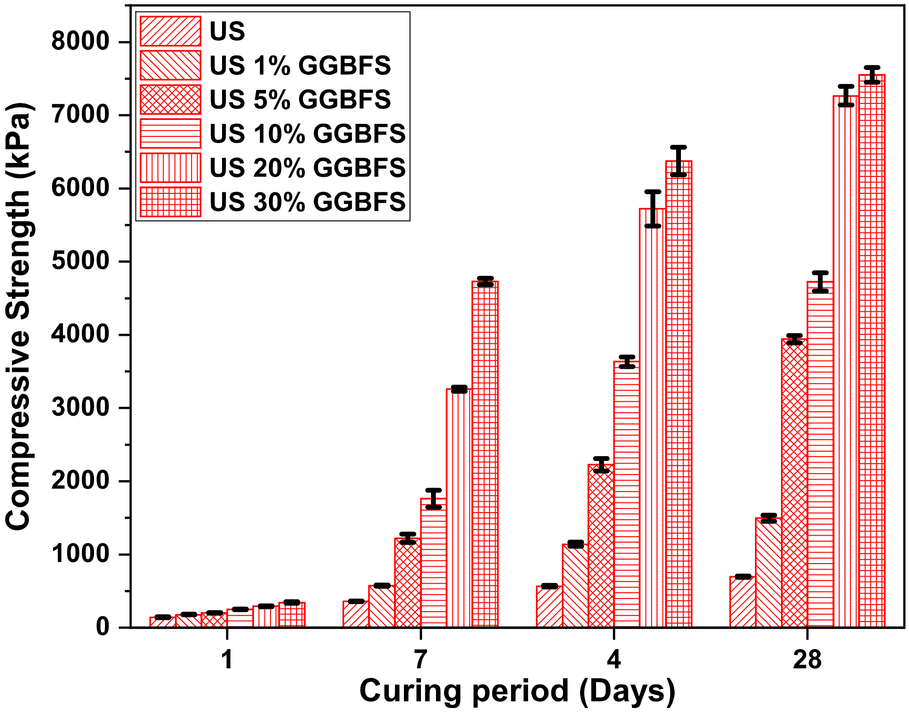


Figure 5.15: Compressive strength of uninteracted soil after GGBFS treatment

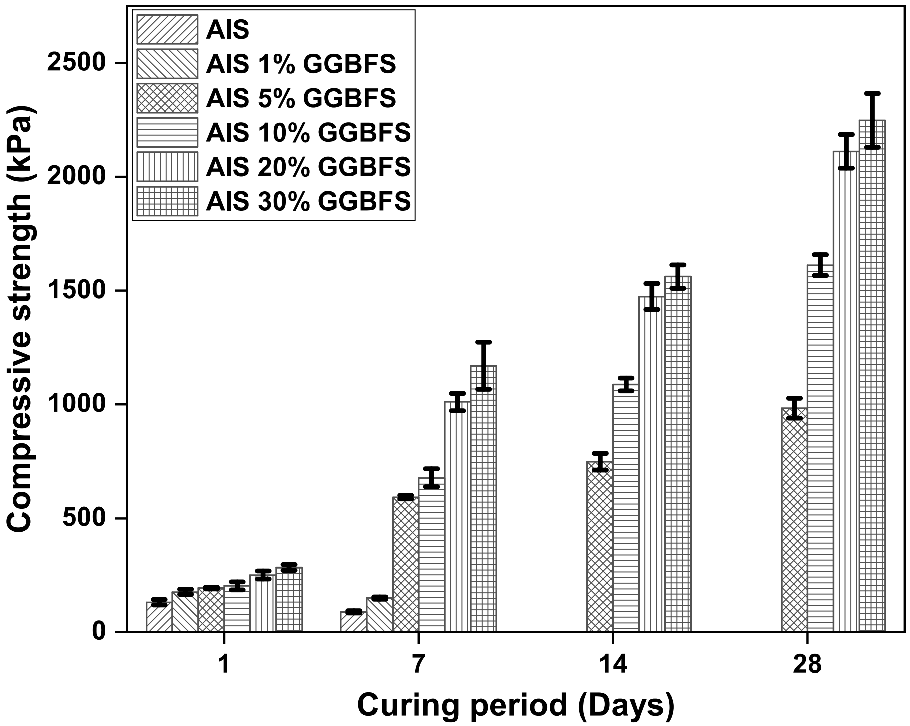


Figure 5.16: Compressive strength of alkali interacted soil after GGBFS treatment

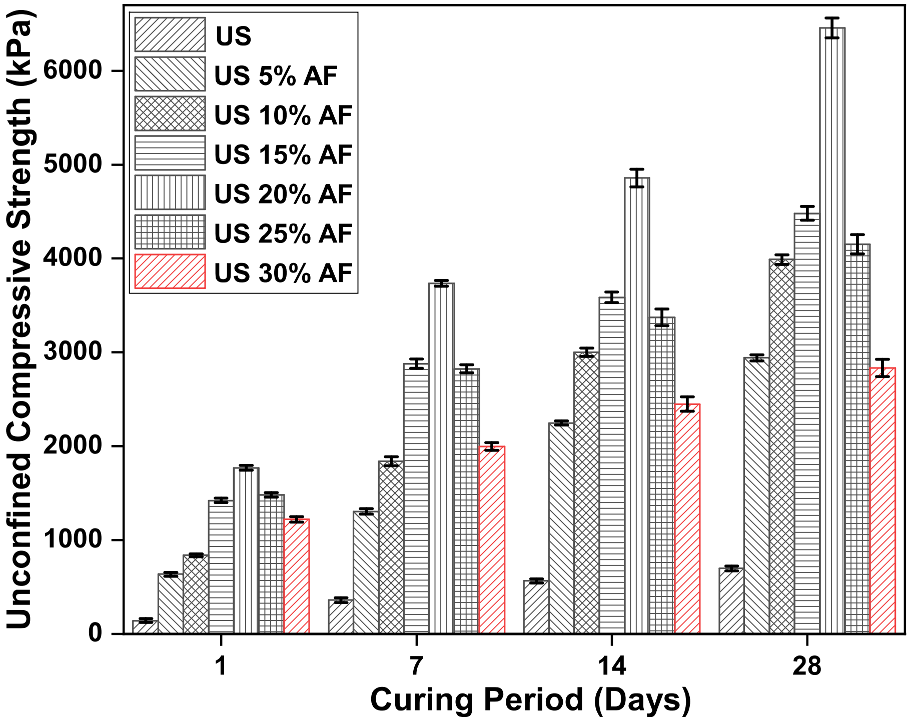


Figure 5.17: . Compressive strength of uninteracted soil after AF treatment

The increase in unconfined compressive strength of soil and alkali interacted soil with the addition of GGBFS and AF is attributed to the formation of pozzolanic products due to geo-polymerization reactions between soil, alkali interacted soil with these additives. Further, these products block the pores and increase the compactness of the structure. The calcium present in the GGBFS and AF reacts with the silica and alumina contents of soils in the presence of alkali which form calcium silicate hydrates gel increase the bonding between the soil particles and results in better bonding and cohesion among the soil particles ultimately the unconfined compressive strength of soil and alkali interacted soil increases. The pozzolanic reaction between soil and admixture results in the formation of cementitious compounds that bind soil particles together are also time dependent phenomena. So, the curing period also plays an important role in increment of unconfined compressive strength of soil and alkali interacted soil with these admixtures. Since the pozzolanic reactions are a continuous process, as the time duration increases, the unconfined compressive strength of soil increases with the increase in the age of specimens due to cementation effect caused by the pozzolanic reactions. Whereas, the reduction in the unconfined compressive strength of soil and alkali interacted soil beyond 20% and 25%

