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Stabilization of Soft Soil by a Sustainable Binder Comprises Ground Granulated Blast Slag (GGBS) and Cement Kiln Dust (CKD)

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Abstract: Due to its significant deficiencies such as low permeability, low bearing and shear strength, and excessive compressibility, soft soil is one of the most problematic types of soil in civil engineering and soil stabilization can be considered a suitable technique for pavements. This study investigates the use of ground granulated blast slag (GGBS) and cement kiln dust (CKD) as stabilizers for soft soil. Thus, this study involves two optimization stages; in the first stage, GGBS was incorporated into 0%, 3%, 6%, 9%, and 12% by the weight of cement to obtain the optimal percentage, which was 6%. Then, the optimal GGBS was blended with CKD in a binary system at 0%, 25%, 50%, 75%, and 100% by the dry weight of the soil. The testing program used in this paper was Atterberg limits with compaction parameters to investigate the physical properties and unconfined compressive strength (USC) at 7 and 28 days to examine the mechanical characteristics. In addition, the microstructures of the soil specimens were tested at 7 and 28 days using scanning electron microscopy (SEM). The findings reveal that the binary system enhanced the physical and mechanical properties of the soft soil. The optimum binder achieved in this study was 6% (25% GGBS and 75% CKD), which generates an increase in strength of about 3.3 times in 7 days, and of 5.5 times in 28 days in comparison to the untreated soil. The enhancement was attributed to the formation of the hydration products as approved by SEM. Consequently, in the case of soft subgrade soils, this technique can increase the pavement's bearing capacity and performance.

Keywords: CKD; GGBS; soft soil; stabilization and sustainability

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1. Introduction

Clay soil with a shear strength of less than 200 kPa is known as soft soil, such as silty clay, clayey sand, and organic clay soil. The main features of such soils are high compressibility, low shear strength, as well as low permeability, which make them undesirable for civil engineering purposes. Thus, soft soil needs immediate treatment when it is presented on construction sites. One of the active techniques to enhance the quality of feeble clay soil is soil stabilization [1]. The two main techniques for stabilizing soil are mechanical and chemical. In mechanical stabilization, the improvement occurred only in the physical properties since it involves mixing soils with different gradations and/or compaction. In the chemical method, which involves mixing the soil with chemical binders, both the physical and geotechnical properties such as strength, permeability, compressibility, etc.,

can be enhanced. This is because a chemical reaction occurs which results in the production of hydration products. Such hydration products bind the particles of the soil together, resulting in better-structured soil [1]. Jafer et al. [2] stated that calcium carbide residue (CCR) and rice husk ash (RHA) can be used to generate an eco-friendly binder for use in the stabilization of fine-grained soil (the binder content was fixed at 10% by the dry mass of virgin soil). When binary mixes were used to treat samples, the findings of the unconfined compressive strength (UCS) test showed a motivating growth in comparison to those that only received CCR treatment. With the usage of CCR alone, it was discovered that the plasticity index (PI) significantly decreased, and further decreases in PI were attained after the incorporation of RHA. When utilizing a binder composed of 60% CCR and 40% RHA, the unconfined compressive strength (UCS) was increased by 18 and 1.5 times, respectively, compared to the untreated soil and the soil stabilized with 100% CCR. Montenegro et al. [3] investigated the application of ladle furnace steelmaking slag (LFS) as a building material for embankments in civil works. The pozzolanic reactions of clay minerals with brucite and portlandite as well as their accommodation within the soil–slag pore structure are responsible for the minor swelling seen during the expansion test on the soil–LFS mixes.

Cement and lime are the most common binders used in chemical soil stabilization. Soil stabilization using lime and cement has been investigated by researchers such as Jauberthie et al. [4], Tremblay et al. [5], Yong and Ouhadi [6], and Vakili et al. [7]. These studies proved that these two binders resulted in substantial enhancements in the physical and geotechnical characteristics, such as strength, durability, soil gradation, and Atterberg limits. It was stated that the cured cemented soil containing 2% cement with 5% slag and 1% sodium silicate (by the mass of dry soil) had an enhanced shear strength, which is approximately three times that of the untreated soil [7]. Nevertheless, cement and lime are associated with many issues since their manufacturers consume natural resources (the manufacture of a ton of cement requires 1.5 tons of clay and limestone), demand high energy (each ton of cement needs 5.6 GJ), in addition to emitting carbon dioxide (cement is accountable for approximately 7% of the total CO_2 emissions) [8]. There are two main stages in the hydration of cement-treated soil. It could take from a few minutes to many hours for the initial stage of cement hydration. This stage is connected to the complex chemical system of cement's dissolution and precipitation, which leads to the development of various hydrate compounds (calcium silicate hydrate gel (C-S-H) and calcium hydroxide (hydrated lime $Ca(OH)_2$) which is called Portlandite) [9–12]. This stage is accountable for the early strength of stabilized soil development and helps to improve the plasticity index and workability. The silica and alumina of the clay minerals in the treated soil or from other cement minerals react with the excess hydrated lime (Portlandite) from the first phase of cement hydration to form the second phase of the cement-treated soil hydration, which is known as the pozzolanic reaction. This reaction only takes place in the presence of water. The pH of the surrounding environment, the availability of silicate and aluminate compounds, and time are all factors that affect the pozzolanic process. Additional C-S-H or calcium aluminate hydrated (C-A-H) compounds are created as a result of this reaction [10,13].

These issues have motivated researchers to find efficient and sustainable alternatives to cement and lime. The use of supplementary cementitious materials (SCMs) as a whole or partial substitution for cement is one of the most popular techniques [14]. SCMs are a by-product and waste materials such as fly ash, ground graduated blast slag, palm oil fly ash, silica fumes, cement kiln dust, rice husk ash, etc. [15]. These materials react with water, initiating hydration reactions and forming hydration products.

GGBS has been used as a soil stabilizer in several studies carried out by Pathak et al. [16], Rajalaxmi [17], Neeraja and Rao Narsimha [18], Sridevi [19], and Goodarzi and Salimi [20]. These studies showed that the increase in GGBS content caused a slight alteration in the Atterberg limits (liquid limits, plastic limits, and plastic index). The compaction parameters (maximum dry density (MDD) and optimal moisture content (OMC)) were also improved. The geotechnical properties represented by unconfined compressive strength (UCS) improved only gradually. This can be attributed to the latent hydraulic properties of GGBS since it is present in the glass phase. Thus, upon mixing GGBS with water, the reaction is very slow, and then an impermeable layer of aluminosilicate is produced on the surface, which prevents any further reaction. An activator is needed to raise the pH of the environment to permit the full hydration of GGBS. Cement and lime are the main activators utilized by researchers such as [21–24]. These studies showed that the activation of GGBS results in significant improvements in the geotechnical and physical characteristics of different soft soils. According to Dulaimi et al. [25], GGBS, which has a high concentration of lime, is a latent hydraulic cement that simply has to be activated. The behavior of the various soil and ladle furnace slag mixtures was said to be comparable to that of the soil and lime mixtures [26].

