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Geotech Geol Eng (2024) 42:5065–5084
https://doi.org/10.1007/s10706-024-02830-4

ORIGINAL PAPER

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Improving Soft Subgrade Stability Using a Novel Sustainable Activated Binder Derived from By-Products

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Received: 12 February 2024 / Accepted: 15 May 2024 / Published online: 11 June 2024

Abstract Soft soil concerns, due to high compressibility and low bearing capacity, prompted an investigation into stabilizing clay soil. Traditionally, binder including cement or lime has been used as stabilizers though a current requirement of alternatives is stem from environmental concerns. The study focused on the viability of using a novel binary activated blended binder composed of environmentally friendly materials, namely ground granulated blast furnace slag (GGBS) activated by cement kiln dust (CKD). The experimental work included investigating the impact of the developed binders on the Atterberg limits, standard Proctor compaction, California Bearing Ratio (CBR), unconfined compressive strength (UCS), and field-emission scanning electron microscopy (SEM)/energy-dispersive X-ray spectroscopy. CBR tests were conducted after 7 days of curing or soaking, while UCS and SEM analyses were conducted after 7 and 28 days of curing. A fixed binder ratio of 9% was maintained, with GGBS blended at 25%, 50%, and 75% with CKD. For comparison, samples of untreated and treated soils with unary binders from GGBS and CKD were also prepared. Results indicated that activated binders notably decreased

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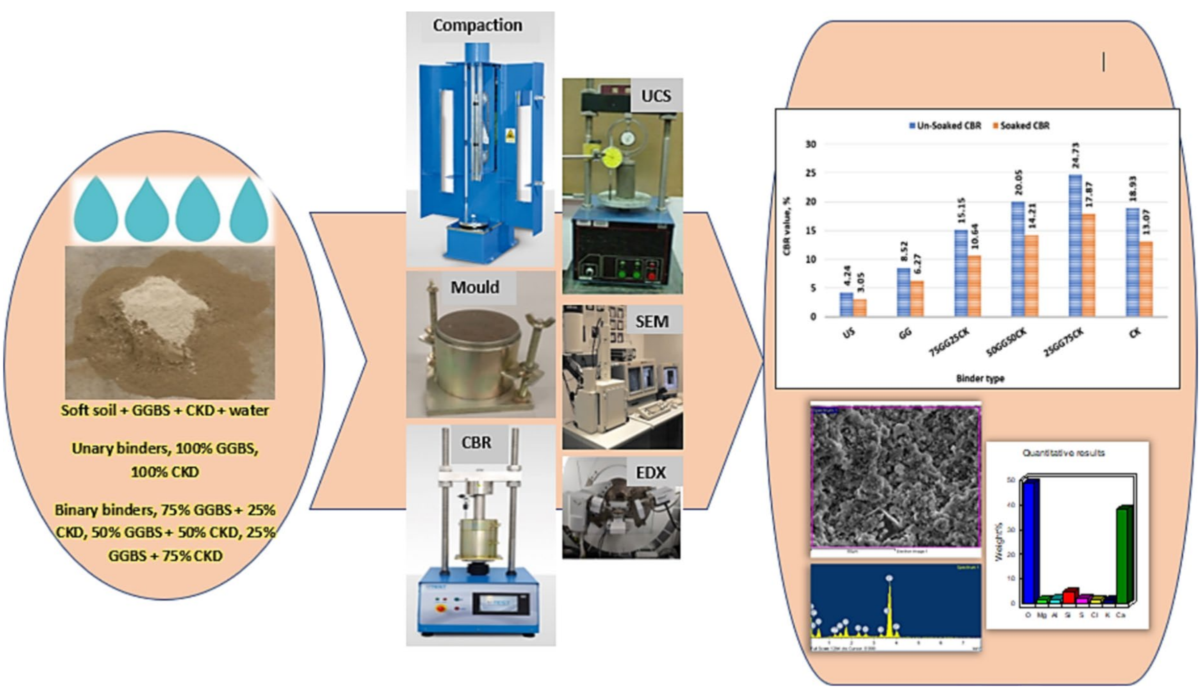
soil plasticity and maximum dry density, while elevating optimum moisture content, CBR, and UCS, especially in later stages of treated soil and unary GGBS binder. Unary CKD binder exhibited a similar trend to activated binders. The activating of 25% GGBS with 75% CKD provided the optimum binder which increased the mechanical strengths by about 6 times than untreated soil. SEM revealed substantial formations of C-S-H and C-A-H gel, along with ettringite, intensifying with time. This research provides viable outcomes for stabilizing clay soil using environmentally friendly binders, demonstrating significant improvements in soil properties, particularly when using the binary activated blended binder consisting of GGBS and CKD.

