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Stabilization of Clayey Soil with Alkali-activated Hybrid Slag/Cement

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Abstract

This study investigates the stabilization performance of clayey soil treated with alkali-activated hybrid slag/cement. Sodium silicate (SS) and sodium hydroxide (SH) are used as alkali activators, whereas ground blast furnace slag (GGBS) and ordinary Portland cement (OPC) are used as sources of aluminosilicate. A total of 27 different types of mixtures are used for stabilization. Unconfined compressive strength (UCS) of untreated clay and stabilized soils are performed at immediately, 3-, 7-, 28-, and 90 days curing times under air-dried and wet-cured conditions. In addition, 90-d volume and mass changes in the samples are measured. Stabilized samples with an SS/SH ratio of 1 under air-dried conditions reveal moistening at early curing ages (≤28 days); afterward, sodium carbonate crystals appear in these samples at longer curing ages. Geopolymer-treated clayey soil exhibits lower volumetric and mass changes compared with OPC. Most of the stabilized clayey soil with alkali-activated hybrid slag/cement exhibits higher strength compared with OPC under air-dried and wet-cured conditions.

Keywords

hybrid slag/cement, alkali activation, geopolymer, soil stabilization, high plasticity clay

1 Introduction

Today, the need for new construction with different properties and sizes has increased with the human population and technology development. Owing to the increasing building stock, unproblematic soil areas have gradually decreased, thus necessitating building structures on soft and weak soils. In particular, clayey soils can cause several constructional problems because of their negative properties, such as high compressibility, dispersibility, low strength, and high volumetric change. Lime and cement is used frequently in the stabilization of clayey soils in field works [1]. The use of cement has numerous disadvantages, particularly its adverse environmental effects. Cement production causes destruction of nature, reduction in natural resources, use of fossil fuels, and carbon dioxide (CO_2) emissions, thereby contributing to global warming [2]. Reportedly, 8% of global CO_2 emissions is associated with the cement industry [3]. As per estimates, approximately 0.8–1.0 tons of CO2 are emitted into the atmosphere per ton of cement production [4, 5]. CO_2 is the primary greenhouse gas that causes global warming owing to human activity [6]. The Paris Agreement was signed to mitigate global warming within certain limits and entered into force in 2016 [7]. This agreement aims to reduce emissions as soon as possible and balance greenhouse gases in the second quarter of the 21st century [7]. Within the framework of this agreement, countries have begun to take precautions to reduce CO_2 emissions. This situation also affects the cement industry, and the search for alternative materials for cement has accelerated. Research on geopolymers as alternatives to cement has been recently conducted. Similarly, geopolymer binders are being investigated as alternatives to cement for soil stabilization [8–10]. In ordinary Portland cement (OPC), the chemical process is hydration, whereas in geopolymers, the chemical process is geopolymerization. Geopolymerization is a reaction that creates a material called geopolymer in an amorphous polymeric structure with Si-O-Al-O-Si bonds by dissolving aluminosilicates in a high-density alkali solution [11]. Ground granulated blast slag (GGBS), fly ash, volcanic ash, palm

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oil fuel ash, rice husk ash, ferrochrome slag, sugarcane bagasse ash, and glass powder are materials with rich aluminate-silicate content [12]. The most commonly used alkali activators are sodium hydroxide (NaOH), potassium silicate (K_2SiO_3), potassium hydroxide (KOH), and sodium silicate (Na_2SiO_3); these activators can be used alone or in combination [13]. In this study, Na_2SiO_3 and NaOH were used as alkali activators. Generally, GGBS is used as an alternative to cement in terms of cost, environment, and CO_2 emission. In soil stabilization, GGBS is used alone or in combination with cement [14], lime [15], fly ash [16], carbide sludge [17], magnesia [18], coir fiber [19], and alkali activators. NaOH and Na_2SiO_3 are predominantly used as activators in most studies. Much of the stabilization work with the activator has been performed on clay soils. Moreover, activators have also been applied to silt [20], silty sand [21], and sandy soils [22]. The curing temperatures in soil improvements using alkali activators are usually between 20 and 30 °C degrees. In some studies, the curing temperature was maintained high (50 °C and above); these studies reported that the unconfined compressive tests (UCS) value increased with increasing curing temperature [23]. A decrease in the permeability value, volumetric compressibility, and degree of swelling and shrinkage was observed in stabilized soils with alkali activation [21, 24, 25]. Similarly, some studies have reported that LL and PI values decrease in stabilized soils with an alkali activator [26, 27]. In addition, an increase in the UCS values of stabilized clayey soils with an alkali activator has been observed [8, 10, 28]. Geopolymer studies are generally conducted to produce environmentally friendly concretes. However, studies on the use of geopolymers in soil stabilization are limited and continue to be developed. Factors such as the soil and activator types, activator ratios, curing conditions and temperature, aluminosilicate sources, activator/precursor ratios, and activator/soil ratios can influence the geopolymer application procedure to soils.

This study investigates the effectiveness of geopolymers formed by the alkali activation of GGBS and GGBS + OPC in stabilizing high-plasticity clay. Herein, SS/SH ratios of 1, 3, 5, and 7 were used as alkali activators. The amount of alkali activator used was 10 wt% of the clay. The amount of GGBS + OPC used was 20 wt% of the clay. Among these mixtures, 20, 18, 16, and 12% were GGBS, and the rest were OPC. The stabilized soils were cured under two conditions: air-dried and wet-cured. The curing times of the treated soils were determined 0 (immediately), 3, 7, 28, and 90 days. The stabilization performances of treated clays with 27 different mixtures were compared with each other, untreated clay, and with OPC.

2 Material

2.1 Soil

In this study, Ukrainian clays, which show fine-grained and mainly kaolinitic properties, were used. These clays are located in the Donbas (Donetsk) basin of Ukraine. The basin consists of Miocene sedimentary deposits [29]. Ukrainian clays have high clay mineral content [30]. The basic engineering and physical properties of the clay used in the study were determined by laboratory studies (Table 1). According to the sieve and hydrometer analysis, the soil contained 3% sand, 29% silt, and 68% clay, as shown in Fig. 1 [31, 32].

Table 1 Engineering properties of clay soil

Properties of Clay	Value
Particle size distribution	
Gravel size (%)	0
Sand size (%)	3
Silt size (%)	29
Clay size (%)	68
Atterberg's limits	
Liquid limits (%)	57
Plastic limits (%)	26
Plasticity index (%)	31
USCS Classification	CH
AASTHO Classification	A-7-6
Compaction characteristics	
Maximum dry unit weight (kN/m^3)	15.4
Optimum water content (%)	23.6
UCS for samples molded at MDD and OWC (kPa)	346.6

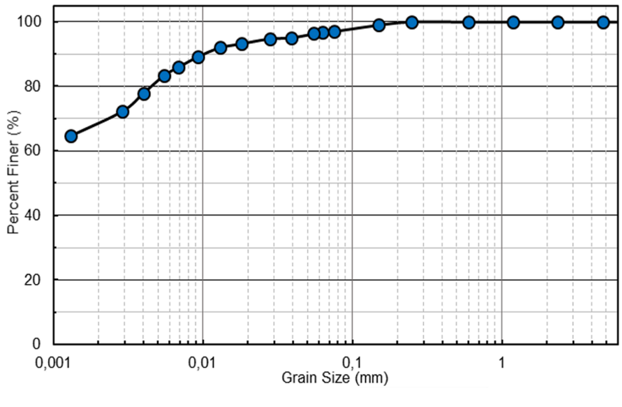


Fig. 1 Particle size distribution of the clay soil

The liquid limit and plastic limit were determined at 57% and 26%, respectively [33]. The clay used in the study was classified as high plasticity (CH) and A-7-6 according to USCS (Unified Soil Classification System) and AASHTO, respectively [34, 35]. The specific gravity of the clay was determined to be 2.67 [36]. The standard proctor compaction tests were performed to determine the optimum water content (OWC) and maximum dry density (MDD) of the clay [37]. The OWC and MDD of the clay were determined 23,6% and 15,4 kN/m^3, respectively. The untreated clay samples were prepared under OWC and MDD conditions, and UCS tests were conducted immediately. The UCS tests were conducted based on ASTM D2166 [38]. The UCS test results of untreated soil samples were found 346.6 kPa. The chemical properties of the clay were shown in Table 2. It was seen that the chemical structure of the clay is mainly composed of SiO_2 and Al_2O_3.