Horpibulsuk et al. [27] and Kampala and Horpibulsuk [28] evaluated the calcium carbide residue (CCR) stabilized clay's engineering characteristics to determine how well it performed in fill and pavement applications. From an engineering, economic, and environmental standpoint, they determined that CCR stabilization is superior to lime stabilization. Al-Homidy et al. [29] suggests that the sabkha soil can be used as a sub-base material in rigid pavements when combined with 2% cement and 30% cement kiln dust (CKD) by the dry weight of such soil. The inclusion of CKD has both technical and economic advantages. CKD has also been used as a soil stabilizer by researchers such as Solanki and Zaman [30], Carlson et al. [31], and Singh et al. [32]. They demonstrated that when CKD is mixed with weak soils, significant improvements in physical and geotechnical properties can be obtained. CKD has been used in many studies as an alkali material in cold bituminous mixes [33,34]. It was found that CKD could activate the fly ash to form a cementitious binder inside these asphalt mixes.

On the other hand, the activation of GGBS by CKD has been examined in mortar and concrete by Konsta-Gdoutos and Shah [35]. They proved that the compressive strength of the concrete at 2 days could be enhanced when GGBS was activated by CKD. Despite that, the activation of GGBS by CKD has not yet been investigated in soil stabilization. There is a significant amount of interest worldwide in recycling waste materials for pavement applications. Thus, this study aims to stabilize the soft soil using a new binary blended binder made of GGBS activated by CKD. The UCS was used to investigate the geotechnical characteristics, while physical properties were examined by Atterberg limits and compaction parameters. A scanning electron microscope was utilized to study the microstructure of the soil samples.

2. Materials and Methods

2.1. Materials

2.1.1. Soft Soil

The soft soil used in this study was collected from the river Alt from a depth of 0.3–0.5 m located in Liverpool, UK. The soil was collected and its natural moisture content (NMC) was tested following BS EN ISO 17892-1:2014 [36]. The particle size distribution, compaction parameters, and Atterberg limits of the natural soil were carried out following the BS EN ISO 17892-4:2014 and BS 1377-2:1990 [36,37]. The unconfined compressive strength was examined by BS 1377-7:1990 [38]. Table 1 lists the findings and categorizes the soil as silty clay with sand (CI) (three specimens were adopted for each test).

Table 1. Soil properties and classification.

The Soft Soil	NMC	Liquid Limit (LL), %	PI	Sand, %	Silt, %	Clay, %	Gs	γ_d max Mg/m^3	OMC, %	pH	UCS, kPa
Value	37.7	39.3	18.37	12	75	13	2.7	1.6	20.2	7.8	195
Standard deviation	0.861	1.64	1.62	1.12	3.04	1.14	0.162	0.093	0.701	0.137	10.5

NMC: natural moisture content; PI: plasticity index; Gs: specific gravity; γ_d max: maximum dry density; OMC: optimal moisture content; UCS: unconfined compressive strength.

2.1.2. Ground Granulated Blast Slag (GGBS)

GGBS is a by-product of iron manufacture, obtained from the rapid chilling of the molten slag. The rapid chilling of GGBS increases the cementitious properties, but it lowers the crystallization of the molten slag. Hence, the glass phase increases from 93 to 99%. Table 2 lists the chemical composition and pH of the GGBS employed in this study. The table reveals that lime, silica, and alumina make up the majority of GGBS. These oxides are similar to those of cement, but their percentages are different [39,40]. Shimadzu's EDX-720 Energy Dispersive X-Ray Fluorescence analyzer was used to conduct the X-ray fluorescence spectrometry (XRF) analysis to determine the oxide contents.

Table 2. GGBS—chemical composition and pH.

Chemical Composition	CaO%	MgO%	SiO_2%	Al_2O_3%	SO_3%	Fe_2O_3%	TiO_2%	K_2O%	pH
GGBS	40.13	4.26	37.73	5.75	0.0	0.01	0.65	0.61	8.5

2.1.3. Cement Kiln Dust

CKD is a by-product of cement manufacture and is extracted from either a wet or dry process. It is a fine powdery substance with an appearance similar to Portland cement. The chemical composition of the CKD and the pH are given in Table 3. The table shows that CKD consists of CaO, SiO_2, sulfate, and alkali. The high alkalinity of CKD, represented by a high pH, makes it an outstanding activator for GGBS, the latent hydraulic material.

Table 3. CKD—chemical composition and pH.

Chemical Composition	CaO%	MgO%	SiO_2%	Al_2O_3%	SO_3%	Fe_2O_3%	TiO_2%	K_2O%	pH
CKD	51.0	0.5	12.5	3.5	4.0	2.5	0.0	5.5	12.7

2.2. Experimental Program

In this study, two optimization phases have been addressed. In the first phase, GGBS was incorporated into 0%, 3%, 6%, 9%, and 12% (by dry weight of soft soil) to optimize it (see Table 4). Secondly, the optimum GGBS was used in a binary blended system with CKD by 0%, 25%, 50%, 75%, and 100% (by dry weight of GGBS) (see Table 5).

The testing protocol includes Atterberg limits, compaction parameters (maximum dry density (MDD), and optimal moisture content (OMC)) to assess the physical properties and unconfined compressive strength (UCS) to investigate the geotechnical characteristics. The microstructure of the soil samples will also be examined using SEM. The curing adopted for UCS and SEM was 7 and 28 days for the treated specimens, with no curing for the untreated samples. The UCS and SEM test specimens were taken out of the mold, weighed, covered in cling film, labeled, put in tightly sealed plastic bags, and kept at room temperature (20 ± 2 °C) for curing.

Table 4. Summary of the test program and performed test for the first stage.

Samples	Untreated Soil	3% GGBS	6% GGBS	9% GGBS	12% GGBS
Designation	U	3G	6G	9G	12G
Atterberg limits	×	×	×	×	×
Standard protector compaction	×	×	×	×	×
UCS with no curing	×				
UCS at 7 days		×	×	×	×
UCS at 28 days		×	×	×	×
SEM with no curing	×				
SEM at 7 days	×		×		
SEM at 28 days			×		

Table 5. Summary of the test program and performed test for the first stage (percentage values were provided in terms of the mass of stabilizing agents).

Samples	75%GGBS + 25%CKD	50%GGBS + 50%CKD	25%GGBS + 75%CKD	100% CKD
Designation	75G-25C	50G-50C	25G-75C	6C
Atterberg limits	×	×	×	×
Standard protector compaction	×	×	×	×
UCS at 7 days	×	×	×	×
UCS at 28 days	×	×	×	×
SEM at 7 days			×	×
SEM at 28 days			×	×

2.2.1. Atterberg Limits Test

Based on its water content, soil can exist in four different states: liquid, plastic, semi-solid, and solid. The boundaries between the liquid limit (LL), plastic limit (PL), and shrinkage limit are known as Atterberg limits (SL) [16].