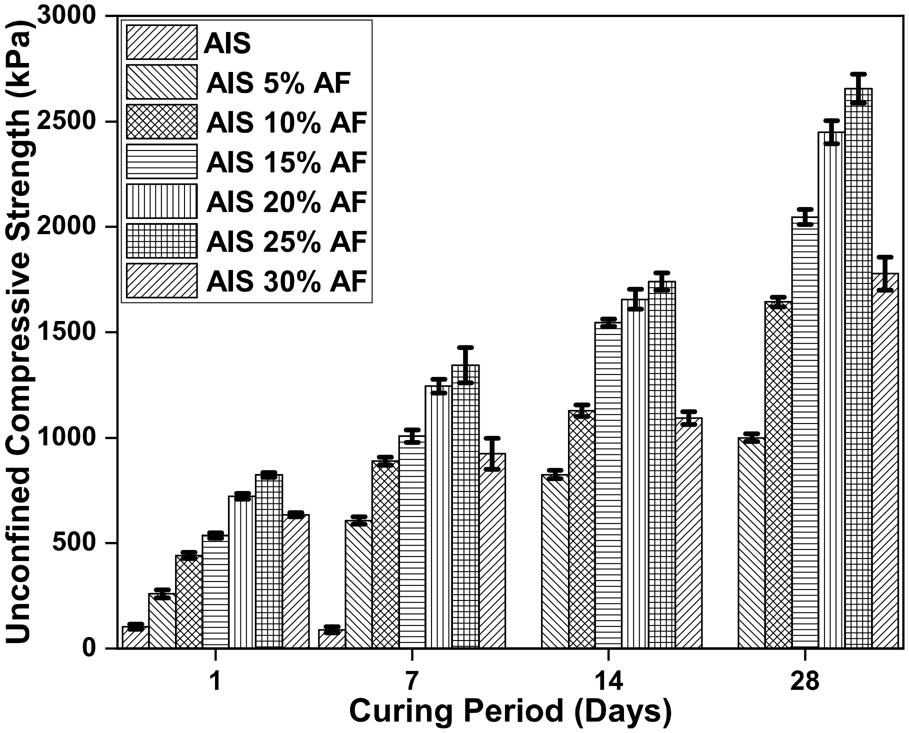


Figure 5.18: . Compressive strength of alkali interacted soil after AF treatment

inclusion of AF can be attributed to the presence of unreacted AF particles which is left over after the chemical reaction between the soil and alkali interacted soil with AF which resulted in the formation of a weak cementitious bond.

5.3.7 Shear Strength Parameters

The unconsolidated undrained tests on the uniteracted soil and alkali interacted soils admixed with 20% of GGBFS and AF and cured for the period of 1, 7, 14, and 28 days were performed at three confining stresses of 50 kPa, 100 kPa, and 150 kPa. Since 20% of GGBFS and AF was observed as the optimum dosage for reduction of heaving at 16 M NaOH inundation, the triaxial tests were planned on both soils for 20% only. The variation in cohesion and angle of internal friction of unitercted soil and alkali interacted soil with GGBFS and AF are shown in Fig. 5.19, 5.20, Fig. 5.21, and 5.22 respectively.