2.2 Binding stabilizing agents

In this study, alkali-activated hybrid cement was used to stabilize the clay. Ground blast furnace slag (GGBS) was used as slag, and 42.5 R ordinary Portland cement (OPC) was used as cement. Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) were used as the alkali activators. The GGBS was provided by Ereğli Iron and Steel Factories located in Ereğli, Turkey. The physical properties and chemical composition of GGBS and OPC were represented in Table 2. The specific gravity of OPC and GGBS were found to be 3.14 and 2.3, respectively. The OPC has a blain-specific surface of 3612 cm^2/g and a GGBS specific surface area of 4341 cm^2/g. GGBS and OPC are mainly composed of SiO_2, CaO, and Al_2O_3, but the amounts of these components are different. GGBS and OPC materials used in the study were compared, and it was seen that GGBS has higher SiO_2, Al_2O_3, and MgO contents.

Different ratios of sodium silicate to sodium hydroxide solutions were used for the alkali activation of mixtures. Sodium silicate is the common name for a chemical compound with the general formula $Na_2(SiO_2)_nO$. The most well-known member is meta silicate (Na_2SiO_3). The sodium silicate used in the study is in liquid form and is also known as water glass or liquid glass. It consists of 8% Na_2O, 27% SiO_2, and 65% H_2O. Sodium silicate (SS) is colorless and has a molecular weight of 122.06 g/mol and a density of 1.35 g/cm^3. Sodium hydroxide is an inorganic and strong base consisting of Na+ and OH- ion (NaOH) and is also known as soda caustic. The sodium hydroxide (SH) used in this study was in the pellet (a flaked solid at room temperature) form and had a molecular weight of 40 g/mol and a density of 2.13 g/cm^3.

Table 2 Physical properties and chemical composition of OPC, GGBS, and clay

Properties	OPC	GGBS	Clay
Chemical composition (%)			
SiO_2	19.82	34.25	59.71
Al_2O_3	4.83	12.30	27.20
Fe_2O_3	3.06	1.44	0.96
CaO	62.55	30.81	0.44
MgO	1.60	9.35	0.49
SO_3	3.03	0.62	-
Na_2O	0.38	0.45	0.41
K_2O	0.86	0.78	1.81
TiO_2	-	1.34	1.31
Mn_2O_3	-	4.01	-
Loss on Ignition	3.02	0.00	-
Physical properties			
Specific gravity	3.13	2.90	2.67
Blaine Specific Surface (cm^2/g)	3612	4341	-
Residue on 0.045 mm sieve (%)	0.50	1.00	-
Residue on 0.09 mm sieve (%)	0.00	0.00	-

2.3 Sample preparation and unconfined compressive strength (UCS) test

The high plasticity clay used in the study was first dried in an oven at 105 °C for 24 h and then ground into powder form. To stabilize the clay, OPC, GGBS, and activators (SS and SH) were mixed at 28 different ratios. The mixtures used in the study are expressed using concise and easy-to-understand notations. The designed notation system defined GGBS with 'S', cement with 'C', geopolymer with 'GP', sodium silicate with 'SS', sodium hydroxide with 'SH', and the ratio of sodium silicate to sodium hydroxide with 'R'. The numbers in the notations (excluding R: SS/SH) indicate the percentage of binding agents in the mixture. The details of the mixtures and notations of the quantity combinations of the samples are listed in Table 3. The amount of alkali activator used was 10 wt% of the clay. Four combinations of the alkali activators were used; these combinations were in the form of SS/SH ratios (SS/SH = 1, 3, 5, and 7). Standard proctor compaction tests were performed on 28 mixtures, as listed in Table 3, and the MDD and OWC values were determined. The required materials for the mixtures (dry clay, GGBS, OPC, SS, SH, and water) were prepared considering the weight percentages in Table 3. The required materials for the mixtures (dry clay, GGBS, OPC, SS, SH, and water) were prepared considering the weight percentages in Table 3. First, dry clay and mixtures (without an alkali activator) were prepared and mixed for homogenization. NaOH was placed in the bottle with the water calculated from the OWC and subsequently shaken continuously by hand. After the liquefied NaOH solution was cooled, sodium silicate was slowly added. The solutions were maintained for a minimum of 24 h in an airtight container at 21 °C (± 2 °C) before use. Given that the temperature of the resulting solution increases after NaOH is dissolved in water, the solutions must be cooled to room temperature before use [39]. The solutions were mixed homogeneously with the other components, as presented in Table 3. The samples were prepared using cylindrical molds, with a diameter of 50 mm and height of 100 mm, for the UCS test of the mixtures listed in Table 3. All the samples were manually compacted into three layers. Subsequently, the samples were removed from the molds and divided into two groups: air-dried and wet-cured (ambient temperature of 21 °C ± 2 °C). The wet-cured samples were wrapped in a plastic film to maintain their water content until the day of UCS testing. Both the air-dried and wet-cured samples were kept in a closed environment without light. After the curing time was complete, the samples were unwrapped and the UCS test was conducted on both air-dried and wet-cured samples at curing times of immediately, 3, 7, 28, and 90 days.

Table 3 The proportions of the mixture used and their notations

Mix #	Notations (Mix Symbol)	Clay (wt%)	GGBS (wt%)	OPC (wt%)	SS (wt%)	SH (wt%)	Ratio (R:SS/SH)
1	S00_C0_GP00_R0	100	0	0	0	0	-
2	S20_C0_GP00_R0	100	20	0	0	0	-
3	S20_C0_GP10_R1	100	20	0	5	5	1
4	S20_C0_GP10_R3	100	20	0	7.5	2.5	3
5	S20_C0_GP10_R5	100	20	0	8.333	1.667	5
6	S20_C0_GP10_R7	100	20	0	8.75	1.25	7
7	S18_C2_GP00_R0	100	18	2	0	0	-
8	S18_C2_GP10_R1	100	18	2	5	5	1
9	S18_C2_GP10_R3	100	18	2	7.5	2.5	3
10	S18_C2_GP10_R5	100	18	2	8.333	1.667	5
11	S18_C2_GP10_R7	100	18	2	8.75	1.25	7
12	S16_C4_GP00_R0	100	16	4	0	0	-
13	S16_C4_GP10_R1	100	16	4	5	5	1
14	S16_C4_GP10_R3	100	16	4	7.5	2.5	3
15	S16_C4_GP10_R5	100	16	4	8.333	1.667	5
16	S16_C4_GP10_R7	100	16	4	8.75	1.25	7
17	S12_C8_GP00_R0	100	12	8	0	0	-
18	S12_C8_GP10_R1	100	12	8	5	5	1
19	S12_C8_GP10_R3	100	12	8	7.5	2.5	3
20	S12_C8_GP10_R5	100	12	8	8.333	1.667	5
21	S12_C8_GP10_R7	100	12	8	8.75	1.25	7
22	S00_C5_GP00_R0	100	0	5	0	0	-
23	S00_C10_GP00_R0	100	0	10	0	0	-
24	S00_C15_GP00_R0	100	0	15	0	0	-
25	S00_C0_GP10_R1	100	0	0	5	5	1
26	S00_C0_GP10_R5	100	0	0	7.5	2.5	3
27	S00_C0_GP10_R3	100	0	0	8.333	1.667	5
28	S00_C0_GP10_R7	100	0	0	8.75	1.25	7