The amount of moisture in the soil that allows it to flow under its weight is the liquid limit. The water content at which soil ceases being plastic and turns brittle is identified as the plastic limit [41]. The numerical difference between plastic and liquid limits is known as the plastic index [42]. The test is conducted following British standard BS 1377-2: 1990 [37]. For each dose of additives, three specimens were prepared.

2.2.2. Compaction Parameters Test

By keeping air out of the spaces and compacting the particles, compaction increases the soil's density. This test is based on the idea that the soil's moisture content influences how much compaction energy is applied and how dense the resulting dry soil becomes. This test determines the ideal moisture content (OMC) and the maximum dry density (MDD) at which nearly all air is evacuated from voids. In many geotechnical tests, including permeability, compressive strength, compressibility, etc., the MDD and the OMC serve as the primary inputs. The standard proctor is employed to determine the compaction parameters (MDD and OMC) of the clay soil [43]. The test is carried out following the British standard BS 1377-4: 1990 [44]. Three specimens were prepared for every dose of additives.

2.2.3. Unconfined Compressive Strength Test

To assess the soil's compressive strength, the unconfined compressive strength (UCS) is measured. In order to estimate the soil strength while designing geotechnical structures such as slopes, retaining walls, foundations, and embankments, compressive strength is a crucial feature [45]. A computerized and motorized triaxial machine was used for this test, although there was no lateral load applied in the triaxial cell [46]. The test was conducted in this investigation in compliance with British Standard BS 1377-7 [38]. This test has been

used by many studies for evaluating the strength of stabilized soil [47,48]. Three samples were made for each dose of additives.

2.2.4. Scanning Electron Microscope Test

This is a technique used to demonstrate the microstructural changes and newly produced cementitious products in the samples. Magnified images of the sample surface at a microscopic level are produced [49]. Both Quanta 200 and Inspect S scanning electronic microscopes were used for the SEM test. Before performing the SEM imaging, the samples of the treated soil were allowed to cure for 7 and 28 days. The specimens were coated to increase visibility before the SEM imaging with a thin layer of Palladium using a sputter coater.

3. Results and Discussion

3.1. GGBS Optimization

3.1.1. Compaction Parameters (MDD and OMC)

Figures 1 and 2a,b illustrate how various GGBS contents affect the MDD and the OMC. It is clear that as GGBS increased up to 9%, MDD increased while OMC decreased slightly. The pattern is the opposite after 9%, with the MDD falling and the OMC rising.

This study's findings are consistent with the findings of Akinmusuru [50] and Yadu and Tripathi [51] who used GGBS to stabilize various types of soft soils. Yadu and Tripathi [51] attributed the decrease in the OMC to the decrease in the clay and silt content of the soil upon GGBS addition, which has a smaller surface area. The smaller surface area needs less water, and consequently less water content is required to compact soil containing GGBS. Meanwhile, the increase in MDD is due to the high specific gravity of GGBS. Akinmusuru [50] indicated that the reverse trend beyond 9% GGBS is due to the very high GGBS content presented in specimens, which is a coarse material. Thus, the void content in the mix increases, making the compaction relatively hard. Thus, the OMC increased and the MDD decreased. It was reported by Lopes et al. [52] that soils with higher clay contents treated with electric arc furnace slag have a tendency to experience more changes in their texture and structure as a result of the Ca^{2+} and Mg^{2+} cations present in the electric arc furnace slag.

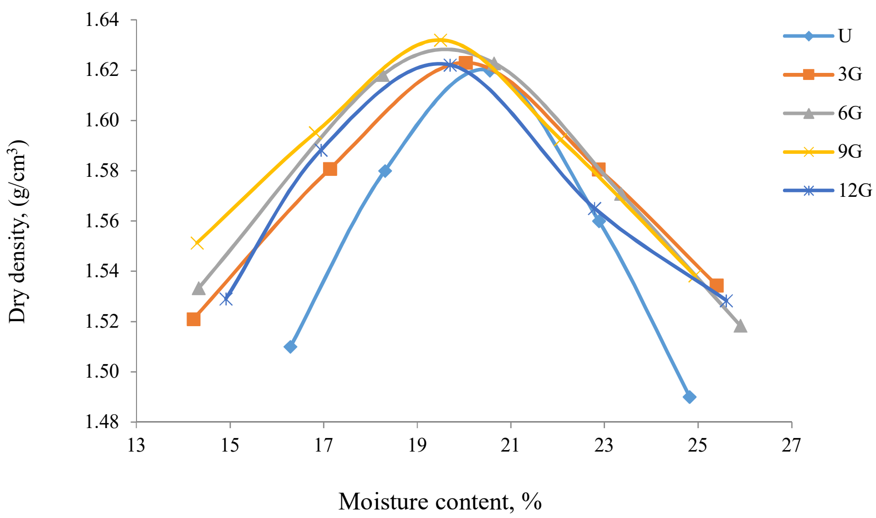
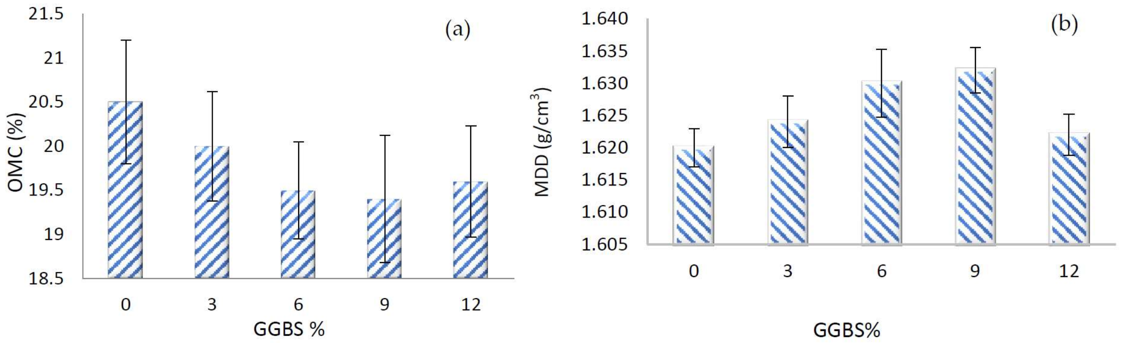


Figure 1. Compaction parameters of soil with different GGBS contents.



(**a**) (**b**)

Figure 2. (**a**) OMC of soil with different GGBS contents; (**b**) MDD of soil with different GGBS contents.

3.1.2. Unconfined Compressive Strength

The unconfined compressive strength (UCS) increased upon the addition of GGBS from 3% to 6%, as seen in Figure 3. Then, the strength dropped as GGBS increased from 9% to 12%. This trend occurred at both curing ages, 7 and 28 days. The figure also showed that the increase in the UCS value upon the incorporation of GGBS is very slight. Additionally, the development in the UCS from 7 to 28 days was gradual for all the treated samples. The UCS of soil with the optimum binder, which is 6% (6G), was increased by only 1.8 times and 1.9 times after 7 and 28 days, respectively. Since 6G gave the highest UCS values, it was selected as the unary mixture to blend with CKD in the binary system in the second optimization stage.