Graphical Abstract



Keywords Microstructure · Soft soil · Subgrade stabilization · Sustainability · Unconfined compressive strength

Abbreviations

BS	British Standard
BS EN	British Standard Version of European Standards
Ca^{+2}	Calcium cation
$Ca(OH)_2$	Calcium hydroxide
C-A-H	Calcium aluminate hydrate
CBR	California bearing ratio
CCR	Calcium carbide residue
CEMEX	A Mexican Multinational Building Materials Company
CKD	Cement kiln dust
CO_2	Carbon dioxide
C-S-H	Calcium silicate hydrates
EDX	Energy dispersive X-ray
EDXRF	Energy dispersive X-ray fluorescence spectrometer
GGBS	Ground granulated blast furnace slag
GJ	A gigajoule
LL	Liquid limit
MDD	Maximum dry density
NaOH	Sodium hydroxide
OMC	Optimum moisture content
pH	Potential hydrogen
PI	Plasticity index
PL	Plastic limit

SEM	Scanning electron microscopy
UCS	Unconfined compressive strength
UK	United Kingdom

1 Introduction

The subgrade layer represents the foundation of pavements as it is located at the bottom of the pavement structure which works to transfer loadings from the layers of the pavements to the ground underneath (Anburuvel 2024). This soil mainly consists of local soil which can be either wet or soft (Gueye et al. 2023; Nik Daud et al. 2019). Constructing the pavement on a weak subgrade is a common issue in engineering and geotechnical fields due to the high compressibility, low permeability, and strength of soils such as silts and clays. Such soil properties can lead to serious pavement issues including deterioration, distress, and roughness represented by rutting or cracking in pavements which require maintenance and rehabilitation as they reduce the serviceability level and the designed service life (Aneke et al. 2023; Athanasopoulou 2016). Thus, remediation is essential for providing a stable and strong supporting subgrade layer (Sudheer Kumar and Janewoo 2016). However, from an engineering perspective, increasing the volume of the subgrade is crucial for a larger distribution of loads which leads to increasing the pavement's thickness. It is essential to perform optimization of the pavement though there will be a point at which the cost is critical, impacting adversely on the remediation. Another method would involve the replacement of soft soils with strong ones though this approach again requires the additional cost of excavation and replacement materials. An effective alternative approach has been developed termed soil stabilization. This simply involves changing the properties of soft soil through mechanical or chemical alterations. Mechanical stabilization involves the use of a physical compaction process to alter the physical properties of the soil, while chemical stabilization is carried out through the use of chemical stabilizers that react with water to form a bonding of the soil particles (Patel 2019; Khanday et al. 2021; Naik et al. 2023).

The use of chemical stabilizers is considered the most efficient approach for stabilizing fine-grained soft soils such as clays and silts (Syed et al. 2020). The approach has traditionally been performed with the use of lime or cement stabilizers (Norouzian et al. 2018; Le Van Tuan and Phung Vinh An 2018; Shirmohammadi et al. 2021; Majumder and Venkatraman 2022). However, nowadays, the rising concerns about climate change have called for the minimizing of cement and lime since they require high energy, and natural resources during their production and emit high levels of CO_2 (Jwaida et al. 2024; Heitor et al. 2021). 8–10% of the global CO_2 emissions are caused by the manufacture of cement (Bildirici 2019). It is predicted that from 2017 to the end of 2050, the yearly output of OPC will rise by almost 50% (Monteiro et al. 2017). A ton of carbon dioxide (CO_2) is predicted to be released during the production of one ton of OPC (Bildirici 2019; Monteiro et al. 2017). Thus, by-products and waste materials have been investigated for soft subgrade as possible alternative stabilizing materials such as rice husk, silica fume, fly ash, jute fiber, glass fiber, waste rubber powder, etc. (Al-Soudany 2018; Farooq and Mir 2020; Hidalgo et al. 2020; Mishra et al. 2022; Jwaida et al. 2023).

This research aimed at the use of ground granulated blast furnace slag (GGBS) combined with the cement kiln dust (CKD) for the development of new binary activated binder for soft subgrade stabilization. Alsalman et al. (2021) reported that GGBS has minimal environmental impacts with only 0.052 tons of CO_2 being produced and 0.857 GJ energy required for producing 1 ton of GGBS. Also, all molten slags are used in the production of GGBS, resulting in minimal to no waste produced. On the other hand, the use of CKD can positively impact the environment as it is produced in significant amounts, requiring a large landfill area.

The possibility of using GGBS or CKD in subgrade soil stabilization has been evaluated by various researchers. Pathak et al. (2014) used various amounts of GGBS from 0 to 25% for the stabilisation of clay soil. The result indicated that the increasing in the level of GGBS slightly ompacted the compaction parameters and reduced the Atterberg limits while The CBR only slightly increased with the increase in the content of GGBS. Bera et al. (2019) investigated the use of GGBS for treatment of silty and clay soils. The results indicated increasing the CBR values with the increase in the GGBS content up to a certain level after which the bearing strength were decreased.

Amadi and Osu (2018) used various mixtures from CKD (0–16%) and quarry fines (10%) for the stabilisation of black corrosion soil. The results indicated increased reduction of plasticity of soil with the addition of CKD which was the same observation as Amadi (2010). Adeyanju and Okeke (2019) blended CKD in different ratios of 10, 12.5, 15%, and 7.5 with clayey soil. The clay soil's unsoaked CBR increased from 1.49 to 28.6%, according to the results, indicating that the soil combined with 10% CKD had the best mechanical improvement.