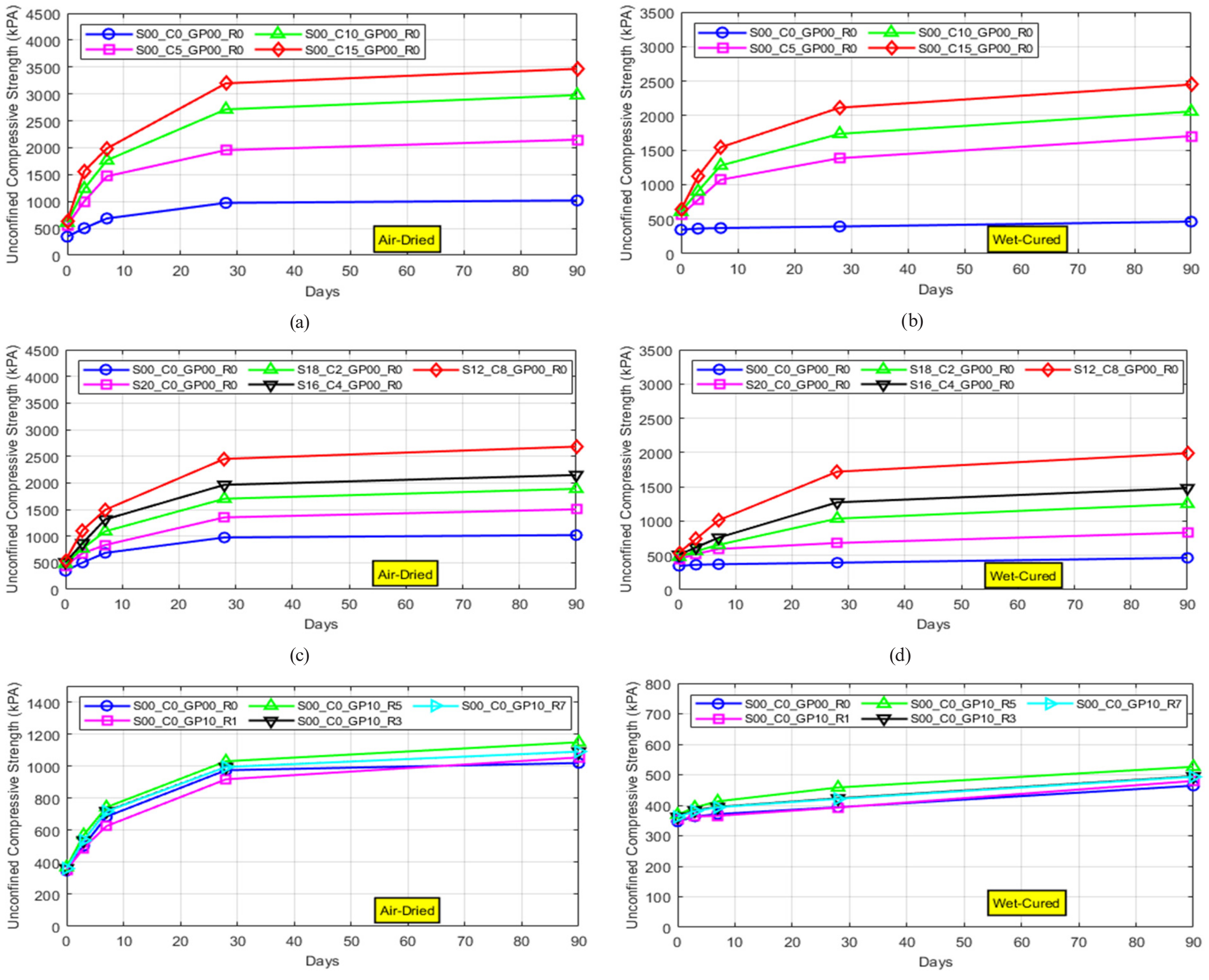
Note: S= Ground Granulated Blast Furnace Slag; C= Cement (Ordinary Portland Cement); SS= Sodium Silicate; SH= Sodium Hydroxide; GP= Geopolymer (SS and SH); Ratio= Sodium Silicate/Sodium Hydroxide Ratio (R: SS/SH).

3 Results and discussion

UCS tests were completed on air-dried and wet-cured specimens at 0-, 3-, 7-, 28-, and 90 days curing times for all mixtures. The UCS time-dependent compressive strength development, mass, and volumetric percentage changes of the mixtures listed in Table 3 were examined and compared.

3.1 Compressive strength development

The time-dependent changes in the UCS values of the untreated clay and the stabilized samples with 5, 10, and 15% OPC are illustrated in Fig. 2(a) and (b). Under air-dried conditions at the end of 90 curing days, the UCS values of samples untreated and stabilized with 5% OPC, 10% OPC, and 15% OPC were 1019, 2149, 2978, and 3466 kPa, respectively. In the same order, under wet-cured conditions, the UCS values were 464.2, 1703, 2059, and 2450 kPa. According to the UCS results for air-dried and wet-cured conditions, the UCS value increased with the amount of OPC. Most of the strengths of the stabilized samples with OPC were completed in 28 days. The UCS values of untreated clay at immediately, 3, 7, 28, and 90 curing times were 346.6, 502.7, 684.7, 974.2, and 1019 kPa under air-dried conditions, and 346.6, 363.1, 371, 393.6, and 464.2 under wet-cured conditions. Under wet-cured conditions, the UCS values of the untreated clay increased by a small amount over 90 days. Stabilized samples with 15% OPC exhibited 3.40 times more strength under air-dried conditions and 5.28 times under wet-cured conditions compared with the untreated clay. Thus, stabilization with cement was proportionally more effective in the samples in the wet-cured conditions compared with the samples in the air-dried conditions. Fig. 2(c) and (d)



(a)

(b)

(c)

(d)

(e)

(f)

Fig. 2 Time-dependent compressive strength development of untreated and treated clay samples under air-dried and wet-cured conditions; (a-b) OPC, (c-d) binary GGBS + OPC mix, and (e-f) only alkali activator illustrate the UCS values of the stabilized soil with mixtures of GGBS + OPC (different proportions) of 20 wt% of the clay. The UCS values of the stabilized samples with mixes S12_C8_GP00_R0, S16_C4_GP00_R0, S18_C2_GP00_R0, and S20_C0_GP00_R0 under air-dried conditions at the end of 90 curing days were 2680, 2147, 1887, and 1503 kPa, respectively. In wet-cured conditions, the UCS values of the same samples were 1989, 1480, 1252, and 831.8 kPa, respectively. The UCS value of the sample increased as the amount of OPC in the GGBS + OPC mixture increased. In this group, the highest UCS values were observed in the stabilized samples with S12_C8_GP00_R0 mixture under air-dried and wet-cured conditions. This mixture was followed by mixes S16_C4_GP00_R0, S18_C2_GP00_R0, and S20_C0_GP00_R0. Accordingly, the effect of GGBS alone on the stabilization of the clayey soil was lower than the other mixtures. In the stabilized samples with GGBS 20 wt% of the clay, the UCS value increase was observed 1.47 times in air-dried conditions and 1.79 times in wet-cured conditions compared with untreated soils. In soil stabilization studies using GGBS, it has been reported that the use of GGBS relatively increases the UCS value of the soil [40, 41]. In addition, the effectiveness of soil stabilization using only an alkali activator was investigated. The amount of alkali activator used (SS/SH ratio = 1, 3, 5, and 7) was 10 wt% of the clay. The UCS results for the stabilized samples with only alkali activators are shown in Fig. 2(e) and (f). The UCS values of untreated clay samples at the 90-day curing times were found 1019 kPa under air-dried conditions and 464.2 kPa under wet conditions. On the other hand, the UCS values of the stabilized samples with S00_C0_GP10_R1, S00_C0_GP10_R3, S00_C0_GP10_R5, and S00_C0_GP10_R7 at the 90 days curing times were found 1054, 1090, 1149, and 1090 kPa under air-dried conditions and 479.7, 494.8, 526.1, and 493.4 kPa under wet-cured conditions, respectively. The UCS values of the stabilized samples with only alkaline activators showed a slight increase. Alkaline activators can dissolve some of the Al and Si in the soil. Similarly, Al and Si in the soil used in the study showed a low alkaline reaction. SS and SH alone did not effectively stabilize the clayey soil. Significant increases in UCS values were observed when GGBS was added to the samples. Similarly, Pourakbar et al. [42] reported a slight increase in strength in samples prepared with only NaOH and KOH.