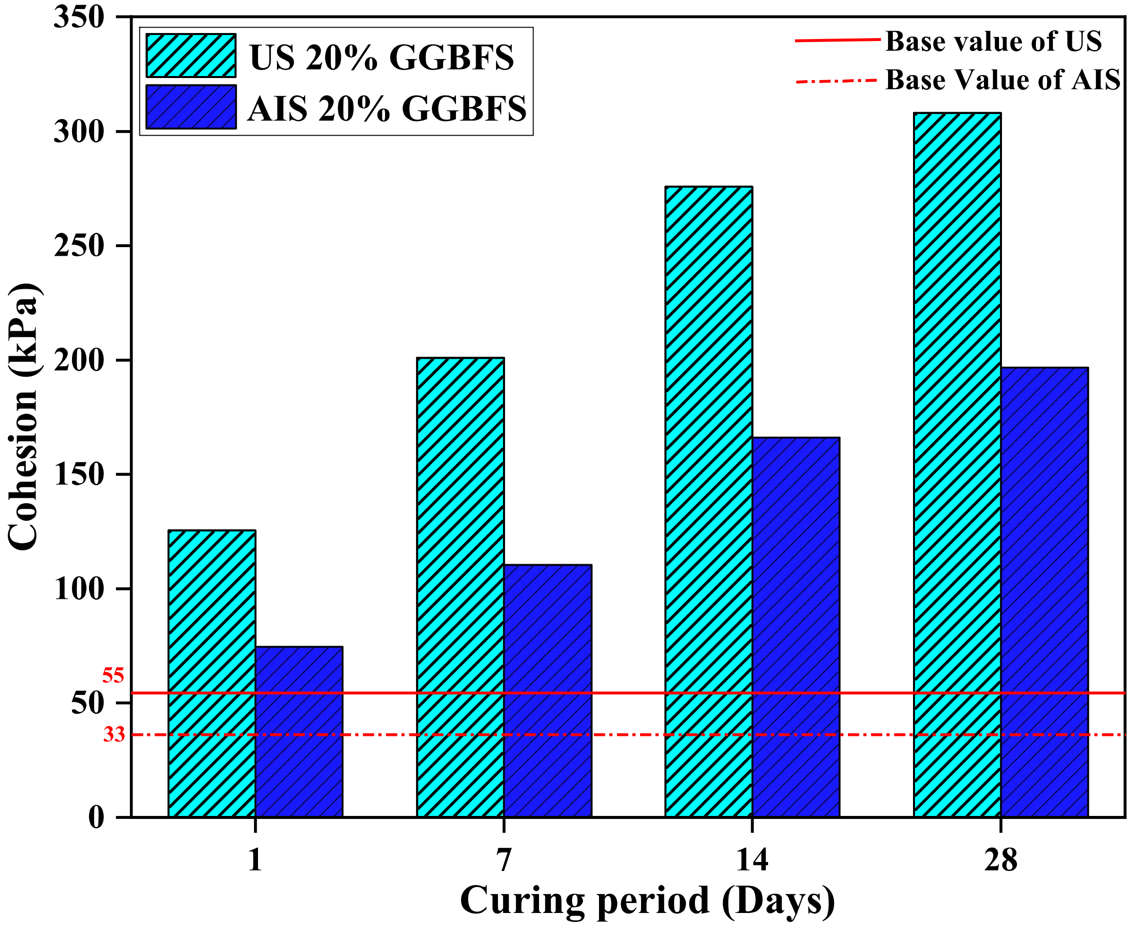


Figure 5.19: Variation in cohesion of US and AIS with 20% GGBFS

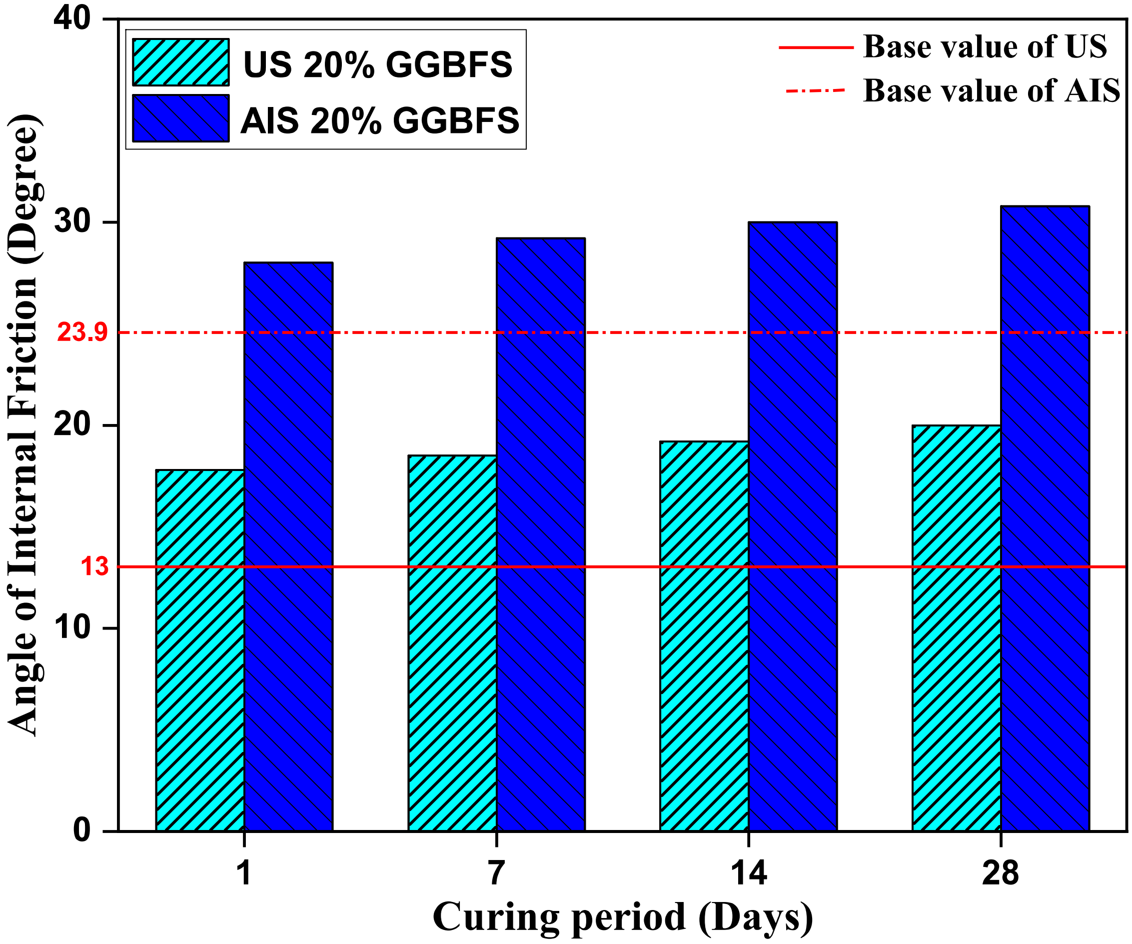


Figure 5.20: Variation in angle of internal friction of US and AIS with 20% GGBFS

It is clarified from the figures that the cohesion value of soil and alkali interacted soil with 20% inclusion of GGBFS and AF increases with the prolongation of the curing period. On the other hand, the friction angles of soil mixed with GGBFS and AF were lower than that of friction angle of alkali interacted soil admixed with GGBFS and AF irrespective of the curing period. However, there was a definite increase in the friction angle for both types of soil with the increase in the curing period. The increase in friction angle was marginal after 14 days of curing. The cohesion value of soil was 55 kPa was increased to 125.6 kPa, 201 kPa, 275.8 kPa and 308 kPa and the angle of internal friction value of soil was 13^o increased to 17.8^o, 18.5^o, 19.2^o and 20^o with the prolongation of curing period 1, 7, 14 and 28 days with 20% GGBFS respectively as shown in Fig. 5.19 and 5.20.

Whereas, the cohesion value of alkali interacted soil was 33 kPa which increased to 74.5 kPa, 110.2 kPa, 165.8 kPa and 196.6 kPa and the angle of internal friction value of soil was 23.9^o which increased to 28^o, 29.2^o, 30^o and 30.8^o with the prolongation of curing period 1, 7, 14 and 28 days with 20% GGBFS respectively as shown in Fig. 5.20. A similar trend has been observed in the case of uninteracted soil and alkali interacted soil stabilized with 20% AF with different curing periods. The cohesion value of uninteracted soil was 55 kPa which increased to 244.7kPa, 304.91 kPa, 385.79 kPa and 470.98 kPa and the angle of internal friction value of soil was 13^o was increased to 22.98^o, 23.35^o, 24.65^o and 24.75^o with the prolongation of curing period 1, 7, 14 and 28 days with 20% AF respectively as shown in Fig. 5.21 and 5.22. Whereas, the cohesion value of alkali interacted soil was 33 kPa which increased to 111.95 kPa, 125.97 kPa, 165.01 kPa and 227.8 kPa and the angle of internal friction value of soil was 23.9^o which increased to 33.06^o, 33.88^o, 34.56^o and 34.98^o with the prolongation of curing period 1, 7, 14 and 28 days with 20% AF respectively as shown in Fig. 5.21 and 5.22 repectively. The increase