The development in the UCS values with the incorporation of GGBS was confirmed by Ouf [53] and Padmaraj and Chandrakaran [54], who stabilized soft soil with GGBS in percentages similar to those used in the study. Ouf [53] credited the ongoing creation of hydration products with the strength enhancement associated with the rise in GGBS. The decrease in strength occurs when GGBS is added beyond 9%. The strength decreases because GGBS becomes excessive, leading to the generation of a weak bond between the binder and the soil. Since GGBS primarily comprises lime, silica, and alumina, this chemical composition can be used to explain how the strength of the soil treated with it has improved. Nevertheless, the slight strength development is due to the latent hydraulic properties of GGBS and its low pH (8.5), which makes its reactivity very low. Thus, an activator is needed to break the glass phase and increase the reactivity of GGBS. In this study, CKD was used as an activator of GGBS.

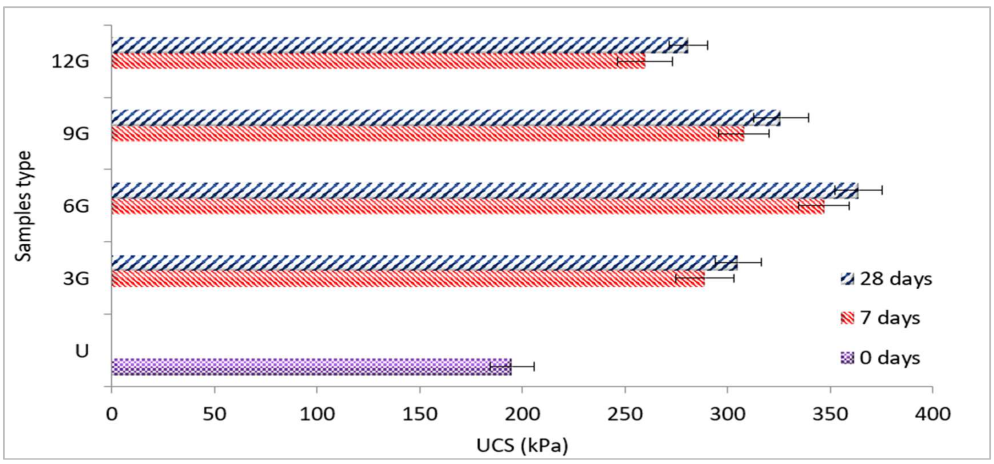


Figure 3. UCS of soil with different GGBS contents at 7 and 28 days of curing.

3.2. Binary Blending Treatment

3.2.1. Atterberg Limits

Figure 4 showed that the liquid limit, plastic limit, and plastic index of the 6G decreased. Nevertheless, the trend became the opposite as GGBS was replaced by CKD since both the plastic limit and liquid limit increased while the plastic index decreased. Upon increasing the substitution of GGBS by CKD, the liquid limit increased slightly with a decrease in the plastic limit and plastic index. This trend shows the influence that CKD has on the Atterberg limits of the mixtures. In terms of the sample with 100% CKD (6C), it exhibited an increase in both the liquid limit and plastic limit while the plastic index decreased.

It can also be noticed that the Atterberg limits of 6G are slightly changed compared with those of the untreated soil (U). However, when CKD activates GGBS, the LL and PL are significantly affected, which leads to a considerable decrease in the plastic index of the soil samples. The greatest decrease in the plastic index is obtained by the 25G-75C sample. Compared with the untreated soil, the plastic index of the 25G-75C sample was lowered from 18.4% to 9.5%. Among all the soil samples, the 6C sample exhibited the highest reduction in the plastic index.

The influence of GGBS content on the Atterberg limits was explained by Yadu and Tripathi [51] as well as Padmaraj and Chandrakaran [54] when they stabilized soft soils using GGBS in relatively similar amounts. They attributed the GGBS behavior to the decrease in water affinity with the decrease in the fine fraction of the soil (silt and clay). The effects of the activated GGBS on the soft soil were correlated with those gained by Wild et al. [55] and Ouf [53] when utilizing lime-activated GGBS in soft soil stabilization. The trend was due to the incorporation of a very fine material, CKD, which has a high affinity for water. CKD has a high CaO content which can dissolve in water. This is very important since CaO governs the water needed to enable the dissolution to provide Ca^{+2} for cation exchange. Though GGBS has a high CaO, its water affinity is low because its CaO is hydraulically latent. In terms of CKD results, they are rather similar to those obtained by Taha et al. [56] and Iorliam et al. [57], which can be explained in light of the aforementioned information.

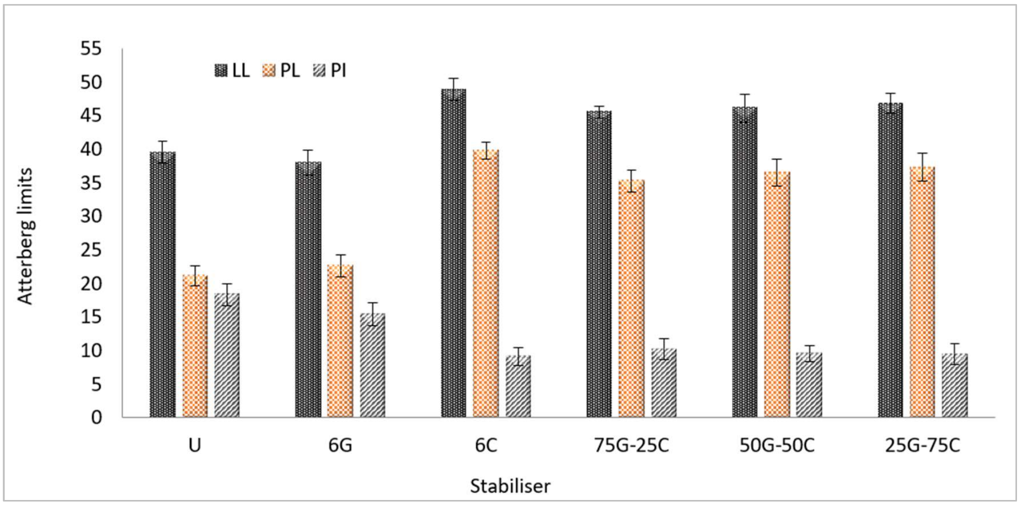


Figure 4. Atterberg limit (LL, PL, PI) results.

3.2.2. Compaction Parameters

Figures 5 and 6a,b show the ideal moisture content (OMC) and the maximum dry density (MDD) of the soil treated with GGBS that is activated by CK as well as the untreated soil. It can be noticed that there is a slight increase in the MDD and a decrease in the OMC of the 6G. Since the MDD of the activated soil samples decreased and the OMC increased, the tendency is reversed in terms of the binary system of the GGBS and CKD. This is influenced by the quantity of CKD in the binary system of the soil samples. While the OMC increased from 20.6% to 23.1%, the 25G-75C's MDD decreased significantly from 1.623 g/cm^3 to 1.595 g/cm^3. Moreover, the MDD of the 6C soil sample decreased, while the OMC increased.