Photographs of the stabilized samples with an SS/SH ratio of 1 under air-dried conditions are shown in Fig. 3. The samples were prepared under the same conditions as those of the others. Photographs of the samples were taken 90 days after preparation. After the samples were prepared, the surface was observed to be moistened; this moistening decreased with time and crystallization occurred subsequently. Fourier transform infrared (FTIR) spectroscopy analysis was performed to identify the crystal formation observed in the stabilized samples. The FTIR spectra of the crystals formed on the samples are shown in Fig. 4. A comparison of the FTIR spectrum data with the literature revealed that the crystals formed on the samples were compatible with sodium carbonate monohydrate ($Na_2CO_3.H_2O$) [43]. The amount of SH (NaOH) in the stabilized samples with an SS/SH ratio of 1 was higher than that of the other SS/SH ratios. Owing to the excess amount of NaOH in these samples, the entire mixture did not participate in the geopolymer formation reaction; some remained in the environment. Unreacted NaOH absorbed humidity from the air in the early stages, and then it reacted with CO_2 in the air and formed $Na_2CO_3.H_2O$ crystals. Among the samples in Fig. 3, the highest crystallization was observed in the stabilized samples containing the soil + alkali activator, that is, samples without an aluminosilicate source.

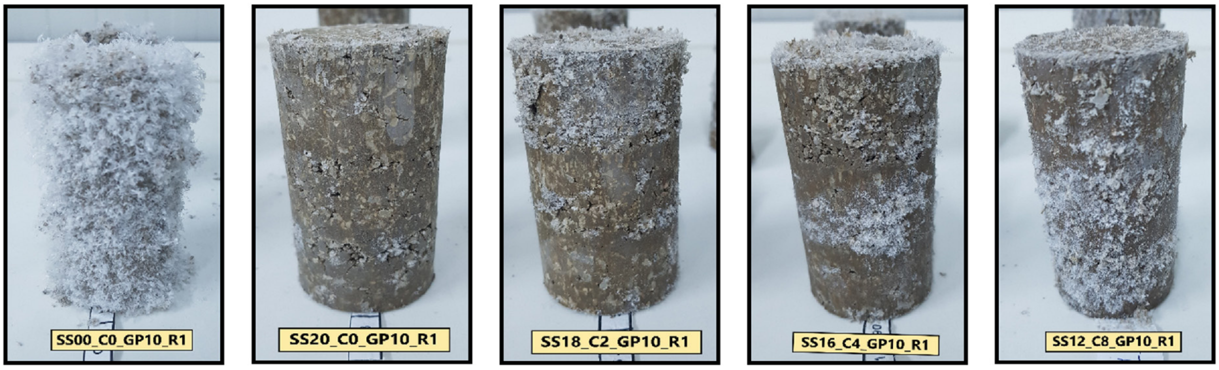


Fig. 3 Crystallization effect of stabilized samples with SS/SH ratio 1

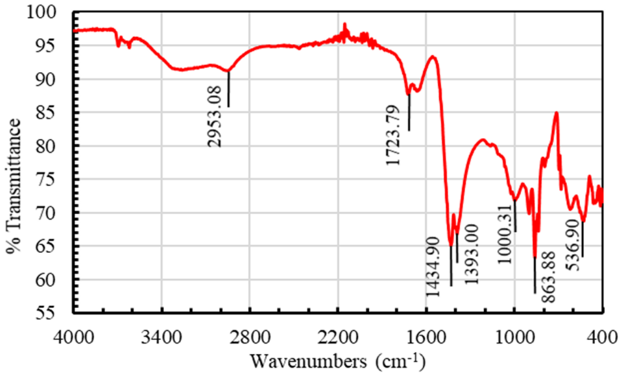
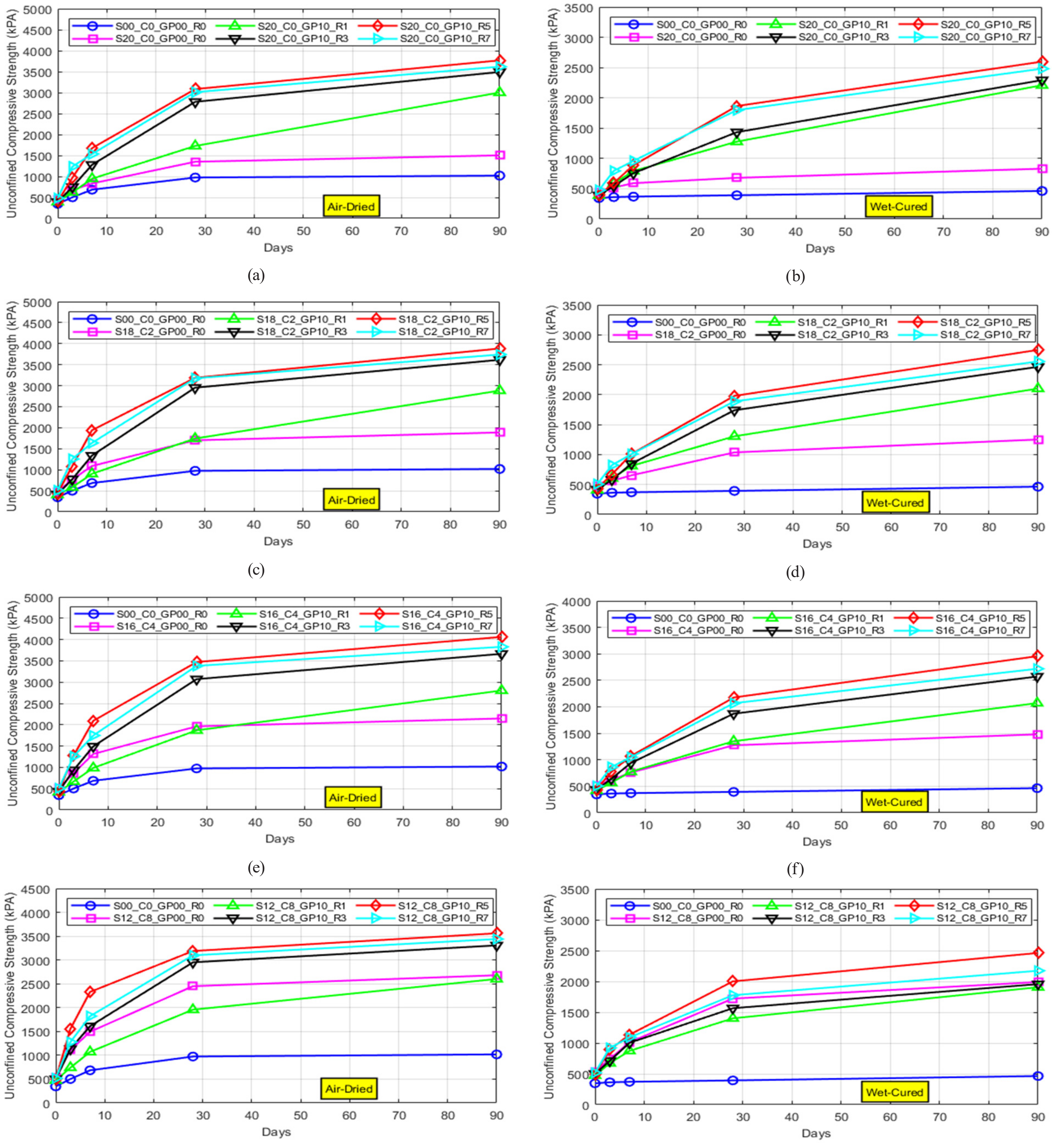


Fig. 4 FTIR spectra of crystals observed in samples

Conversely, the least crystallization was observed in the sample containing 100% GGBS. Thus, with the increasing amount of slag, SH was used more in the geopolymer formation; with the decreasing amount of slag, SH was used less, and the unused SH turned into sodium carbonate monohydrate crystals. Zheng et al. [44] and Singh et al. [45] reported that sodium carbonate crystals unstabilize the structure and reduce the mechanical strength. Sodium carbonate crystallization in the samples shown in Fig. 3 negatively affected the samples' UCS values. Given that crystallization took place on the contact surface with air, crystallization occurred only on the surface of the samples and not in the inner parts. No crystallization was observed in the samples wrapped with stretch film that prevented air contact. This is another indication that crystallization occurred through the reaction of NaOH with CO_2 in the environment. Sodium carbonate increases the pH level of the soil. With the increase in the pH level, the ground exhibits alkaline properties. Furthermore, the high amount of sodium carbonate crystals in solid form has potentially harmful and relatively toxic properties in terms of health and the environment.