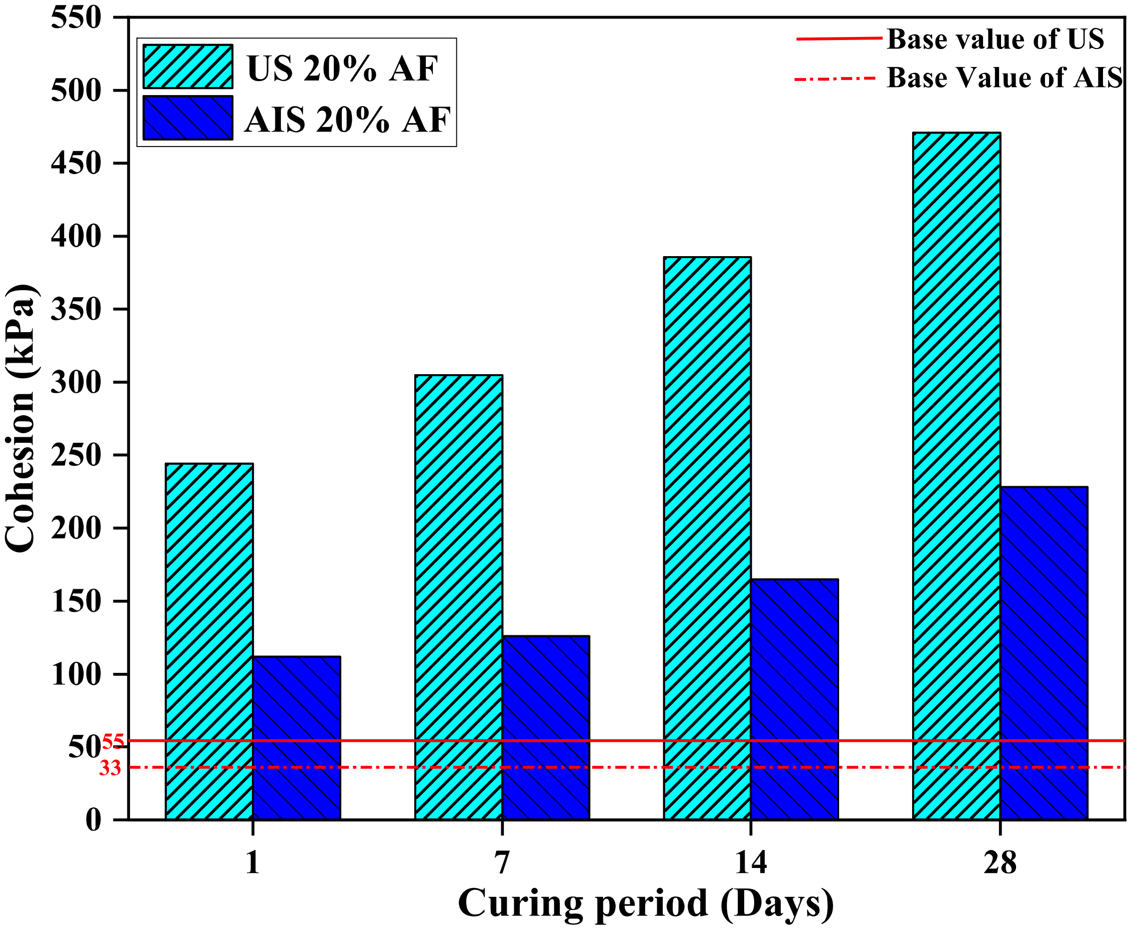


Figure 5.21: Variation in cohesion of US and AIS with 20% AF

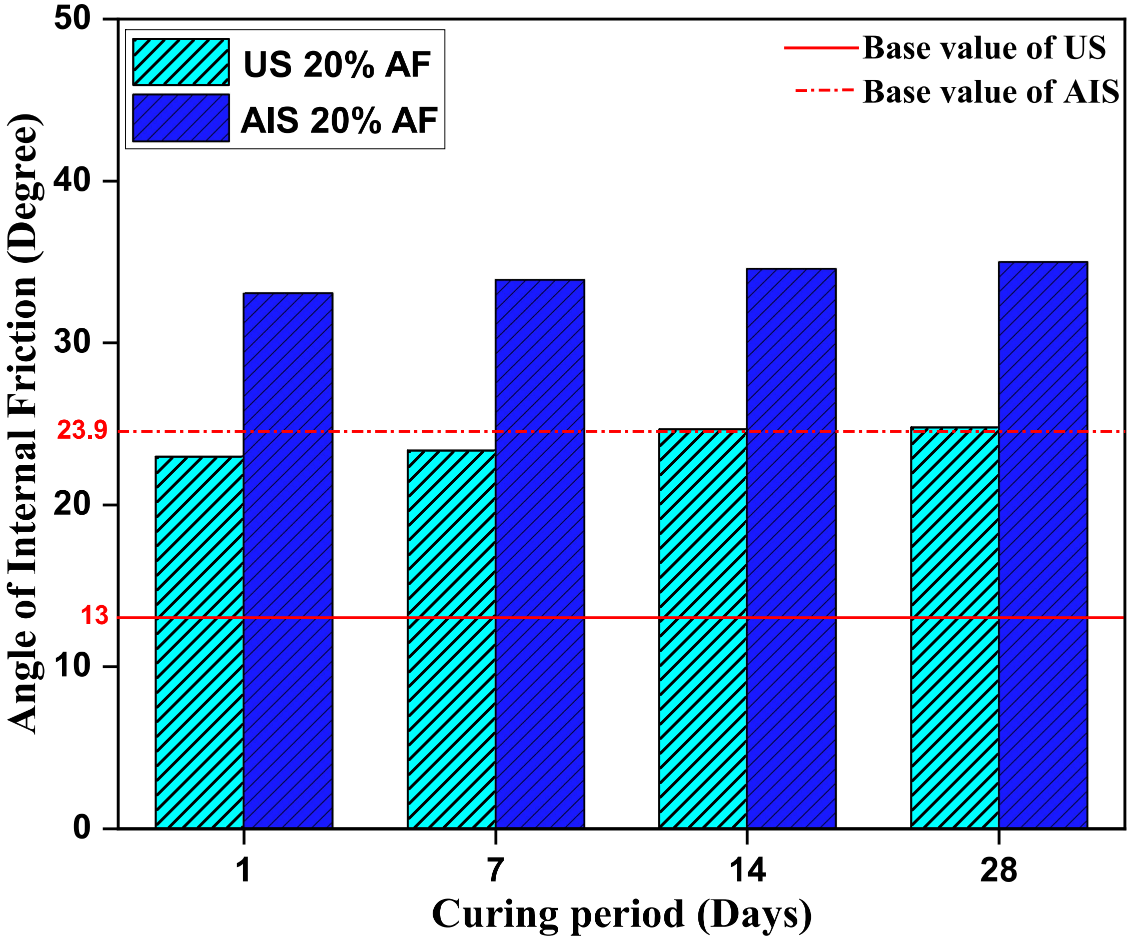


Figure 5.22: Variation in angle of internal friction of US and AIS with 20% AF

in cohesion and angle of internal friction of soil and alkali interacted soil stabilized with GGBFS and AF is mainly due to the presence of ca^{2+} ions attached to the surface of the clay particles, replacing the existing cations which lead to coagulation of clay particles. Due to the coagulating of soil particles the value of cohesion as well as the friction angle increases. The calcium present in GGBFS and AF also results in the cation exchange between the ca^{2+} ions of the soil clay fraction which caused the formation of cementitious compound between the soil particles leading to the increase in cohesion and angle of internal friction value of stabilized soil. An increase in the shear strength parameters is also observed with the increase in the age of specimens. During the initial phase of curing the specimen, the increase in shear strength parameters may be due to the formation of primary cementitious products such as $C_3S_2H_X$ (hydrated gel) and $Ca(OH)_2$ resulting in short-term hardening of composites. The formation of secondary cementitious products such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) formed by the reaction of Ca^{2+} with dissolved silica and alumina content of the soil with prolongation of the curing period results in an increase in shear strength parameters of stabilised soil. In the last phase, the bonding of particles of mixtures is enhanced due to the crystallization and hardening of these products with time which increases the strength of mixed soil specimens.

5.3.8 Mineralogical Studies

X-ray diffraction (XRD) studies were conducted to evidence whether the interaction of soil with 16M NaOH solution and the addition of optimum dosage of 20% of GGBFS and AF leads to any mineralogical changes in the soil. Fig. 5.23 and Fig. 5.24 show the XRD pattern of uninteracted soil, alkali interacted soil and soil stabilized with GGBFS and AF. It is evident from Fig. 5.23 that new peaks have been formed corresponding to NASH, which is a mineral of the zeolite group (Sodium aluminium silicate hydrate). XRD pattern of GGBFS treated soil has also shown peaks pertaining to Gagarinite (G), Augite (A), and Hibschite (H) also shown in Fig. 5.23. The addition of GGBFS to the 16M inundated soil promotes the production of sodium and calcium-based aluminium silicates hydrate gels resulting from a combination of cation present in alkali solution with aluminosilicates of clay and GGBFS. This gel has a cementitious property which reduces the heaving as well as increases in strength of stabilized soil. The suppression in peaks of Quartz (Q) has been also observed after GGBFS treatment.

The peak of new mineral compositions like calcium silicate hydrate (C-S-H) and calcium aluminosilicate hydrate (C-A-S-H) are found on the addition of 20% AF in the soil as shown in Fig. 5.24. The intensity peaks of calcium hydroxide $Ca(OH)_2$ and ettringite in the presence of AF at 2θ equal to 15.23^o and at 2θ equal to 28.86^o are found after the stabilization of soil. The formation of CSH is more in with AF treated soil due to $Ca(OH)_2$ converted to secondary CSH and therefore enhancing the strength of the soil. The formation of Calcium Silicate Hydrate (C-S-H) gel and Calcium hydroxide (CH) is mainly due hydration of soil with AF as a result of pozzolanic reactions.