The increase in the MDD in the 6G sample can be attributed to the coarse particles of GGBS, while the decrease in the OMC was due to a decrease in the fine fractions of the soil upon the substitution of GGBS [51].

The decrease in the MDD and the increase in the OMC when the soil is mixed with GGBS activated by CKD is similar to that obtained by Ouf [53] and Swamy et al. [58] when stabilizing soft soils utilizing GGBS activated by other materials such as lime. Due to the soil particles flocculating as the activator amount in the mix increased, the MDD decreased, resulting in an increase in the clay particles' size and the introduction of more voids. The increase in the OMC was due to the high volume of water required to achieve the optimum compaction.

The influence of CKD on both OMC and MDD was investigated by Miller and Azad [59] and Amadi [60]. They indicated that the increase in the OMC is due to CKD being a fine material having a high surface area, so it absorbs a high amount of water. The reduction in the MDD was attributed to the immediate flocculation and agglomeration taking place as CKD was added to the soil, resulting in a decrease in the density and an increase in the void content.

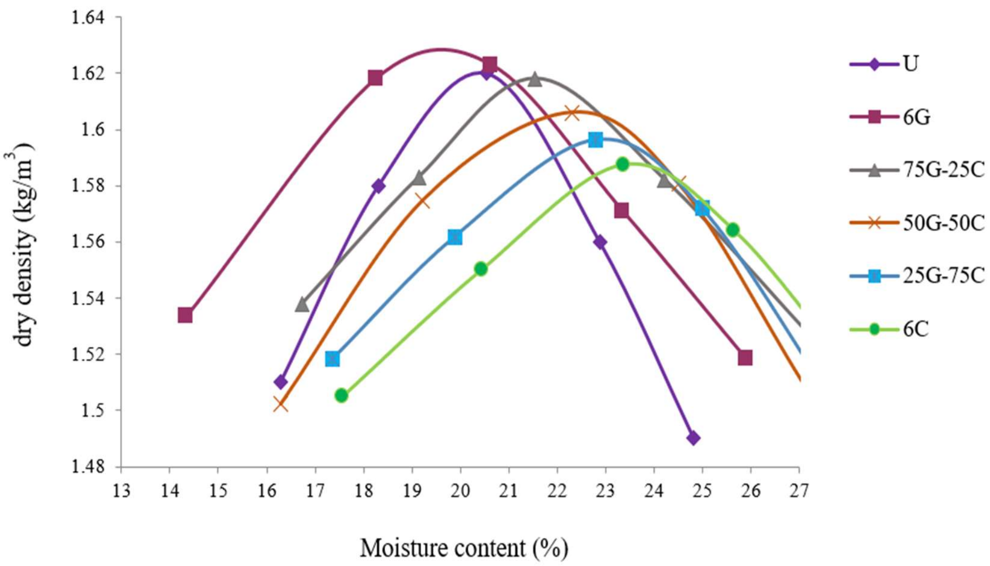
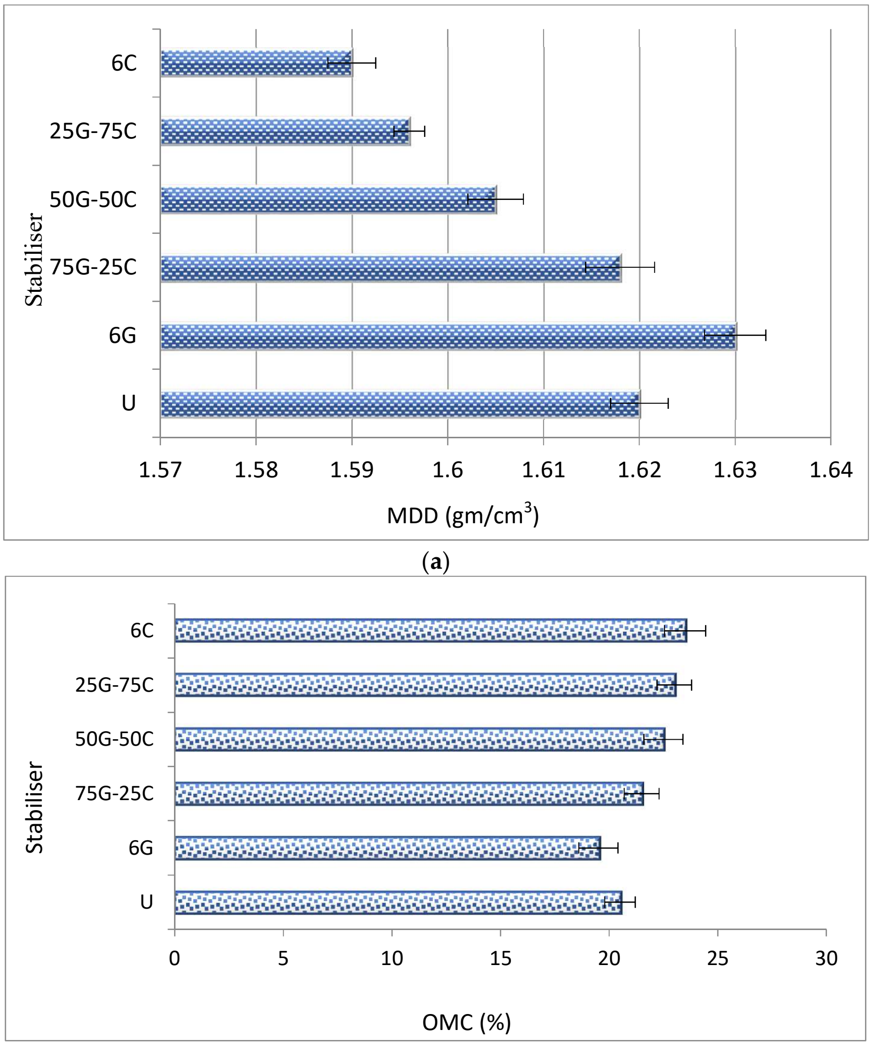


Figure 5. The compaction parameters of untreated and treated soil samples.



(**a**)

(**b**)

Figure 6. (**a**) MDD of untreated and treated soils; (**b**) OMC of untreated and treated soils.

3.2.3. Unconfined Compressive Strength

The UCS of the soil treated with GGBS activated by CKD is shown in Figure 7. Upon activation of GGBS by CKD, the enhancement in the UCS of the soil specimens was very significant. The binary blending of 25% CKD and 75% GGBS (75G-25C) increased the UCS at 7 days by 3.3 times and by 5.5 times at 28 days in comparison to the untreated soil. Additionally, the UCS of each activated binary mixture significantly increased due to the increase in the curing time from 7 to 28 days. The findings also demonstrated a consistent rise in UCS when GGBS was increasingly replaced by CKD in the binary system. The soil that included 25% GGBS and 75% CKD (25G-75C) produced the largest improvement in the UCS.