Sargent (2015b), Amaludin et al. (2023), and Dulaimi et al. (2020) reported that the GGBS is glassy latent hydraulic material upon mixing with water producing an impermeable aluminosilicate layer on the slag surface and inhibiting the occurrence of further reactions. Thus, activation is essential to trigger the reaction by breaking the bonding within the layer. Researchers have investigated the possibility of activating the GGBS in subgrade stabilization (Beygi and Khazaei 2024; Razeghi et al. 2024). Sargent (2015a) used NaOH as an activator for the GGBS on sandy silty soil. The results indicated significant strength development compared with unary GGBS binder with the intensive amount of C-S-H gel indicated through SEM test. Bandyopadhyay (2016) used calcium carbide residue (CCR) activated GGBS for the stabilization of silty clay soil. The findings revealed significant improvements in the compaction parameters and Atterberg limits of the treated soil. The CBR of the untreated soil increased by 85.33% with the use of 10% GGBS − 0.75% CCR. Padmaraj (2017) investigated the activation of GGBS with lime for stabilizing clayey soil with intermediate plasticity. It was indicated that the CBR value of untreated soil increased from 1.89 to 60% with the use of an activated binder of 10% GGBS and 5% lime. Significant improvements in the Atterberg, compaction, and CBR values were reported. Also, experiments were carried out by Konsta-Gdoutos and Shah (2003) and Chaunsali and Peethamparan (2011) for a novel approach development by combining CKD and GGBS to investigate their effectiveness as a binder in concrete and reported significant development in concrete compressive strength even at early curing days. Furthermore, El-Didamony et al. (1997) conducted a study to examine the possibility of using washed and calcined CKD as an activator to GGBS through microstructural and mineralogical testing. The result shows ettringite formation at an early and C-S-H gel was dominating at late ages, indicating the successful activation of GGBS. Although there is various research regarding the incorporation of GGBS or CKD binders, the use of activated CKD-GGBS binder has not been investigated for soft subgrade stabilization.

1.1 Research Significance

This research represents an innovative attempt to investigate the effects of using CKD to activate GGBS and create a new binary blended binder for stabilizing soft subgrade soil. The ultimate goal is to produce a binder that can dramatically enhance the characteristics of soft soil used in the subgrade layer, thus revolutionizing soil stabilization methods. Traditional methods of stabilizing soft subgrades, such as using lime or cement, can be costly and may have environmental implications. Therefore, there is a need for more sustainable and cost-effective methods for stabilizing soft subgrades. This study differs from existing literature by employing a novel approach that integrates an activated binder with a soft subgrade soil, providing an innovative approach to improves soil stability. Through testing, the mechanical and strength properties of the stabilized soil were thoroughly examined to ensure the effectiveness of the new binder as well as establishing the optimum GGBFS and CKD mix ratios for stabilizing soft subgrades. GGBFS and CKD are industrial by-products, and their utilization in soft subgrade stabilization could reduce the overall construction costs. By utilizing industrial by-products, the research promotes sustainable construction practices and reduces the environmental impact associated with the disposal of these materials.

2 Materials

2.1 Soil

The soil was taken at a depth of 0.3–0.5 m below the ground level from River Alt, Northern Liverpool, UK. The soil was transferred to the Liverpool John Moores University lab in bags sealed properly that weighed 20–25 kg. Natural soil samples were tested to determine the water content following the BS EN 17892-1:2014+A1:2022 (Institution 2022). The rest of the soil was oven dried at 110 °C for 24 days for use in further tests. The soil was sieved following the BS EN 17892-1:2014+A1:2022 (Institution 2022), and the Atterberg limits were determined according to BS 1377-2:2022 (Standard 2022). BS1377-4:1990 (Standard 2002a) was used for determining the compaction parameters and California bearing ratio. A pH of 7 is neutral, so this soil is slightly alkaline. Specific gravity can be defined as the mass of a certain volume of solid soil divided by the mass of the same volume of water at a defined temperature. The density of the soil is indicated by it. CBR value of shows a poor soil for subgrade layer. BS1377-7:1990 (Standard 2002b) was used for determining the unconfined compressive strength of the soil. Based on the results, the properties of the soil are shown in Table 1. According to the Unified Soil Classification System, the classification of the soil was an intermediate plasticity clayey silt soil.

2.2 Ground Granulated Blast-Furnace Slag (GGBS)

It is a by-product of the cooling of molten iron slag in the iron and steel industry. Iron manufacture involves the use of raw materials including iron ore and limestone charged to furnaces operating at 1300–1600 °C. The iron ore is reduced to iron and the remaining substances are mixed to form the molten slag which floats on the iron surface. This slag is removed from the iron continuously and subjected to high-pressurized water for cooling and forming the granulated slag. The resulting slag has a shape similar to coarse sand which is then grounded to produce the GGBS. Each ton of iron provides 250–300 kg of GGBS (Sekhar et al. 2017; Kioumarsi et al. 2023). The chemical composition of the GGBS employed in this investigation is displayed in Table 2. A pH of 8.5 indicates that GGBS is alkaline. The GGBS includes different amounts of silica, lime, and alumina, presenting similar constituents to cement. It is rich in lime and silica, making about 77.8% of total oxides. It has higher levels of SiO_2 and Al_2O_3 compared to CKD. Hanson Heidelberg Cement Institution in England, the United Kingdom, provided the GGBS. Shimadzu EDX-720 Energy Dispersive X-ray Fluorescence Spectrometer (EDXRF) was used to analyse the elemental composition of GGBS.