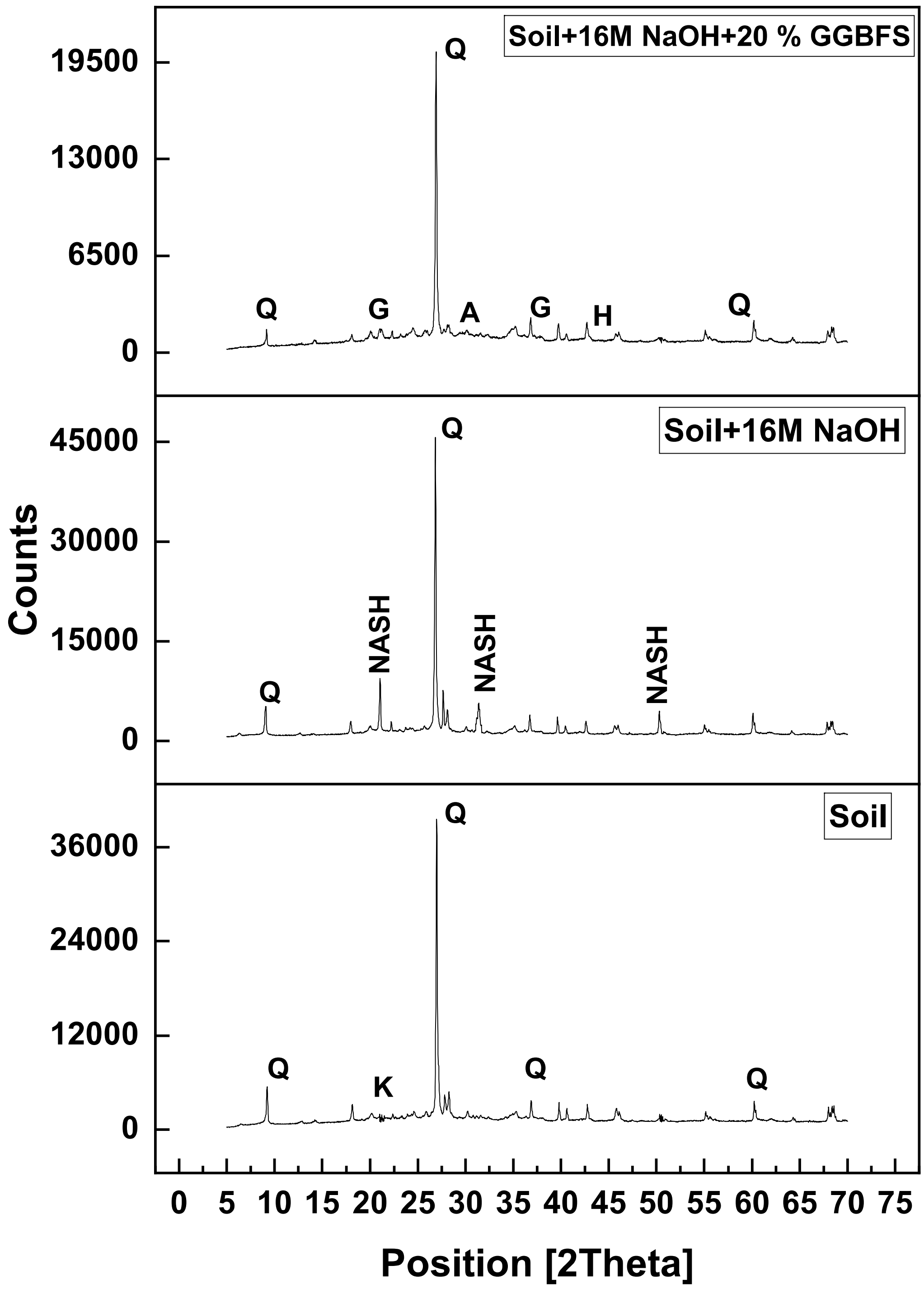


Figure 5.23: XRD of uninteracted soil and interacted soil treated with 20% GGBFS

5.3.9 Microstructural studies

To investigate the morphological transformation of soil interacted with alkali solution and stabilized with 20% GGBFS and AF a series of scanning electron microscopy (SEM) has

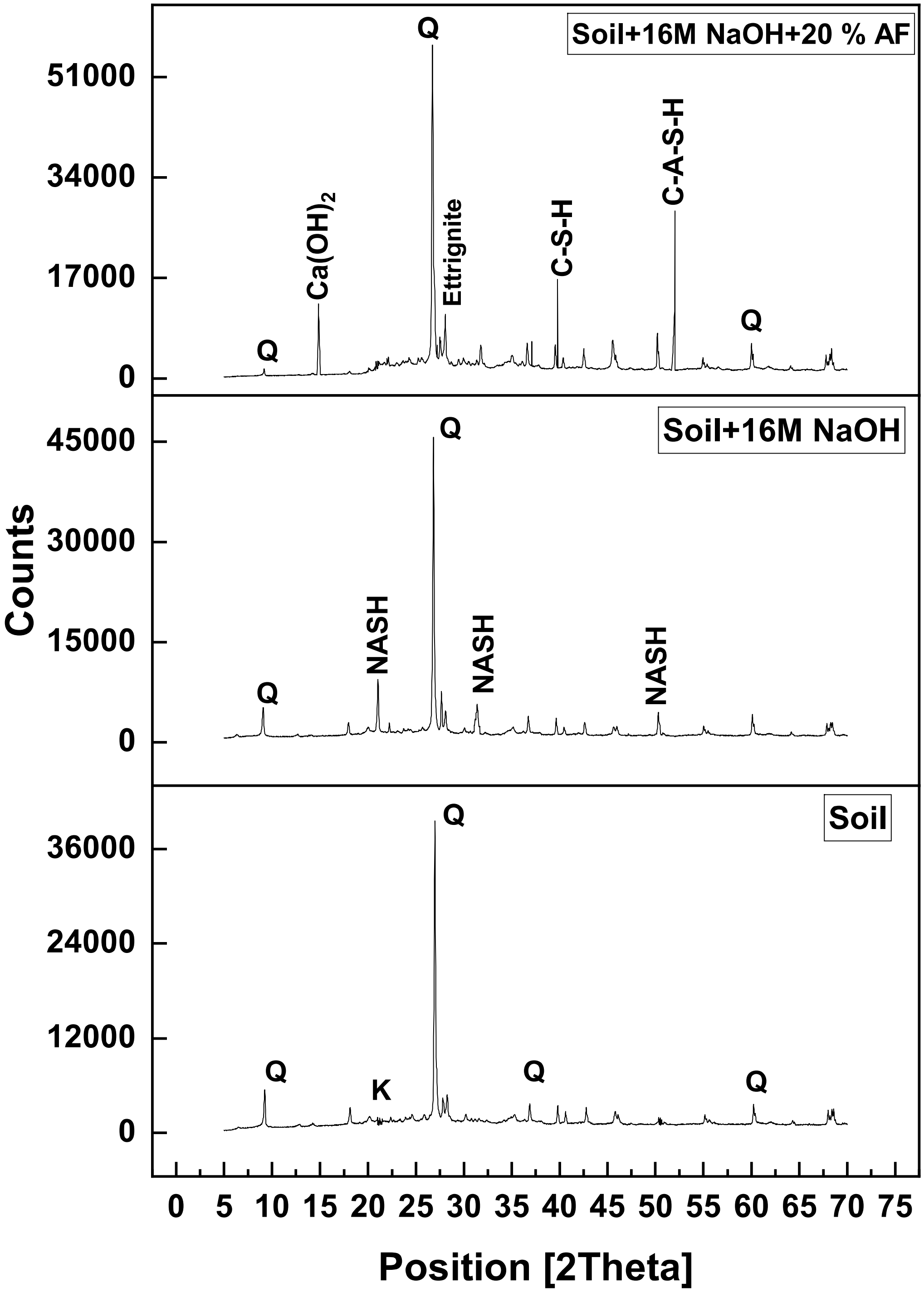
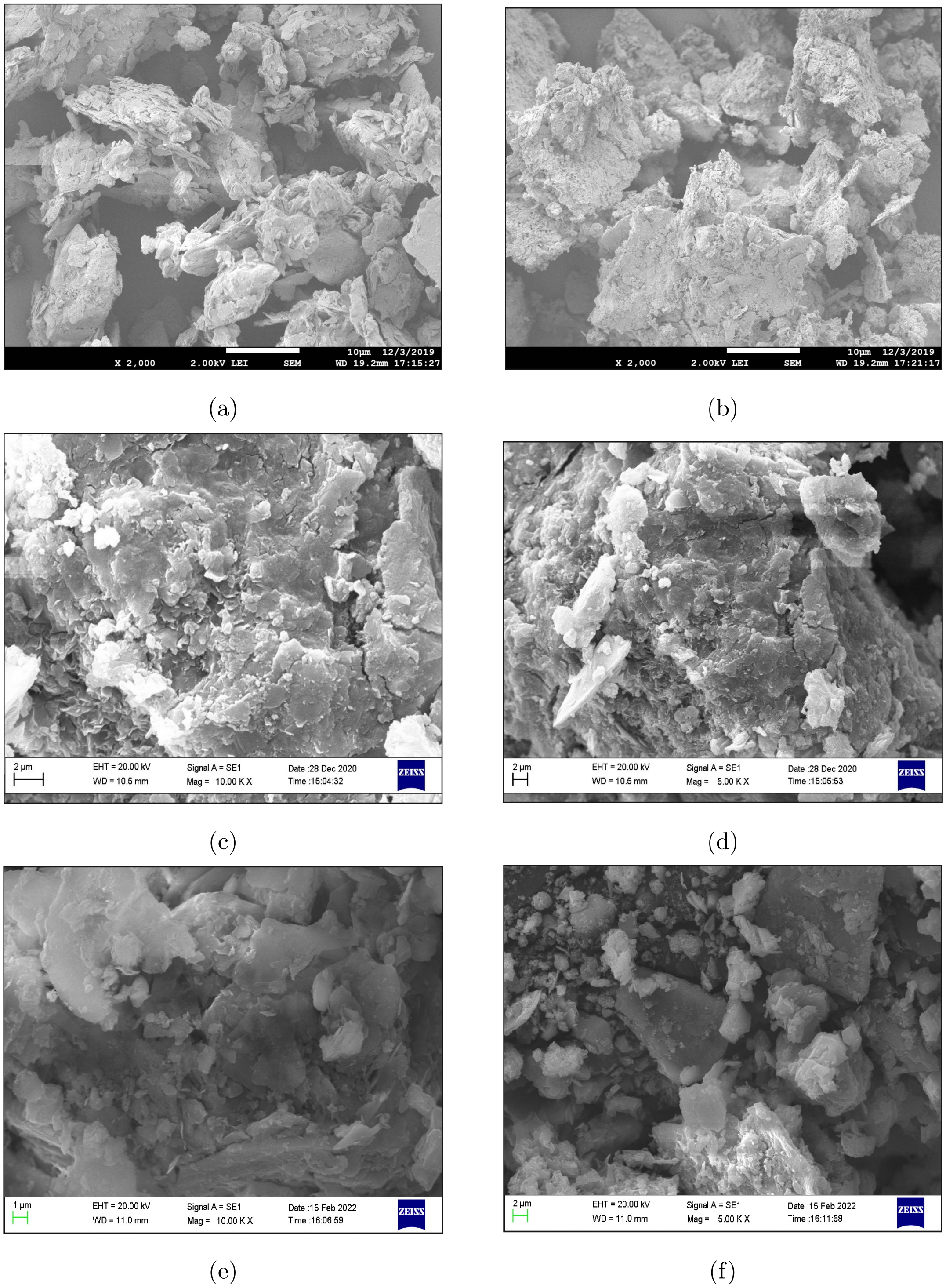