The improvement in the strength of the soil with CKD-GGBS was confirmed by Konsta-Gdoutos and Shah [35] when manufacturing mortar from GGBS and CKD. In their study, they also found that the optimum binder was gained when 75% CKD was mixed with 25% GGBS. The strength development was attributed to the formation of the C-S-H product and continuous hydration. The substantial enhancement in the UCS of the soft soil, when stabilized with activated GGBS, was in line with Pai and Patel [61] when utilizing lime as an activator for GGBS. In addition, the strength of CKD soil was ascertained by Al-hassani et al. [62] when using CKD at 5% to enhance the characteristics of CL cohesive soil.

The slower rate of strength development of CKD in comparison to the (25G-75C) binder, especially after 28 days, may be due to the presence of more $Ca(OH)_2$ than was

required for the pozzolanic reaction. The unreacted $Ca(OH)_2$ that is still present weakens the matrix [35].

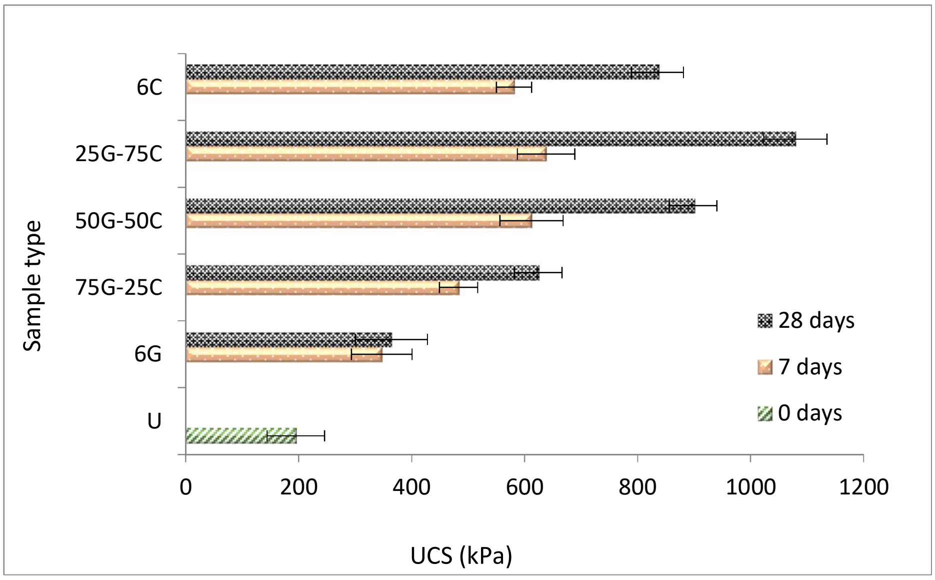


Figure 7. UCS of both treated and untreated soil samples at 7 and 28 days.

3.2.4. Scanning Electronic Microscopy (SEM)

In cement and soil stabilization research, SEM imaging testing has become more prevalent, especially for microstructural analysis requirements. These high-resolution micrograph images aid in identifying how the microstructure changes during the curing process and facilitates an understanding of the evolution of the treated material's geotechnical qualities [63]. In order to track changes in the stabilized clay's microstructure, the technique was carried out after the UCS test. The SEM of the untreated soil (U), unary 6% GGBS soil (6G), soil with 6% binder (25% GGBS and 75% CKD) (25G-75C), and soil with unary 6% CKD binder (6C) was carried out in the study at curing of 7 and 28 days. Figure 8a indicated the presence of a discontinuous structure with well-observed voids due to the lack of hydration products for the untreated soil. The flaky arrangement of clay between the fine silt and sand fraction is also presented. The figure also showed the dominant silt particles in dark grey, arranged mainly edge-to-edge and/or inter-particle edge. The lack of physical bonding can be confirmed as the edges and surfaces of the silt and clay grains seem well-defined and clean.

The soil treated with 6% binder (25%GGBS and 75%CKD) (25G-75G) and the SEM of the 7 days (Figure 8b1,b2) showed the formation of a dense structure, in addition to considerable flakes of C-S-H and some needle-like ettringite. It was stated that the C-S-H morphology ranges from reticular networks to poorly crystalline fibers, while ettringite forms needle-shaped prismatic crystals [64]. Both C-S-H and ettringite are the major cause of the strength development in the soil structure. At 28 days of curing, the formation of this product (C-S-H) increased with the progression of curing time as shown in Figure 8c1,c2. Moreover, no CH is found in the treated soil structure at both days (7 and 28) as they are all consumed in the fabrication of hydration products. The morphology of CH generally differs from nondescript to stacks of large plates [64]. Furthermore, a thick packing of the binder and soil particles was seen. The hydration products completely covered the soil's surface and caused the microstructure of the stabilized soil to become denser. Previous studies on the stabilization of clayey soils with calcium-based additions revealed similar results [65–68]. Additionally, Horpibulsuk et al. [69] claimed that clay's inter-cluster bonding and ability to control pore space were two benefits of continuous hydration product growth. This resulted in a decrease in the volume of pores smaller than 0.1, which resulted in increased clay strength.

The SEM of the 6G sample at 7 days indicated that a considerable amount of CH and a few calcium silicate hydrates (C-S-H) were formed, as seen in Figure 9a. The high amount of CH was produced due to the reaction taking place between the CaO of lime and the pore water without completely exhausting it due to silica's slow rate of dissolution, and the alumina of GGBS, since it is a low-reaction material with a low pH (8.5). The hydration products that form on the soil's surface fill some of the gaps between them. Thus, the strength derived from the soil–GGBS sample is the lowest among all the treated soil samples. At 28 days, the formation of C-S-H can be observed due to the reaction between silica and alumina and CH, as seen in Figure 9b. In addition, portions of the soil have not been covered with C-S-H gel.

At seven days, the soil's microstructure of the CKD stabilized. Figure 9c demonstrated how the formation of C-S-H, as well as ettringite in the shape of needles on the silt particles, caused the soil structure to change from flakes to compacted. The pore size was reduced and has been partially filled with hydration products. All these alterations contribute to strength development. In Figure 9d, the CKD soil at 28 days showed that the soil structure has relatively no voids due to the generation of a significant amount of needle-like ettringite and C-S-H. This justified the remarkable development in the strength of the soil treated with 6% CKD. Although the application of CKD had an impact on improving soil strength, in the 25G-75G-stabilized soil, the clay became denser and stiffer due to the intercrossing of ettringite crystals with C-S-H and clay clusters as well as the CSH fabric filling in the pore space between clay particles. It was reported that the stabilized clay's strength may rise as a result of the CKD and its hydration products [66]. However, the combination of CKD and other pozzolanic materials such as slag and fly ash may be more advantageous due to their mechanical properties [70–72].