Table 1 Characteristics of the tested soil

Property	Results
Natural water content, %	37.5
Liquid limit, LL, %	39.5
Plastic limit, PL, %	19.56
Plasticity index, PI, %	19.94
Specific gravity (SG)	2.67
pH	7.78
Optimum moisture content (OMC), %	20.7
Maximum dry density (MDD), g/cm^3	1.62
California bearing ratio (CBR) %	4.24
Unconfined compressive strength (UCS), kN/m^2	195
Silt, %	75.03
Clay, %	12.9
Sand, %	12.07
Unified soil classification system (USCS)	CL-ML

2.3 Cement Kiln Dust (CKD)

It is a by-product of the cement industry produced from the calcining process in the kiln of cement manufacturing. During the heating of the raw materials of the cement to 1400–1650 °C for the production of clinker, particles of dust are produced. Then, this dust is transferred with other gases to the top of the kiln. Then, gases are cooled to collect the dust through a collection system. The chemical composition of the CKD utilized in this investigation is displayed in Table 2. The chemical composition of CKD is similar to that of cement though with high amounts of sulfate and chloride (Hakkomaz et al. 2022; Sargent 2015a). CKD has significantly higher levels of CaO, K_2O and SO_3 compared to GGBS and contains Fe2O3, which is not present in

Table 2 Chemical composition of GGBS and CKD

Material	pH	SiO%	CaO%	Fe_2O_3%	Al_2O_3%	K_2O%	MgO%	TiO_2%	SO_3%
GGBS	8.5	37.73	40.13	0.01	5.75	0.61	4.26	0.65	0.0
CKD	12.75	12.5	51.0	2.5	3.5	5.5	0.5	0.0	4.0

GGBS. A pH of 12.75 indicates that CKD is highly alkaline. The CEMEX Ltd. institution in Warwickshire, UK, provided the CKD. Shimadzu EDX-720 Energy Dispersive X-ray Fluorescence Spectrometer (EDXRF) was used to analyze the elemental composition of GGBS.

3 Laboratory Work

3.1 Experimental Design

It has been reported in various studies that activated GGBS binder was found or taken the optimum GGBS binder to 10% or lower (Sargent 2015b; Ouf 2001; Higgins 2006). Also, Yadu and Tripathi (2013) reported optimum strength at a 9% binder of GGBS on a similar soil to the one used in this study. Thus, a 9% fixed binder was adopted in this study. Different binary activated binders were made by replacing the 9% binder of GGBS with CKD in 0%, 25%, 50%, 75%, and 100%. Unary binders of GGBS and CKD were prepared for comparison purposes. The replacement levels were considered adequate for good coverage for investigation and evaluation purposes per Kaliannan et al. (2017), who used a similar replacement in their work on mixtures made from GGBS and cement.

Table 3 shows the designations, mix proportions of the binders, and the conducted tests. Figure 1

Table 3 Designations, mix proportions, and conducted tests of the selected binders

Binders	Designations	CBR			UCS			SEM			EDX
		Curing period (days)									
		0	7	Soaking, 7	0	7	28	0	7	28	7
Untreated soil	US	#		#	#			#			
Unary binder, 100% GGBS	GG		#	#		#	#		#	#	
Binary binder, 75% GGBS + 25% CKD	75GG25CK		#	#		#	#				
Binary binder, 50% GGBS + 50% CKD	50GG50CK		#	#		#	#				
Binary binder, 25% GGBS + 75% CKD	25GG75CK		#	#		#	#		#	#	#
Unary binder, 100% CKD	CK		#	#		#	#		#	#	

Note: Atterberg limits and compaction parameters tests were conducted for all binders separately

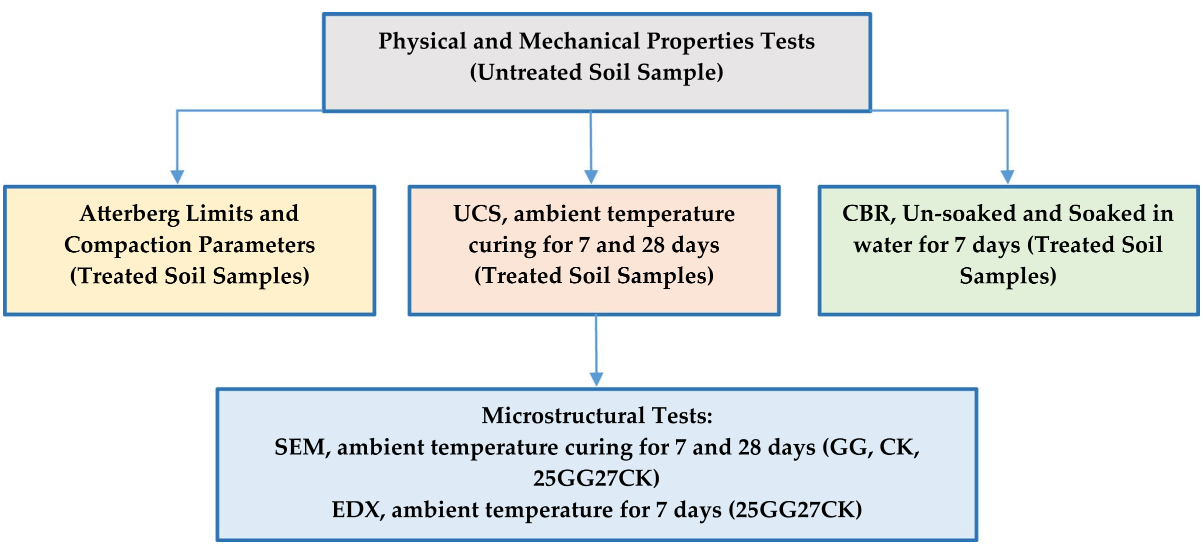


Fig. 1 A schematic diagram of the adopted methodology

shows a schematic diagram of the adopted methodology. The symbols GG and CK represented GGBS and CKD, respectively, so these were adopted for the unary binders. For the binary binders, the number before the symbol represented the content of material. For example, 75GG25CK designated the use of 75% GGBS and 25% CKD. The curing of samples was carried out for 7 and 28 days for UCS and SEM to indicate the development of cementitious products and structural changes in the soil. While CBR samples were subjected to dry and soaked curing for 7 days. All binders were tested for Atterberg Limits and Compaction parameters while SEM/EDX were conducted on US, GG, CK, and 25GG27CK.