Figure 5.24: XRD of uninteracted soil and interacted soil treated with 20% AF

been performed on a broken sample of unconfined compressive strength tests. The SEM images of uninteracted soil and alkali interacted soil are shown in Fig. 5.25a and Fig. 5.25b and GGBFS and AF treated uninteracted soil as well as alkali interacted soil presented



(a) (b)

(c) (d)

(e) (f)

Figure 5.25: SEM image of (a) Uniteracted soil, (b) alkali interacted soil, (c), (d) soil treated with 20% GGBFS, (e), (f) soil treated with 20% AF

in Fig. 5.25c, Fig. 5.25d, Fig. 5.25e, and Fig. 5.25f respectively. The SEM image of soil interacted with alkali shows some disintegration or weathering. The morphological change in soil supports the formation of a new compound sodium aluminosilicate hydrate (N-A-S-H) due to alkali interaction. A relatively closed and denser structure along with cementitious gel type formation in GGBFS and AF treated soil can be seen as compared to a relatively more porous and deterioration in case of soil and alkali interacted soil. The production of cementitious compounds such as C–S–H is the main governing factor for the increase in strength.

5.4 Bench Scale Study through Electrokinetics

Despite of these test, the efficiency of 20% GGBFS and AF slurry were also analysed in stabilising the alkali interacted soil. For this a bench scale model study through electrokinetics were conducted. The deatils of experiment procedure and model are discussed in detail in subsequent sections.

5.4.1 Alkali Interacted Soil

Electrokinetic stabilisation tests using additives and chemicals were performed on alkali interacted soil in the current research. The preparation method of alkali interacted soil has already been discussed in chapter 2. The particle size distribution curve and geotechnical properties of the alkali interacted soil have also been discussed in chapter 3.

5.4.2 Model Chamber

The design and fabrication of the bench scale EK model and sensors used in the EK tests are already discussed in detail in chapter 3. The image of the model, electrode, voltage sensors, motorized stirrer and DC supplier are also shown in chapter 3.

5.4.3 Sample Preparation for Bench-Scale Model Study

The alkali interacted soil specimens were prepared at 85% of maximum dry density and water content corresponding to saturated density to make the soil more permeable (Keykha et al., 2014). The prepared sample was compacted in the soil chamber in three layers.

The filter papers were placed at both ends to prevent the migration of soil particles in the electrolyte chamber. GGBFS and alccofine slurry solution (20% W/V) was injected into the anode chamber, and the distilled water was injected into the cathode chamber during the EK process. To avoid settlement of the GGBFS and alccofine particles during the EK process the slurry solution was stirred at regular intervals with the help of a motorized stirrer. The voltage gradient of 1V/cm was maintained across the electrode during the experiment, and the change in voltage, current, pH and electroosmotic flow was monitored over time across the sample. After ceasing the EK process the soil in the soil chamber is allowed to keep for a period of 14 days, and after the soil sample was extracted from three different locations. These extracted samples were again kept undisturbed for another 14-days to allow the residual reactions to take place. At the end of this period, the samples were tested for unconfined compressive strength.

5.4.4 Experimental Results of the Electrokinetic Bench-Scale Study

In this section the parameters measured during the EK test as well as after EK test are discussed in details.

5.4.4.1 Variation in Voltage During EK Test

Fig. 5.26 and Fig. 5.27 shows the variation of voltage at regular intervals during the EK test. Initially, the voltage was in increasing trend due to the movement of GGBFS and AF, which contains a high amount of calcium ion from anode to cathode. After reaching the peak value at day 7, voltage goes on decreasing till the end of test duration. The decrement in voltage trend is mainly due to the precipitation of GGBFS and AF solution in the soil, which creates a zone of high electrical resistance.

5.4.4.2 Variation in pH of Electrolytic Solution During EK Test

The variation of pH in the anode and cathode chamber during EK experiment period are shown in Fig. 5.28 and Fig. 5.29 respectively. The initial pH of GGBFS solution, AF solution and water were 8.4, 7.39 and 7.0, respectively.

The change in pH value occurs due to the electrolysis of water under the application