Fig. 5(a) and (b) illustrate the time-dependent UCS graphs of untreated clay, stabilized samples with GGBS 20 wt% of clay, and stabilized samples with alkali activator (SS/SH ratio = 1, 3, 5, and 7) and GGBS 20 wt% of clay. The UCS values of the stabilized samples with S20_C0_GP00_R0, S20_C0_GP10_R1, S20_C0_GP10_R3, S20_C0_GP10_R5, and S20_C0_GP10_R7 under air-dried conditions at the end of 90 curing days were 1503, 3000, 3490, 3768, and 3618 kPa, respectively. In wet-cured conditions, the UCS values of the same samples were 831.8, 2209, 2293, 2598, and 2482 kPa, respectively. In this group, the stabilized samples with an SS/SH ratio of 5 and GGBS 20 wt% of clay (S20_C0_GP10_R5) exhibited the highest UCS values under air-dried and wet-cured conditions. The UCS values of stabilized samples with S20_C0_GP10_R5 (mix symbol) increased 3.7 times in air-dried conditions and 5.6 times in wet-cured conditions compared with untreated clay. In this group, where GGBS 20 wt% of clay was used as precursor, the UCS increase rate of the stabilized sample with SS/SH ratio of 7 and 3 was considerably close to the stabilized sample with SS/SH ratio of 5. The UCS values of the stabilized samples without the alkali activator were lower than those with the alkali activator. In this group, the UCS values of stabilized samples with SS/SH ratio of 1 were lower than those with alkali activators in the 28 days curing time on air-dried conditions. Meanwhile, the degree of strength gains between 28 and 90 days was higher than the stabilized samples with the other alkali activator. This situation can be explained by the moistening of the sample due to the high amount of NaOH in the alkali activator. These samples absorbed humidity from the air, particularly in the initial days after preparation. In the following days, the humidity gradually decreased, and sodium carbonate crystals were formed on the surface of the samples. This situation was not observed under wet-curing conditions. Fig. 5(c) and (d) illustrate the time-dependent UCS values when 18% GGBS + 2% OPC was used as the precursor, and Fig. 5. e and f illustrate the time-dependent UCS values when 16% GGBS + 4% OPC is used as the precursor. The SS/SH ratios used were 1, 3, 5, and 7 in both groups. The variation of time-dependent UCS values of the stabilized samples of these groups was similar to each other. After 90 days curing in both groups, the highest UCS value was obtained in the samples stabilized with an SS/SH ratio of 5. In the group using 18% GGBS + 2% OPC as the precursor, the UCS values of stabilized samples with S18_C2_GP10_R5 under air-dried and wet conditions at the end of 90 days curing times were 3884 and 2747 kPa, respectively. At the same curing time, in the group using 16% GGBS + 4% OPC as the precursor, the UCS values of the stabilized samples with S16_C4_GP10_5 under air-dried and wet conditions were 4061 and 2956 kPa, respectively. The UCS values of the stabilized samples with S16_C4_GP10_R5 increased 3.99 times in the air-dried conditions and 6.37 times in the wet-cured conditions compared with the untreated samples. The UCS values of the stabilized samples with S18_C2_GP10_R5 increased 3.8 times in the air-dried conditions and 5.9 times in the wet-cured conditions compared with the untreated samples. Fig. 5(g) and (h) illustrate time-dependent UCS changes of the stabilized samples using 12% GGBS + 8% OPC as the precursor under air-dried and

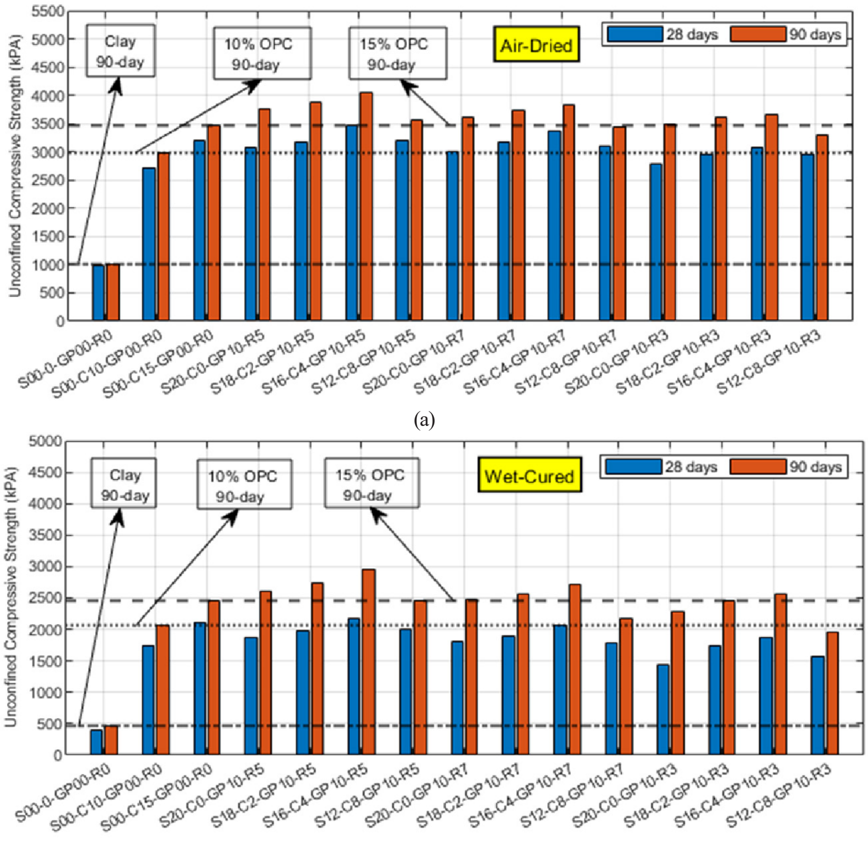


(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 5 Time-dependent compressive strength development of untreated and treated clay samples under air-dried and wet-cured conditions; (a–b) GGBS 20 wt%, OPC 0 wt%, and alkali activator 10 wt% of the clay, (c-d) GGBS 18 wt%, OPC 2 wt%, and alkali activator 10 wt% of the clay, (e–f) GGBS 16 wt%, OPC 4 wt%, and alkali activator 10 wt% of the clay, (g-h) GGBS 12 wt%, OPC 8 wt% and alkali activator 10 wt% of the clay

wet-cured conditions. Accordingly, the UCS values of the stabilized samples with S12_C8_GP_R0, S12_C8_GP_R1, S12_C8_GP_R3, S12_C8_GP_R5, and S12_C8_GP_R7 at the end of 90 days curing times were 2680, 2601, 3306, 3560, and 3440 kPa under air-dried conditions and 1989, 1905, 1956, 2461, and 2172 kPa under wet-cured conditions, respectively. Stabilized samples in this group showed the highest UCS values in the samples with an alkali activator ratio (SS/SH) of 5, as in the other groups. Owing to the high amount of cement in this group, the stabilized samples without an alkali activator exhibited relatively high UCS values. The UCS values in Fig. 5 show that the grade of strength gains of the samples in wet-cured conditions was proportionally higher than those in air-dried conditions. The UCS values of the stabilized samples with an SS/SH ratio of 5 in all groups exhibited the highest UCS values at the 90 days curing times, followed by the SS/SH ratios of 7, 3, and 1. In both air-dried and wet-cured conditions, the UCS values increased with the increase in curing time in all mixtures, as was also observed in previous studies [8, 9, 14].