3.2 Laboratory Tests

The performed laboratory tests for investigating the physical and mechanical properties of the stabilized soil were as follows:

3.2.1 Atterberg Limits

These included Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI). All tests were conducted following the procedure given in the BS 1377-2:2022 (Standard 2022). The test was replicated 3 times for each binder, and the average results were taken.

3.2.2 Standard Proctor Compaction

It was performed following the procedure given in the BS 1377-4:1990 (Standard 2002a). In summary, five different water contents were combined with two kilogrammes of dried powdered untreated or treated soil. The soil was split into three layers for each water content, and each layer was compacted with a 2.5 kg rammer inside a conventional mould using 25 blows. The purpose of the test was to determine Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) for the untreated and treated soil samples. The test was replicated 3 times for each binder, and the average results were taken.

3.2.3 California Bearing Ratio (CBR)

This test was performed following the procedure given in the BS 1377-4:1990 (Standard 2002a). The test provides a bearing strength value of compacted soil with the strength of crushed rock. It involves measuring the loads required for penetrating the plunger of 19.35 cm^2 in the area into a soil sample at a given penetration rate. Initially, 5 kg of dried powdered soil was mixed with their respective OMC from the proctor test. Then, the soil was divided into three layers and each layer was compacted with a 2.5 kg rammer with 25 blows inside a standard mold. The curing was carried out within the molds after using cling film to wrap the samples and storing them in well-sealed plastic bags. The specimens were allowed to dry cure for 7 days at room temperature (20 ± 2 °C). In the meantime, additional soil samples were equipped with a 4.52 kg surcharge load to simulate the field pavement load and soaked for 7 days in soaking tanks after a filter paper was placed on top of the sample. Samples were soaked and then drained for fifteen minutes. Following drying, curing, or soaking, the samples were tested by passing them through the CBR test at a rate of 1.27 mm/min. For every 0.25 mm, the penetration load was measured. The penetration loads at 2.5 mm and 5 mm were proportioned to standard values of 13.2 kN and 20 kN, respectively, to obtain the CBR values. The test was replicated 3 times for each binder, and the average results were taken.

3.2.4 Unconfined Compressive Strength (UCS)

The UCS of soil represents a crucial feature in designing engineering structures such as embankments, slopes, and foundations. The test was carried out following the procedure in the BS 1377-7:1990 (Standard 2002b). A motorized and computerized tri-axial machine was used with no lateral load application in the tri-axial cell (Holtz et al. 1981). Briefly, the samples were inserted into the tri-axial machine after the machine was set to zero deformation and the upper plate was adjusted to make contact with the sample. A continuous strain of 1%/min was applied during testing. The loads were monitored until the strain increased and they either decreased or stayed constant. At this point, the samples were considered a failure. The test was replicated 3 times for each binder, and the average results were considered.

3.2.5 *Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Analyzer (EDX)*

This test is used to provide insight into the soil surfaces at a microscope level. In this study, FEI Quanta 200 SEM was used. Specimens were prepared according to the BS 1377-7:1990 (Standard 2002b) of the UCS test. After being properly sealed in plastic bags, the specimens were allowed to dry cure for seven and twenty-eight days at room temperature (20 ± 2 °C). After curing, pieces from the specimens were taken by finger pressure and after trimming, these were subjected to drying in the oven for 24 h at 40 °C. While handling, care was ensured to minimize surface disturbance of the pieces. Then, the dried pieces were placed on top of the aluminum stud with carbon tape and coated with gold for adequate conductivity. Finally, these coated samples were placed inside the SEM machine for observation by different magnifications. This is a common procedure for the SEM test. An Energy Dispersive X-ray Analyzer (EDX) was also used to provide quantitative compositional information of activated binder paste after dry curing for 7 days at a room temperature of (20 ± 2 °C).

4 Results and Discussions

4.1 Atterberg Limits

The Atterberg Limits values of stabilized and untreated soil samples using different GGBS and CKD binders are displayed in Fig. 2. The use of unary GGBS binder slightly reduced the LL, PL, and PI of the soil. The LL was reduced by 1.6 while the PL and PI were reduced by 0.66 and 0.94, respectively. However, the use of activated binders showed the opposite trend. The increase in the amount of GGBS replacement noticeably increased the LL and PL though significantly reduced the plasticity of the soil. However, this impact was slightly increased by increasing the CKD content between the activated binders. The greatest impact on the soil was from the replacement of GGBS with 75% CKD. For this binder, the LL