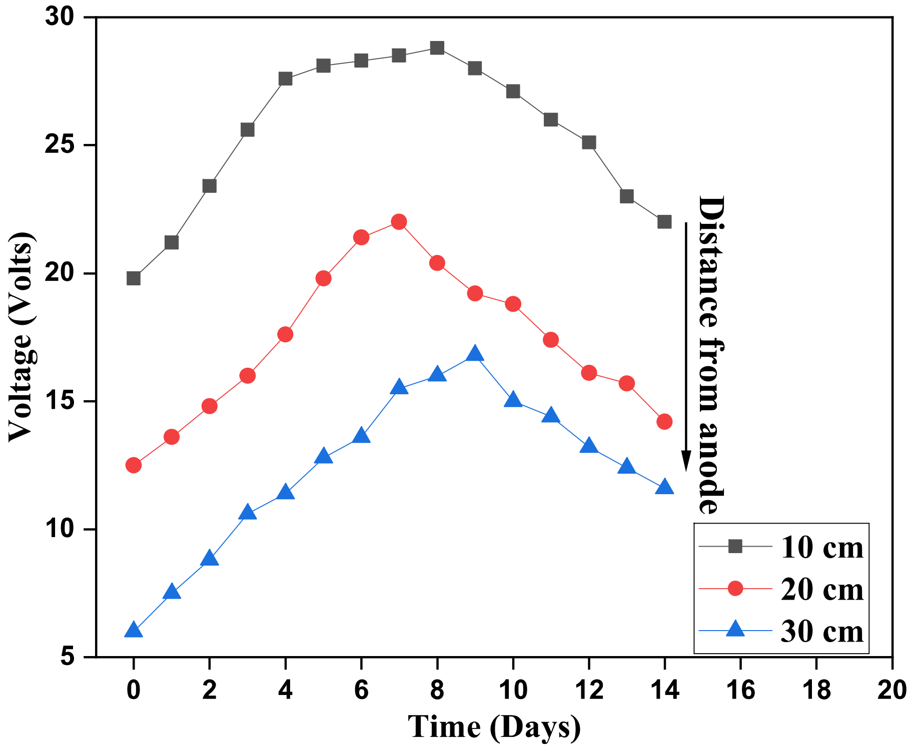


Figure 5.26: Variation of voltage in bench-scale EK set-up with GGBFS

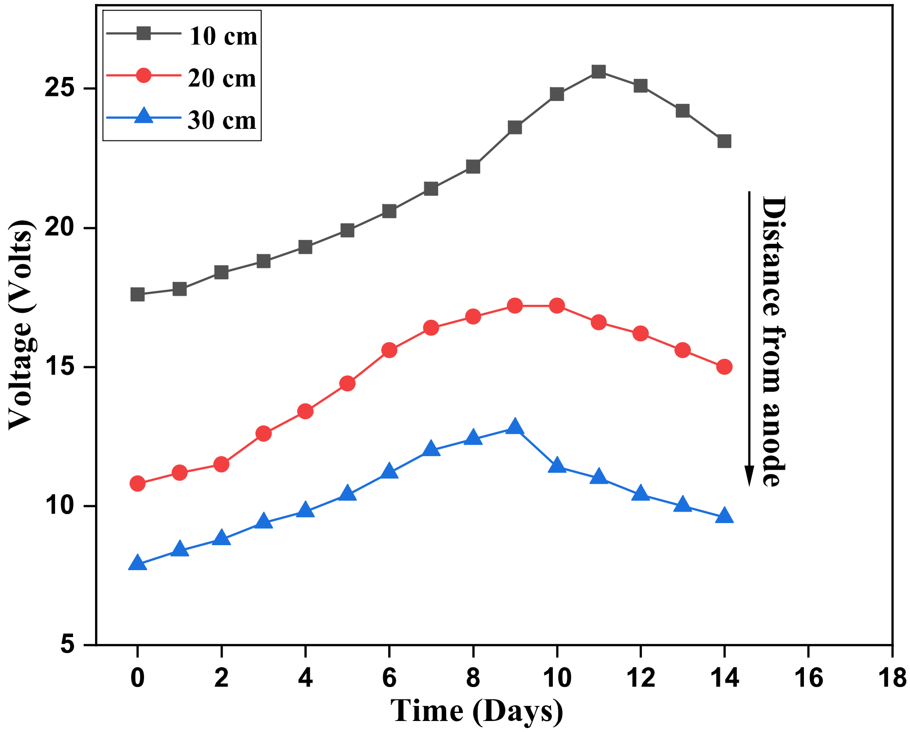


Figure 5.27: Variation of voltage in bench-scale EK set-up with AF

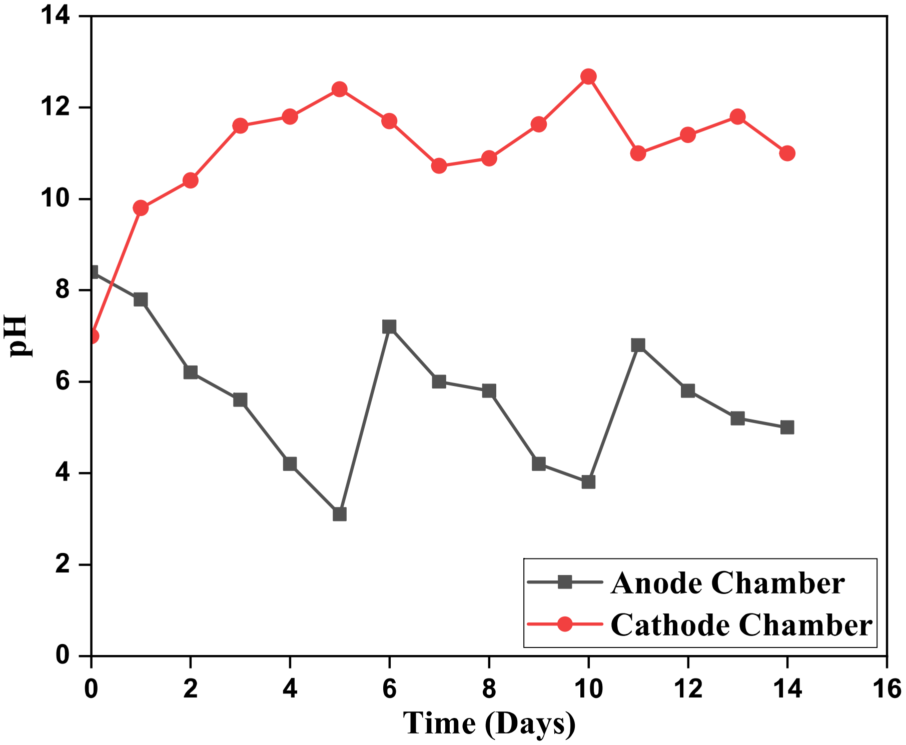


Figure 5.28: Variation in pH of electrolytes during EK test with GGBFS

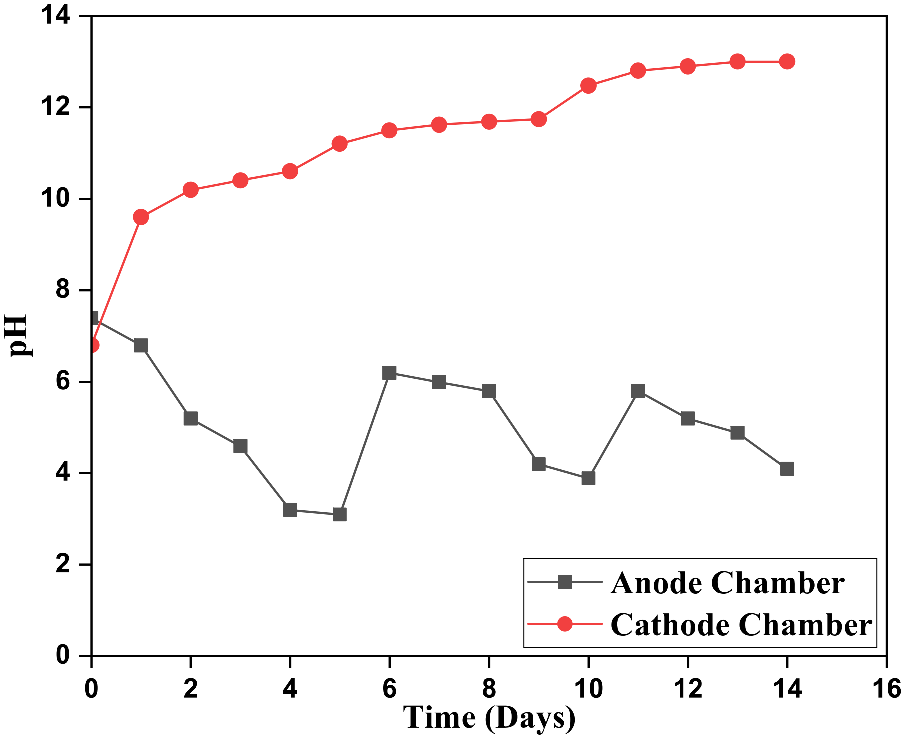


Figure 5.29: Variation in pH of electrolytes during EK test with AF

of voltage gradient, which leads to the production of oxygen at the anode (oxidation) and hydrogen at the cathode (reduction). The oxidation and reduction reaction of solution generates acidic medium and basic medium that cause pH gradient across the electrodes. As the pH value goes below 4.0 the GGBFS solution again fills the anode chamber to maintain pH and GGBFS content. The maximum and minimum values of pH were found 12.68 and 3.1, respectively. whereas, the maximum and minimum value of pH were found 13 and 4.09 in case of AF respectively.

5.4.4.3 Variation in Electroosmotic Flow During EK Test

The electrokinetic technique is associated with electroosmosis and electromigration was initiated under applied electrical potential into the soil. The admixture slurry solutions were moved from the anode chamber through the soil specimen towards the cathode chamber by both electromigration and electroosmosis. The cumulative discharge volume with time in the cathode collecting chamber under electroosmotic is shown in Fig. 5.30 respectively. The electroosmotic flow also indicates the continuity of the electrokinetic test.

5.4.4.4 Unconfined Compressive Strength Studies

After the completion of the electrokinetic test, the treated soil samples were extracted at a distance of 10 cm, 20 cm, and 30 cm from the anode. The extracted sample was then tested for unconfined compressive strength to analyse the improvement in the strength of alkali interacted soil. Fig. 5.31 and Fig. 5.32 show the UCS value of GGBFS and AF treated alkali interacted soil. The values of UCS were obtained after 14 days of the EK test followed by 14 more days as an interaction period after stopping the EK test. The UCS value of GGBFS treated soil was in the range of 1770 – 1140 kPa. Whereas, the UCS value of AF-treated soil was in the range of 1052 – 612 kPa. The increase in UCS value was due to the geopolymerization after the ingression of admixture slurry into the soil. A higher UCS value was obtained near the anode because of the high concentration of admixture.