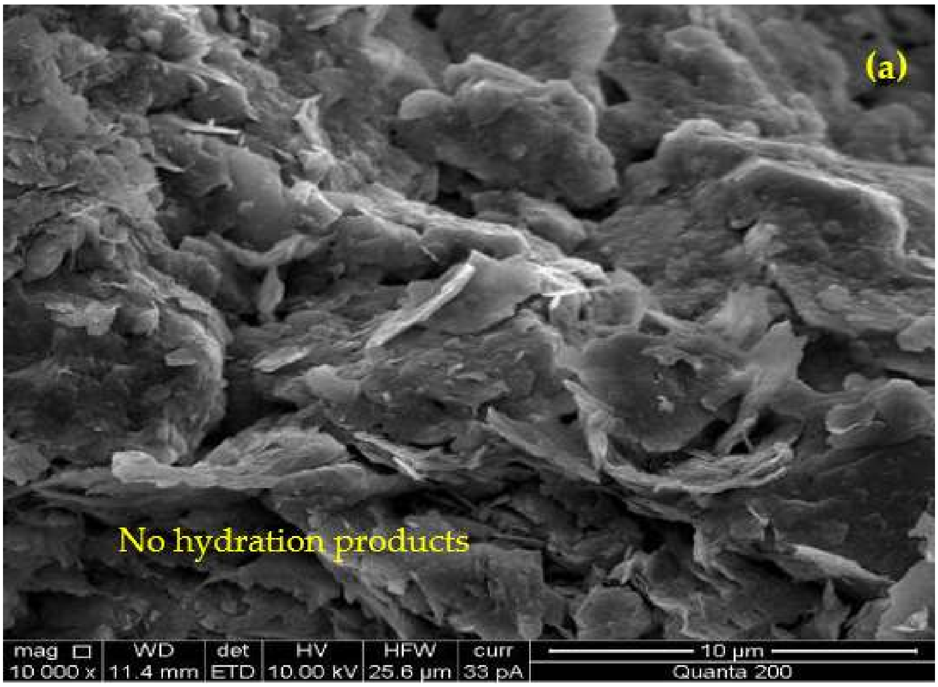


Figure 8. *Cont.*

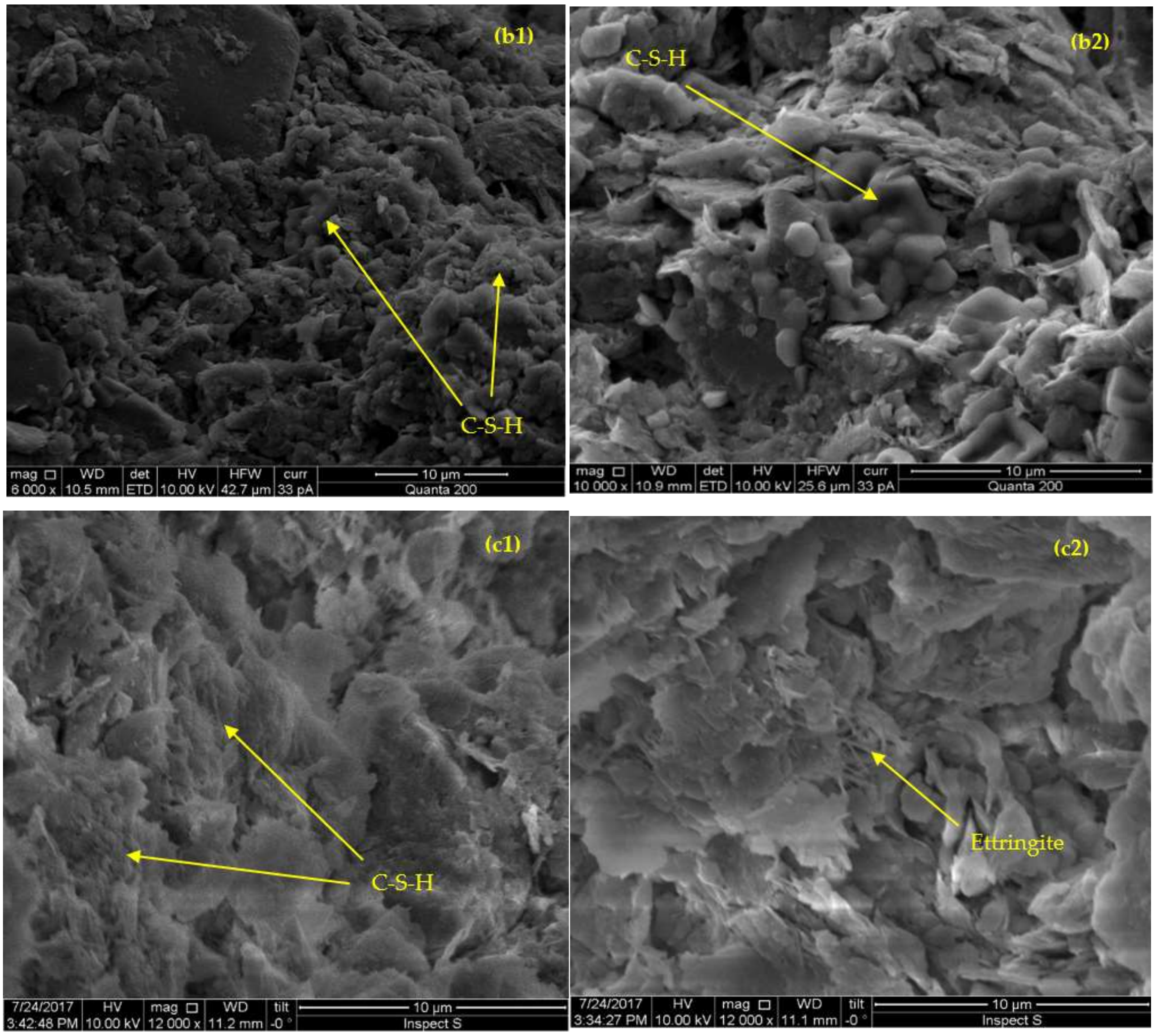


Figure 8. SEM of (**a**) untreated soil (U), (**b1**,**b2**) soil with 6% binary binder (25%GGBS, 75%CKD) (25G-75C) at 7 days, (**c1**,**c2**) soil with 6% binary binder (25%GGBS, 75%CKD) (25G-75C) at 28 days.