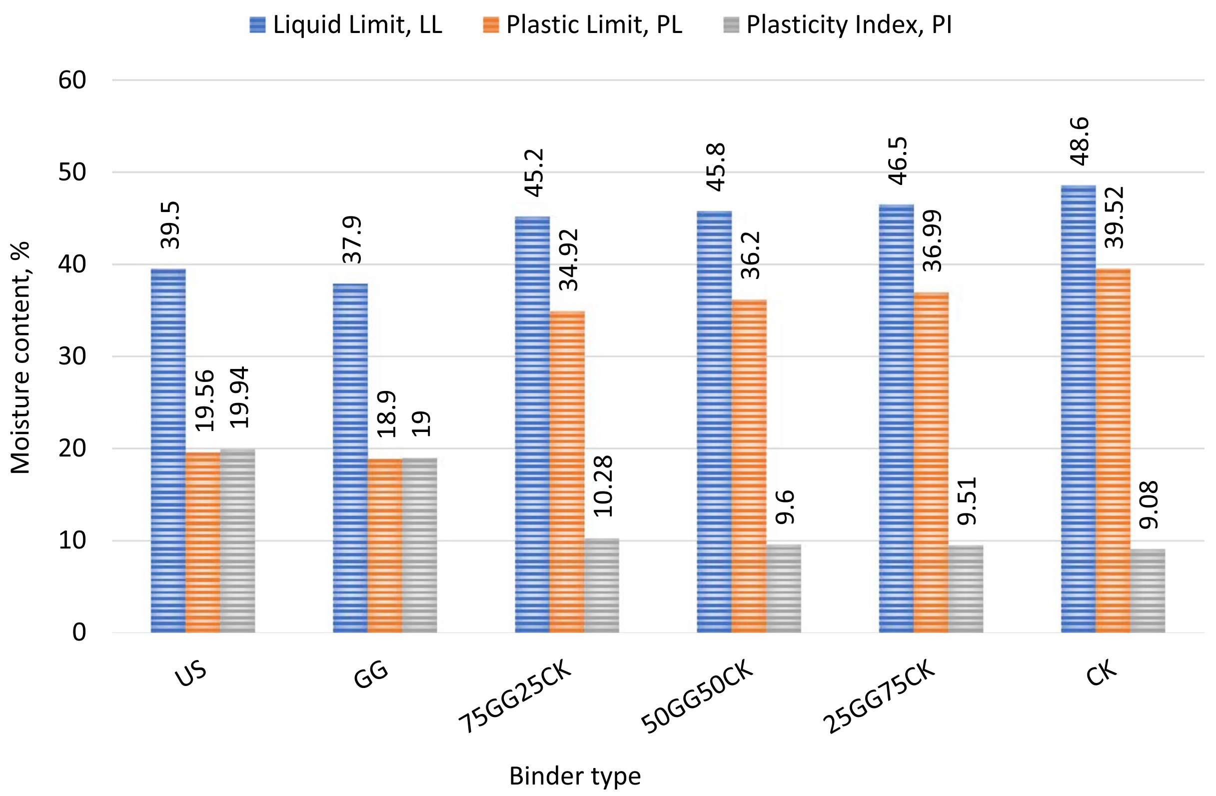


Fig. 2 Impact of binders on the Atterberg limits of the tested soil

and PL increased by 7 and 17.43, respectively while the PI reduced by 10.43. As the activated binder, the unary CKD binder had the biggest effect, raising the LL and PL and decreasing the PI. The LL and PL increased by 9.1 and 19.96, respectively while the PI reduced by 10.86.

The influence of GGBS content on the Atterberg limits was attributed to increasing the fines from the addition of GGBS, which led to reducing the affinity to water (Yadu and Tripathi 2013; Padmaraj 2017). The impact of activation agreed with Wild et al. (1996) and Ouf (2001) as they used lime for the activation of GGBS and reported a reduction in the plasticity of clay soil that increased with the increase in the activator content. The trend was due to the incorporation of a very fine material, i.e. CKD, that increases the affinity to water. CKD contains a high amount of lime, as indicated in Table 2, which increased with the increase in the CKD content in the binder. The lime can dissolve in water, and this is very important since it determines the required quantity of water to disassociate Ca^{+2} for cation exchange (Ogila and Eldamarawy 2022; Iorliam 2012). Though GGBS has a high CaO, its water affinity is low because its CaO is hydraulically latent. Thus, CKD was the dominant for the trend of the impact of the activated binders. CKD results agreed with Iorliam (2012) and Taha et al. (2001), which can be explained in light of the aforementioned information.

4.2 Compaction Parameters

The compaction values of untreated and stabilized soil samples with different GGBS and CKD binders are displayed in Figs. 3 and 4. The soil OMC was lowered by 0.2 and its MDD was marginally raised by 0.01 when unary GGBS binder was used. On the other hand, the tendency with activated binders was the opposite. The soil MDD was significantly decreased and its OMC was significantly raised when the quantity of GGBS replacement was increased. Nevertheless, by raising the CKD content between the active binders, this effect was somewhat amplified. The greatest impact on the soil was from the replacement of GGBS with 75% CKD. For this binder, the MDD reduced by 0.027, while the OMC increased by 2.7. Unary CKD binder showed the maximum impact, reducing the MDD of the soil by 0.036 and increasing the OMC of the soil by 4%.