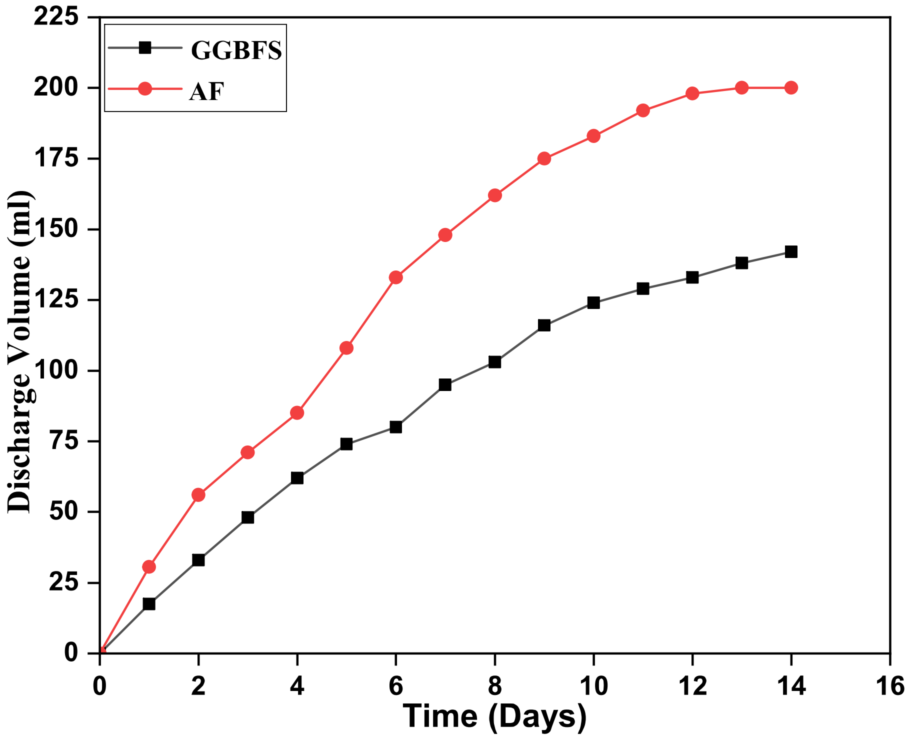


Figure 5.30: Variation in cumulative discharge with time in bench scale EK setup

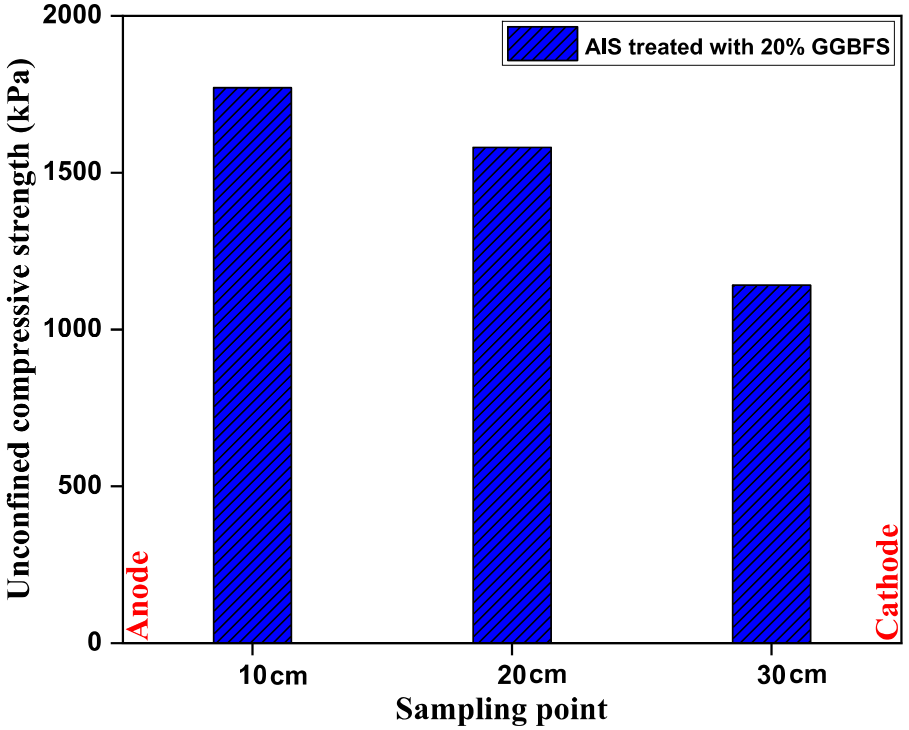


Figure 5.31: Variation in Unconfined Compressive Strength of soil after GGBFS treatment

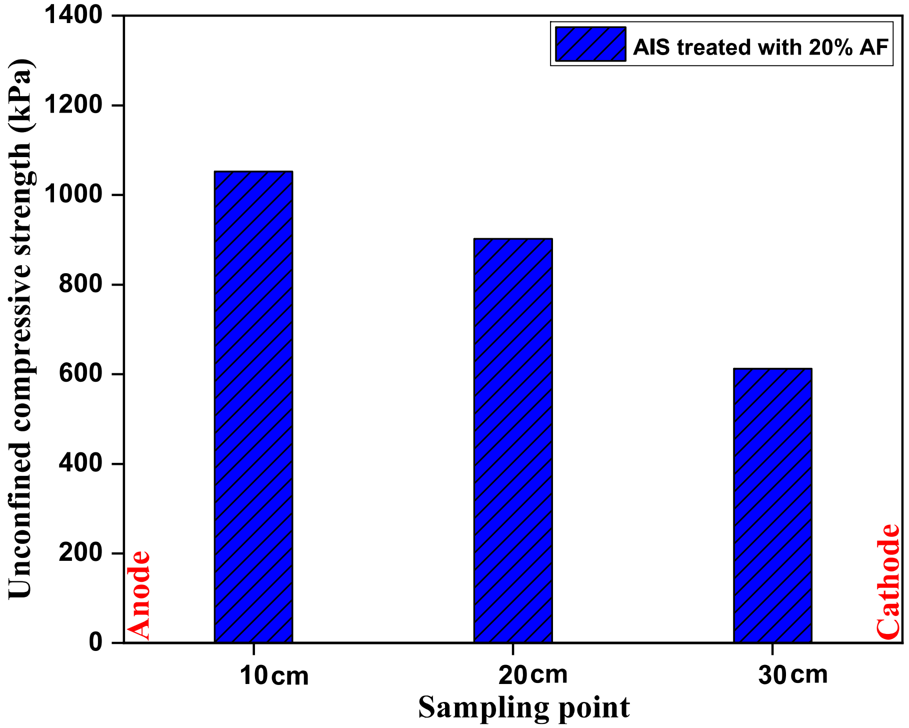


Figure 5.32: Variation in Unconfined Compressive Strength of soil after AF treatment

5.5 Summary

In the present chapter, the effect of varying percentages of GGBFS and AF on the alkali-induced heaving of soil has been discussed. It has been observed that the inclusion of 20% GGBFS and AF was found effective in controlling heaving in soil due to inundation with 16M NaOH solution. The impact of GGBFS and AF inclusion on the geotechnical properties of soil and alkali-interacted soil also has been investigated and compared. Extensive studies to evaluate the effect of GGBFS and AF treatment on the unconfined compressive strength at various admixture contents and curing periods have been conducted. It has been observed that the unconfined compressive strength of soil and alkali interacted soil has been increased with an increase in GGBFS and AF content. The observed results have been supported by the XRD analysis and SEM analysis in order to elucidate the effects of microscopic alterations leading to changes in macroscopic behaviour. Further, a bench scale electrokinetic model test is also performed to examine the efficiency of stabilizing effect of GGBFS and AF on alkali interacted soil in the field. From the test results, it is worth mentioning that the GGBFS and AF may be used as a barrier around the foundation soil of structures to prevent the interaction of alkali contaminants with the soil, and they can also be used with the foundation soil to control the alkali induced heaving in the soil in the field.