Fig. 6 shows the UCS test results of stabilized samples with 10% OPC, 15% OPC, and alkali activators under air-dried and wet-cured conditions at 28- and 90-days curing times. The UCS values of the samples stabilized with 10% OPC were lower than those of the samples stabilized with alkali activators under air-dried conditions at the end of 90 curing days. Similarly, under wet-cured conditions, the UCS values of the stabilized samples with 10% OPC were lower than those with other alkali activators, except for the S12_C8_GP10_R3 mixture. Under air-dried conditions at the end of 90 curing times, the UCS test results of stabilized samples with 15% OPC were slightly higher than those of the stabilized samples with S12_C8_GP10_R7 and S12_C8_GP10_R3; however, the UCS values were lower than those of the other mixtures (Fig. 6). When the UCS values of the stabilized samples with 10% OPC and 15% OPC were compared with those of the stabilized samples with an alkali activator of SS/SH ratio of 1, the UCS values of the stabilized samples with 15% OPC were higher under air-dried and wet-cured conditions, and the stabilized samples with 10% OPC demonstrated better results than the others, expect for stabilized samples with S20_C0_GP10_R1 under air-dried conditions. The UCS values of the stabilized samples with 5% OPC were lower than those with alkali activators. It has been reported that the rate of strength gain of soil stabilized with activators develops more slowly than soils stabilized with OPC [46]. Similarly, in this study, although the rate of strength gain of the samples stabilized with alkali activators was slower than that of OPC, most of the samples exhibited higher strength over the long term.



(a)

(b)

Fig. 6 UCS test results of untreated clay, stabilized samples with 10% OPC, 15% OPC and alkali activators (at 3, 5, and 7 SS/SH ratios) at the 28 and 90 days of curing. Alkali activators were used for mixtures of 20% GGBS, 18% GGBS + 2% OPC, 16% GGBS + 4% OPC and 12% GGBS + 8% OPC;(a) Air-dried conditions, (b) Wet-cured conditions

Fig. 7 shows the percentage changes between the UCS values of the clay and stabilized samples at 28 to 90 days curing times. In all mixtures, the UCS value increased when the curing time increased from 28 to 90 days. The UCS percentage change of untreated clay between 28–90 days under air-dried conditions was lower than that of all other mixtures. The increase in the UCS values of the stabilized samples with OPC and GGBS + OPC were approximately close to each other. The percentage changes in the UCS values of the stabilized sample groups with the GGBS + OPC + alkali activator between the 28- and 90 days curing times were higher than those of the other groups. The percentage change in the UCS value between 28- and 90 days curing times decreased as the SS/SH ratio increased. Similarly, in stabilizations with OPC, as the amount of OPC increased, the percentage change in the UCS value decreased. In the stabilized sample groups with the alkali activator, the highest percentage changes in the UCS values were observed in the stabilized samples with an SS/SH ratio of 1. This is because as the amount of NaOH in the alkali activator was high, the prepared sample absorbed moisture, and the water content increased partially. The percentage of UCS change was higher between 28 and 90 days in the wet-cured samples than in the air-dried samples.

3.2 Mass and volumetric change

Volume and mass changes of untreated and stabilized samples were investigated during the 90 days curing period. Fig. 8. a demonstrates the percentage changes in the volume of untreated clay and stabilized samples. The untreated samples under air-dried conditions exhibited the highest percentage changes in volumetric and mass. The percentages of volumetric change of the untreated clay and stabilized samples with only alkali activators were close to each other in air-dried and wet-curing conditions. In the stabilized sample groups with GGBS + OPC, the percentage of volume change was high in air-dried conditions. In this group, the volume changes in the stabilized samples under wet-cured conditions were close to that of untreated clay. The percentage of volume change in stabilized samples decreased as the amount of OPC increased. The volume changes of the stabilized sample groups with GGBS + OPC + alkali activators were lower than those with OPC. As the SS/SH ratio increased, the volumetric variation of the stabilized samples increased. The volumetric change of the stabilized samples with an SS/SH ratio of 1 had the lowest percentage. Different volume changes were exhibited depending on the type and amount of activators and precursors. Low-volume changes have been reported in soil stabilization studies using alkaline activators [24, 47, 48]. Fig. 8(b) demonstrates the percentage changes in the mass of untreated clay and stabilized soils. The mass change characteristic of the untreated clay and stabilized sample groups was similar to the volumetric change. The stabilized samples with SS/SH ratios of 1 have been observed to have higher water contents than the others. The volumetric and mass changes of stabilized samples with GGBS + OPC + alkali activators were lower than those with OPC.

4 Conclusions

This study investigated the effectiveness of alkali-activated hybrid slag/cement in stabilizing clayey soil and compared it with that of OPC. The SS and SH mixtures were used as alkali activators (10 wt% of clay), whereas GGBS and OPC were used as the aluminosilicate sources (20 wt% of clay). Twenty-seven mixtures were prepared in different proportions using these materials, and the stabilization of the clayey soil was performed. The significant conclusions obtained from the tests, measurements, and observations in this study are as follows.

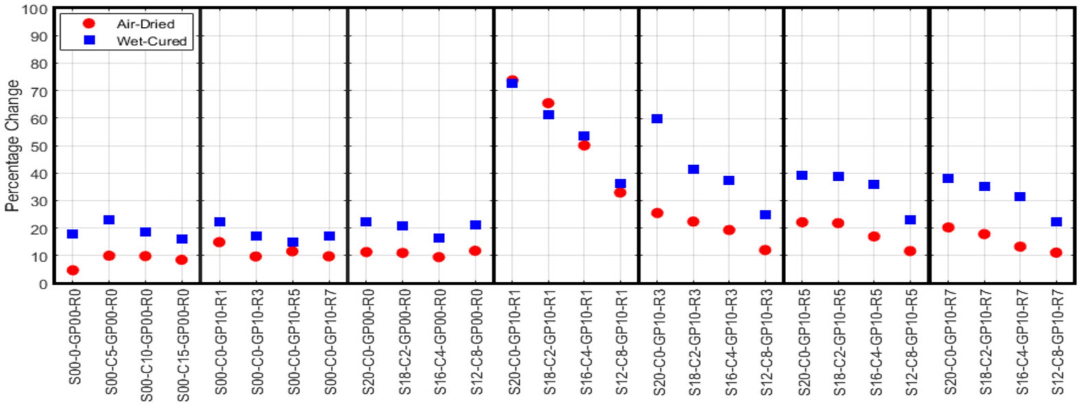
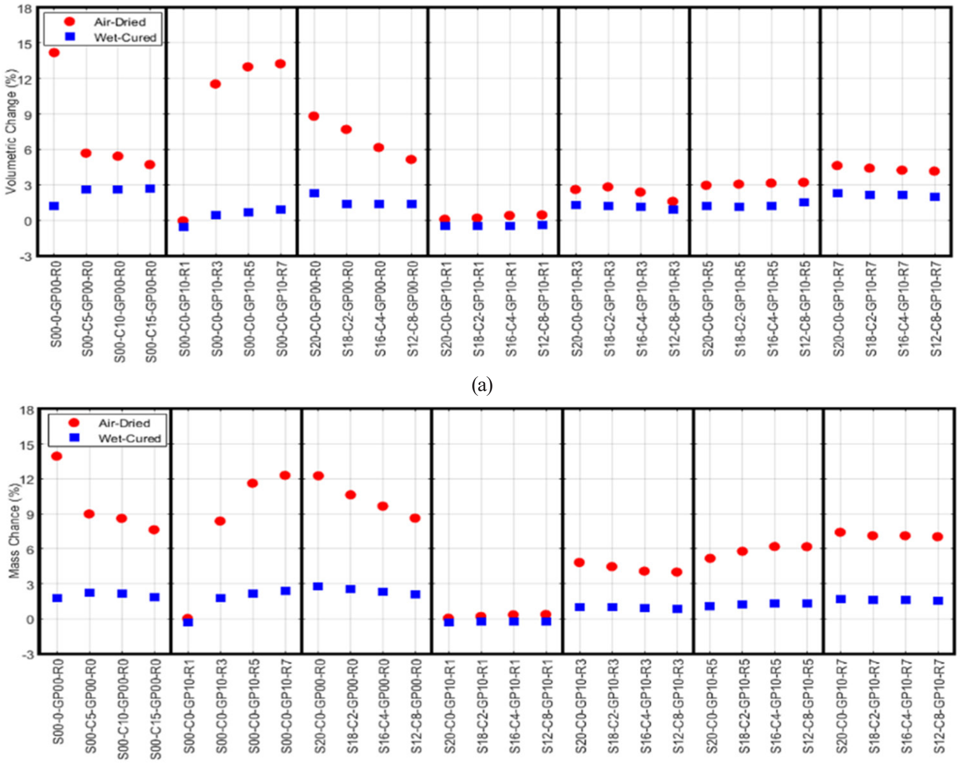