Padmaraj (2017) and Yadu and Tripathi (2013) reported that the GGBS's high specific gravity (2.89) allowed it to fill in the holes in the soil, raising the MDD [50]. In the meantime, using GGBS reduces the quantity of loose silt and clay in the soil, which lowers surface area and hence the amount of water needed (Yadu and Tripathi 2013). The same trend of activated binders was reported by Ouf (2001) and Swamy et al. (2015), who used lime for the activation of GGBS binders. The MDD dropped as the amount of activator in the mix rose due to the flocculating soil

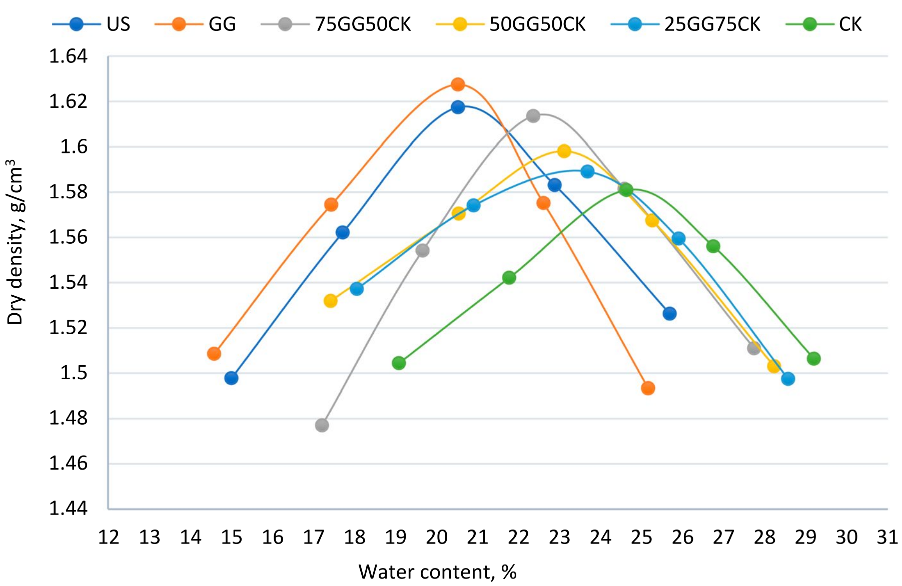


Fig. 3 Impact of binders on the compaction parameters of the tested soil

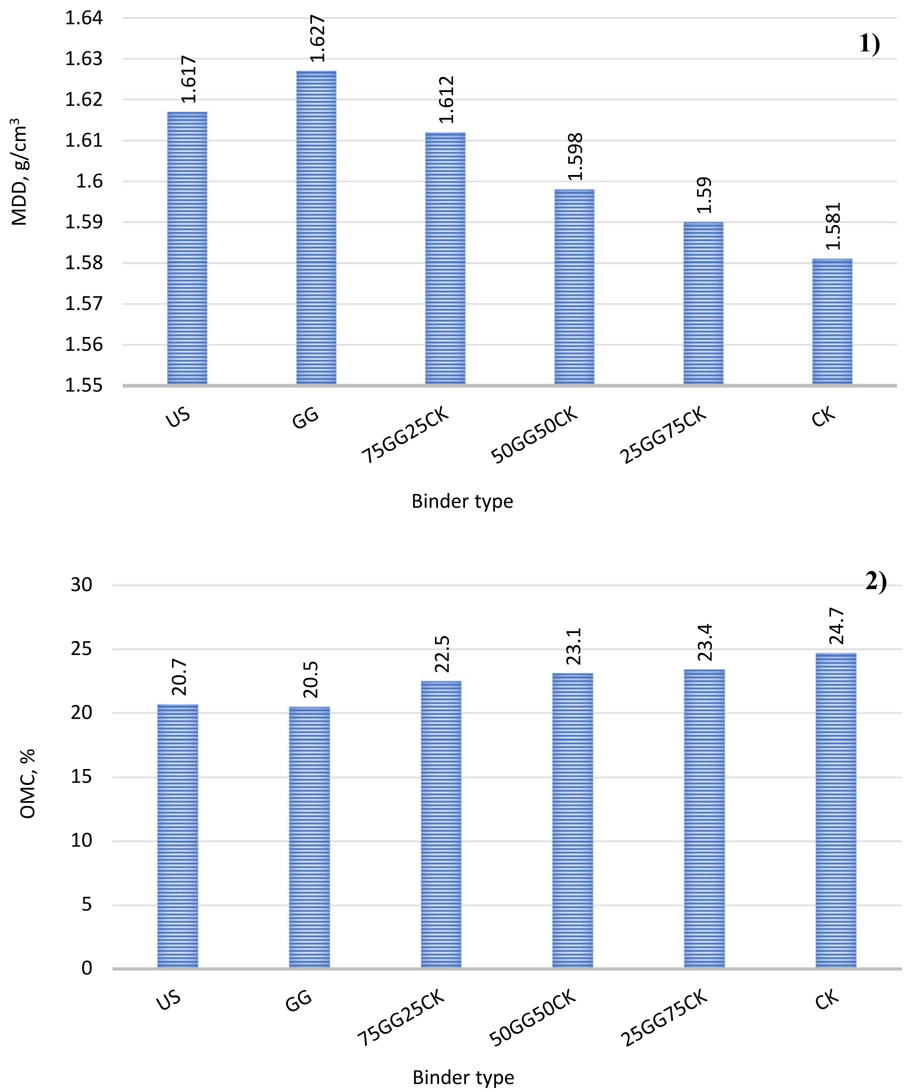


Fig. 4 Impact of binders on the compaction parameters **1** MDD, and **2** OMC of the tested soil