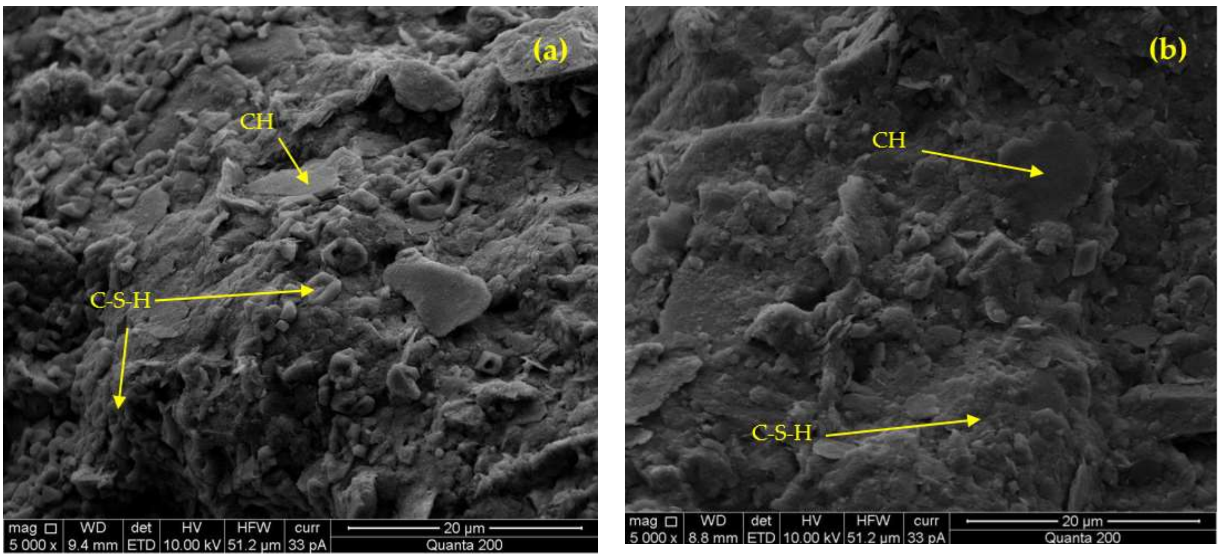


Figure 9. *Cont.*

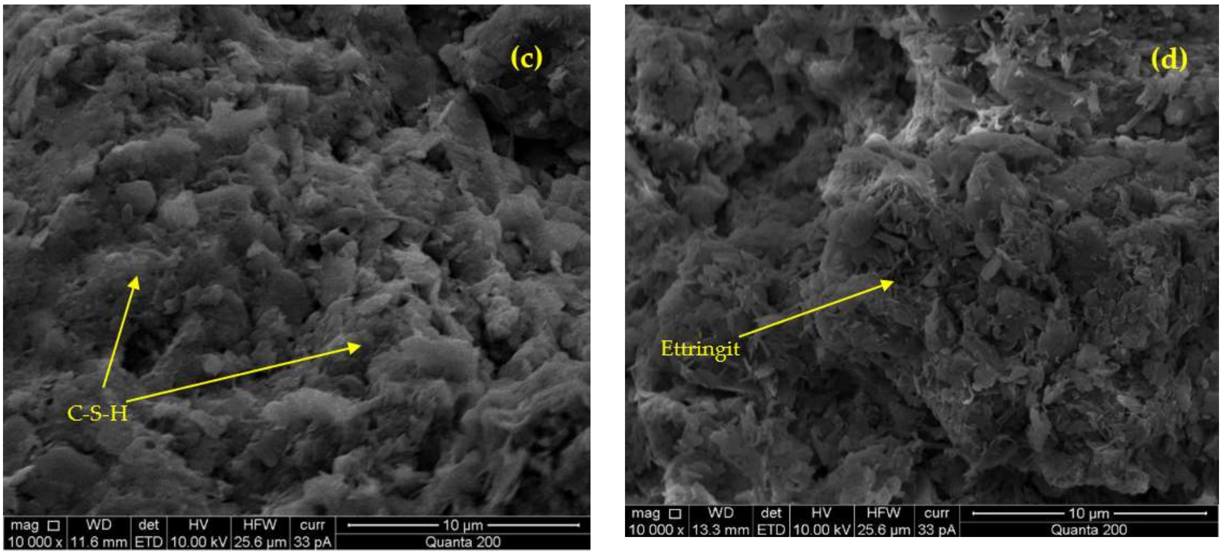


Figure 9. SEM of (**a**) soil treated with 6% GGBS (6G) at 7 days, (**b**) soil treated with 6% GGBS (6G) at 28 days, (**c**) soil treated with 6% CKD (6C) at 7 days, (**d**) soil treated with 6% CKD (6C) at 28 days.

4. Conclusions

This study aims at the usage of cement kiln dust (CKD) and ground granulated blast slag (GGBS) as stabilizers for soft soil. From the aforementioned results, the following can be concluded:

1. In the GGBS optimization, there was an increment in the MDD and at the same time, a decrease has been noticed in the OMC due to the incorporation of GGBS up to 9%, and then the trend reversed. In terms of soil strength, the UCS increased gradually and 6% GGBS was selected as the optimum binder (unary binder). The slight improvement by utilizing GGBS in soil stabilization was attributed to its glassy phase, which reduces the reactivity.
2. The binary blending cementitious binder produced from by product materials (GGBS with CKD) was developed from 25% GGBS activated with 75% CKD. This binder can be used in soft soil stabilization, which contributes to the reduction in the negative environmental footprint. A modification in the physical properties has been achieved (Atterberg limits and compaction parameters). The LL and PL of 6G decrease, while they increase upon activating GGBS by CKD.
3. In terms of the compaction parameters, the MDD decreased, and the OMC increased when GGBS was substituted by CKD in the binary blending cementitious binder. On the other hand, the UCS of the soil treated with GGBS and CKD was enhanced significantly. The optimum binary blending cementitious binder achieved in this study was 6%, composed of 25% GGBS and 75% CKD (25G-75C). Substantial developments in UCS were achieved in association with an improvement in the physical properties. In comparison with untreated soil, the strength of 25G-75C was 3.3 times greater after 7 days and 5.5 times greater after 28 days. The UCS of the 25G-75C exceeded that for the samples treated with GGBS as well as the sample treated with CKD.
4. Microstructural examinations revealed a significant impact on the structure of the stabilized samples from the addition of the 25G-75C binder. The addition of this binder results in the formation of cementitious products (C-S-H and ettringite) and binds the soil's particles strongly, creating a strong bond between them and leading to an increase in UCS. Soil with only CKD (6C) also has an improved structure, but it is still inferior to the 25G-75C soil structure.

The results of this research are limited to the particular stabilized soil type, the particular geotechnical qualities that were examined, and the particular waste materials employed to create the cementitious binder. In addition, the findings of the liquid limit and plastic

limit tests in this research should also be viewed as a restriction because the ability to conduct these tests depends largely on the skills and experience of the person performing these tests.

Since not all of the stabilized soil's geotechnical characteristics have been discussed in this research, it is advised to investigate how the produced binder affects the other geotechnical characteristics of the stabilized soil, such as the hydraulic conductivity, California bearing ratio (CBR), and resilient modulus of elasticity. In addition, further research is needed, especially to increase the knowledge of treated soil mixture behavior based on X-ray diffraction (XRD), thermogravimetric analysis (TGA), Raman spectroscopy, mercury intrusion porosimetry (MIP), and Fourier-transform infrared spectroscopy (FTIR).

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