Fig. 7 Percentage change of UCS value of untreated clay and stabilized samples at 28 to 90 days curing times



(a)

(b)

Fig. 8 In air-dried and wet-cured conditions, 90 days volumetric and mass percentage change of untreated clay and stabilized soils; (a) Percentage of volumetric change, (b) Percentage of mass change

- The UCS values increased with the amount of OPC in the stabilized samples with only OPC.
- No significant increase was observed in the UCS values of the stabilized samples with only alkali activators compared with the untreated sample. The use of SS and SH mixtures alone was found to be ineffective in the stabilization of clay soil.
- UCS values of stabilized samples with 20 wt% GGBS of the clay were 1.48 times higher under air-dried conditions and 1.79 times higher under wet-cured conditions compared with untreated clay under the same conditions.
- The UCS value of the sample increased with the amount of OPC in the stabilized samples with GGBS + OPC mixture. In this group, the highest UCS values were observed in the stabilized samples with S12_C8_GP00_R0 mixture under air- and wet-cured conditions.
- The ratio of sodium silicate to sodium hydroxide affected the stabilization performance. Among the stabilized samples with GGBS + OPC + alkali activator, the highest UCS values were observed in the samples with an SS/SH ratio of 5, followed by 7, 3 and 1. The highest strength in the stabilized samples in the same group was S16_C4_GP10_R5, according to the GGBS + OPC mixture ratio, followed by the S18_C2_GP10_R5, S20_C0_GP10_R5, and S12_C8_GP10_R5 samples.
- Most of the stabilized clayey soil with alkali-activated hybrid slag/cement exhibited better stabilization performance than the stabilized clayey soil with OPC under air-dried and wet-cured conditions.
- The stabilized samples with OPC gained faster and more strength at early curing ages (28 days), whereas stabilized samples with alkali-activated samples gained more strength at longer curing ages.
- The UCS values of the stabilized samples maintained under air-dried conditions were higher than those under wet curing. However, the strength gain rate of the geopolymer-treated clayey soil under wet curing conditions was higher than that under air-dried conditions.
- Owing to the high amount of SH in stabilized samples with an SS/SH ratio of 1, these samples collected environmental humidity and increased in volume and mass at early curing ages. Sodium carbonate crystals were formed in these samples during the subsequent curing ages. High-extent sodium carbonate crystals increase

the pH level of the floor and give it alkaline properties. The increase in sodium carbonate crystals negatively affected the UCS values of the soil. Excess sodium carbonate crystals in solid form have the potential to cause adverse health and environmental effects.

- The volume and mass changes of the geopolymer-treated clayey soil were lower than those of the OPC-treated clayey soil. The ratio of sodium silicate to sodium hydroxide affected the volumetric and mass changes of the samples. The volume and mass changes increased with the SS/SH ratio.

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References

[1] Harichane, K., Ghrici, M., Kenai, S., Grine, K. "Use of Natural Pozzolana and Lime for Stabilization of Cohesive Soils", Geotechnical and Geological Engineering, 29, pp. 759–769, 2011. https://doi.org/10.1007/s10706-011-9415-z

[2] Habert, G., Miller, S. A., John, V. M., Provis, J. L., Favier, A., Horvath, A., Scrivener, K. L. "Environmental impacts and decarbonization strategies in the cement and concrete industries", Nature Reviews Earth & Environment, 1(11), pp. 559–573, 2020. https://doi.org/10.1038/s43017-020-0093-3

[3] Petroche, D. M., Ramirez, A. D. "The environmental profile of clinker, cement, and concrete: a life cycle perspective study based on Ecuadorian data", Buildings, 12(3), 311, 2022. https://doi.org/10.3390/buildings12030311

[4] Arora, S., Singh, B., Bhardwaj, B. "Strength performance of recycled aggregate concretes containing mineral admixtures and their performance prediction through various modeling techniques", Journal of Building Engineering, 24, 100741, 2019. https://doi.org/10.1016/j.jobe.2019.100741

[5] Manjunath, R., Narasimhan, M. C. "Alkali-activated concrete systems: a state of art", In: Samui, P., Kim, D., Iyer, N. R., Chaudhary, S. (eds.) New Materials in Civil Engineering, Elsevier, 2020, pp. 459–491. ISBN: 978-0-12-818961-0 https://doi.org/10.1016/B978-0-12-818961-0.00013-2

[6] Yoro, K. O., Daramola, M. O. "CO2 emission sources, greenhouse gases, and the global warming effect", In: Rahimpour, M. R., Farsi, M., Makarem, M. A. (eds.) Advances in Carbon Capture, Woodhead Publishing, 2020, pp. 3–28. ISBN: 978-0-12-819657-1 https://doi.org/10.1016/B978-0-12-819657-1.00001-3

[7] United Nations "Adoption of the Paris Agreement", In: UNFCCC COP 21, The 21st session of the Conference of the Parties to the UNFCCC is expected to take place in December 2015, in Paris, France, FCCC/CP/2015/L.9/Rev.1, 2015.

[8] Ghadir, P., Ranjbar, N. "Clayey soil stabilization using geopolymer and Portland cement", Construction and Building Materials, 188, pp. 361–371, 2018. https://doi.org/10.1016/j.conbuildmat.2018.07.207

[9] Arun, E., Arumairaj, P. D., Janaki Raman, S. "Application of Geopolymer in Stabilization of Soft Clay", International Journal of Recent Technology and Engineering (IJRTE), 8(1S4), pp. 996–999, 2019.

[10] Amulya, S., Ravi Shankar, A. U., Praveen, M. "Stabilisation of lithomargic clay using alkali activated fly ash and ground granulated blast furnace slag", International Journal of Pavement Engineering, 21(9), pp. 1114–1121, 2020. https://doi.org/10.1080/10298436.2018.1521520

[11] Dimas, D., Giannopoulou, I., Panias, D. "Polymerization in sodium silicate solutions: a fundamental process in geopolymerization technology", Journal of Materials Science, 44(14), pp. 3719–3730, 2009. https://doi.org/10.1007/s10853-009-3497-5

[12] Sikder, A., Saha, P. "Effect of different types of Waste as Binder on Durability Properties of Geopolymer, Concrete: A Review", IOP Conf. Series: Earth and Environmental Science, 796, 012018, 2021. https://doi.org/10.1088/1755-1315/796/1/012018

[13] Doğan-Sağlamtimur, N., Bilgil, A., Ertürk, S., Bozkurt, V., Süzgeç, E., Akan, A. G., Nas, P., Çetin, H., Szechynska-Hebda, M., Hebda, M. "Eco-Geopolymers: Physico-Mechanical Features, Radiation Absorption Properties, and Mathematical Model", Polymers, 14(2), 262, 2022. https://doi.org/10.3390/polym14020262

[14] Preetham, H. K., Nayak, S. "Geotechnical Investigations on Marine Clay Stabilized Using Granulated Blast Furnace Slag and Cement", International Journal of Geosynthetics and Ground Engineering, 5, 28, 2019. https://doi.org/10.1007/s40891-019-0179-5

[15] Saravanan, R., Udhayakumar, T., Dinesh, S., Venkatasubramanian, C., Muthu, D. "Effect of addition of GGBS and lime in soil stabilisation for stabilising local village roads in Thanjavur region", IOP Conference Series: Earth and Environmental Science, 80, 012060, 2017. https://doi.org/10.1088/1755-1315/80/1/012060

[16] Sharma, A. K., Sivapullaiah, P. V. "Soil stabilisation with waste materials based binder", In: Proceedings of Indian Geotechnical Conference, Kochi, India, 2011, pp. 413–416.

[17] Li, W., Yi, Y., Puppala, A. J. "Comparing carbide sludge-ground granulated blastfurnace slag and ordinary Portland cement: Different findings from binder paste and stabilized clay slurry", Construction and Building Materials, 321, 126382, 2022. https://doi.org/10.1016/j.conbuildmat.2022.126382

[18] Estabragh, A. R., Jahani, A., Javadi, A. A., Babalar, M. "Assessment of different agents for stabilisation of a clay soil", International Journal of Pavement Engineering, 23(2), pp. 160–170, 2022. https://doi.org/10.1080/10298436.2020.1736293

[19] Bindu, G. H., Mallikarjuna, V. "Improving the geotechnical properties of silty sands by using GGBS and coir fibre", In: Kumar, P. G., Subramaniam, K. V. L., Santhakumar, S. M., Satyam, D. N. (eds.) Recent Advances in Civil Engineering, Springer, 2022, pp. 277–288. ISBN: 978-981-19-0191-1 https://doi.org/10.1007/978-981-19-0189-8_24

[20] Yaghoubi, M., Arulrajah, A., Disfani, M. M., Horpibulsuk, S., Leong, M. "Compressibility and strength development of geopolymer stabilized columns cured under stress", Soils and Foundations, 60(5), pp. 1241–1250, 2020.
https://doi.org/10.1016/j.sandf.2020.07.005

[21] Rios, S., Cristelo, N., da Fonseca A. V., Ferreira, C. "Stiffness behavior of soil stabilized with alkali-activated fly ash from small to large strains", International Journal of Geomechanics, 17(3), 04016087, 2017.
https://doi.org/10.1061/(ASCE)GM.1943-5622.0000783

[22] Al-Rkaby, A. H. J. "Evaluating Shear strength of Sand-GGBFS based geopolymer composite material", Acta Polytechnica, 59(4), pp. 305–311, 2019.
https://doi.org/10.14311/AP.2019.59.0305

[23] Sukmak, P., Horpibulsuk, S., Shen, S.-L. "Strength development in clay–fly ash geopolymer", Construction and Building Materials, 40, pp. 566–574, 2013.
https://doi.org/10.1016/j.conbuildmat.2012.11.015

[24] Sargent, P., Hughes, P. N., Rouainia, M., White, M. L. "The use of alkali activated waste binders in enhancing the mechanical properties and durability of soft alluvial soils", Engineering Geology, 152(1), pp. 96–108, 2013.
https://doi.org/10.1016/j.enggeo.2012.10.013

[25] Syed, M., GuhaRay, A., Kar, A. "Stabilization of expansive Clayey soil with alkali activated binders", Geotechnical and Geological Engineering, 38(6), pp. 6657–6677, 2020.
https://doi.org/10.1007/s10706-020-01461-9

[26] Mishra, M., Sahoo, P. K., Singh, S. P. "Plasticity and swelling characteristics of geopolymer treated expansive soil", In: Proceedings of the Indian Geotechnical Conference 2019, Springer, 2021, pp. 195–209. ISBN: 978-981-33-6443-1
https://doi.org/10.1007/978-981-33-6444-8_17

[27] Onyelowe, K. C., Bui Van, D., Nguyen Van, M. "Swelling potential, shrinkage and durability of cemented and uncemented lateritic soils treated with CWC base geopolymer", International Journal of Geotechnical Engineering, 15(4), pp. 389–404. 2021.
https://doi.org/10.1080/19386362.2018.1462606

[28] Abdullah, H. H., Shahin, M. A., Sarker, P. "Use of Fly-Ash Geopolymer Incorporating Ground Granulated Slag for Stabilisation of Kaolin Clay Cured at Ambient Temperature", Geotechnical and Geological Engineering, 37, pp. 721–740, 2019.
https://doi.org/10.1007/s10706-018-0644-2

[29] Mariani, M. "Ukrainian clays for ceramics", In: Handbook of Ceramic Raw Materials, Italian Ceramic Society, Bologna, Italy, 2010, pp. 81–83. (in Italian)

[30] Zanelli, C., Iglesias, C., Domínguez, E., Gardini, D., Raimondo, M., Guarini, G., Dondi, M. "Mineralogical composition and particle size distribution as a key to understand the technological properties of Ukrainian ball clays", Applied Clay Science, 108, pp. 102–110, 2015.
https://doi.org/10.1016/j.clay.2015.02.005

[31] ASTM "ASTM D1140-17 Standard Test Methods for Determining the Amount of Material Finer than 75-μm (No. 200) Sieve in Soils by Washing", ASTM International, West Conshohocken, PA, USA, 2017.
https://doi.org/10.1520/D1140-17

[32] ASTM "ASTM D7928-17 Standard Test Method for Particle Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis", ASTM International, West Conshohocken, PA, USA, 2017.
https://doi.org/10.1520/D7928-17

[33] ASTM "ASTM D4318-00 Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils", ASTM International, West Conshohocken, PA, USA, 2000.
https://doi.org/10.1520/D4318-00

[34] ASTM "ASTM D2487-17 Standard practice for classification of soils for engineering purposes (unified soil classification system)". ASTM International, West Conshohocken, PA, USA, 2017.
https://doi.org/10.1520/D2487-17

[35] American Association of State Highway and Transportation Officials (AASHTO) "Standard Specification for Transport Materials and Method Sampling and Testing", 14th ed.; AASHTO: Washington, DC, USA, 1986.

[36] ASTM "ASTM D854–14 Standard test methods for specific gravity of soil solids by water pycnometer", ASTM International, West Conshohocken, PA, USA, 2014.
https://doi.org/10.1520/D0854-14

[37] ASTM "ASTM D698-12 Standard test methods for laboratory compaction characteristics of soil using standard effort", ASTM International, West Conshohocken, PA, USA, 2012.
https://doi.org/10.1520/D0698-12

[38] ASTM "ASTM D2166-00 Standard test method for unconfined compressive strength of cohesive soil", ASTM International, West Conshohocken, PA, USA, 2000.
https://doi.org/10.1520/D2166-00

[39] Manimaran, E., Mohankumar, G. "Influence of sodium hydroxide concentration on the strength of flyash based GPC", International Journal of Engineering Sciences & Research Technology, 6(1), (2017) pp. 85–89, 2017.

[40] Yadu, L., Tripathi, R. K. "Effects of granulated blast furnace slag in the engineering behavior of stabilized soft soil", Procedia Engineering, 51, pp. 125–131, 2013.
https://doi.org/10.1016/j.proeng.2013.01.019

[41] Pathak, A. K., Pandey, V., Murari, K., Singh, J. P. "Soil stabilisation using ground granulated blast furnace slag", International Journal of Engineering Research and Applications, 4(5), pp. 164–171, 2014.

[42] Pourakbar, S., Huat, B. B. K., Asadi, A., Fasihnikoutalab, M. H. "Model study of alkali-activated waste binder for soil stabilization", International Journal of Geosynthetics and Ground Engineering, 2, 35, 2016.
https://doi.org/10.1007/s40891-016-0075-1

[43] Nickolov, Z. S., Ozcan, O., Miller, J. D. "FTIR analysis of water structure and its significance in the flotation of sodium carbonate and sodium bicarbonate salts", Colloids and surfaces A: physicochemical and engineering aspects, 224(1–3), pp. 231–239, 2003.
https://doi.org/10.1016/S0927-7757(03)00317-0

[44] Zheng, C., Wang, J., Liu, H., GangaRao, H., Liang, R. "Characteristics and microstructures of the GFRP waste powder/GGBS-based geopolymer paste and concrete", Reviews on Advanced Materials Science, 61(1), pp. 117–137, 2022.
https://doi.org/10.1515/rams-2022-0005

[45] Singh, B., Rahman, M. R., Paswan, R., Bhattacharyya, S. K. "Effect of activator concentration on the strength, ITZ and drying shrinkage of fly ash/slag geopolymer concrete", Construction and Building Materials, 118, pp. 171–179, 2016.
https://doi.org/10.1016/j.conbuildmat.2016.05.008

[46] Cristelo, N., Glendinning, S., Teixeira Pinto, A. "Deep soft soil improvement by alkaline activation", Ground Improvement, 164(2), pp. 73–82, 2011.
https://doi.org/10.1680/grim.900032

[47] Zhang, M., Guo, H., El-Korchi, T., Zhang, G., Tao, M. "Experimental feasibility study of geopolymer as the next-generation soil stabilizer", Construction and Building Materials, 47, pp. 1468–1478, 2013.
https://doi.org/10.1016/j.conbuildmat.2013.06.017

[48] Samuel, R., Puppala, A. J., Radovic, M. "Sustainability benefits assessment of metakaolin-based geopolymer treatment of high plasticity clay", Sustainability, 12(24), 10495, 2020.
https://doi.org/10.3390/su122410495