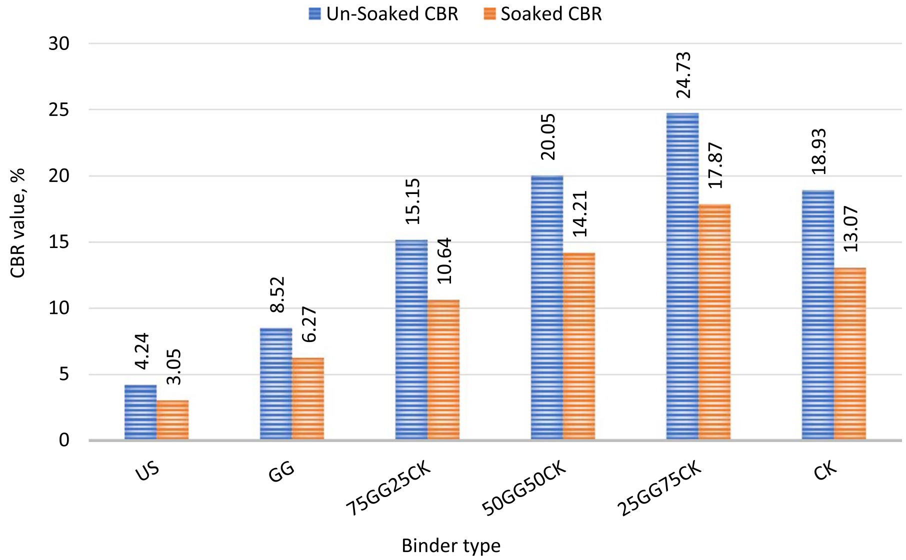
particles, which increased the size of the clay particles and introduced more voids. The large amount of water needed to attain optimum compaction was the cause of the OMC increase. The same trend of the unary CKD binder was reported by Sharifi Teshnizi et al. (2022) and Al-Homidy et al. (2017). As explained by Al-Homidy et al. (2017), CKD is a very fine material that increases the fines when added to the soil. This increased the surface area and demanded high quantities of water. Meanwhile, the CKD immediately reacted with the soil leading to agglomeration and flocculation of the soil particles and thus, increasing the voids within the soil and reducing its density.

4.3 California Bearing Ratio (CBR)

The soaked and un-soaked CBR results of the untreated soil and stabilized soil using different GGBS and CKD binders are displayed in Fig. 5. According to the classification provided by Holtz et al. (1981), the soaked and un-soaked CBR values of the untreated soil were 3.05% and 4.24%, respectively, classifying the soil as very poor and poor to fair subgrade. As a result, the soil needed to be treated because it was completely inappropriate to utilize in the pavement's subgrade layer.

For the binders, the soaked and un-soaked CBR values showed the same pattern. The differences between the values of soaked and un-soaked

Fig. 5 Impact of binders on the CBR values of the tested soil



CBR were about 28%, 27.5%, 26.1%, 26%, 25.3%, and 26.4% for US, GG, 75GG25CK, 50GG50CK, 75GG25CK, and CK binders, respectively. The variation is reduced by the use of unary and activated binders. A noticeable reduction occurred for the 25GG75CK binder.

With the use of a unary GGBS binder, the soaked and un-soaked CBR values increased to 6.27% and 8.52% by about two times the untreated soil. Such impact was also reported by Naidu (2012), who attributed the results to the amount of silica, alumina, and lime that produce hydration products.

Activated binders, on the other hand, substantially improved the soil soaked and unsoaked CBR. Only 25% of CKD activation of the GGBS resulted in CBR values that were twice as high as those of the untreated and unary binder stabilized soils, respectively. The improvement in the CBR value increased as the amount of CKD activator in the binder increased and this was attributed to the insufficient amount of activator for activating all the GGBS in the binder (Konsta-Gdoutos and Shah 2003; Nidzam and Kinuthia 2010). The highest CBR increase was produced by the activated binder 25GG75CK, which yielded a 6 times CBR value than the untreated soil. Pai and Patel (2018) compared soil-lime- GGBS mixtures to soil-GGBS mixtures and reported substantial improvement of CBR after 7 days of curing for the soil-lime- GGBS mixtures than for the soil-GGBS mixtures. Chaunsali and Peethamparan (2011) also found the optimum mixture as 25%G/70%C when studying the compressive strength of the activated GGBS/CKD binder in concrete. The bearing strength development with the use of unary GGBS-CKD can be attributed to the formation of hydration products. In comparison to the 50GG50CK binder, the unary CKD binder produced a CBR value that was almost 1% lower. As explained by Mosa et al. (2017), the creation of cementitious compounds from the interactions of CKD with soil can be linked to the strength growth by the usage of unary CKD binder after 7 days of curing or soaking.

4.4 Unconfined Compressive Strength (UCS)

The UCS results for the untreated soil and the stabilized soil using different GGBS and CKD binders are displayed in Fig. 6. The UCS increased by 2.3 times when a unary GGBS binder was used though slightly developed at later ages. Such impact was also reported by Padmaraj (2017) and Ouf (2001).

However, the use of activated binders significantly increased the UCS of the soil, particularly at later ages. The activation of the GGBS by only 25% of CKD provided UCS values higher by 3 and 3.7 times than untreated soil at 7 and 8 days of curing, respectively. With the increase in the CKD activator in the binder, the improvement in the UCS increased. The highest improvement was produced by the activation of 25% GGBS with 75% of CKD. After 7 and 8 days

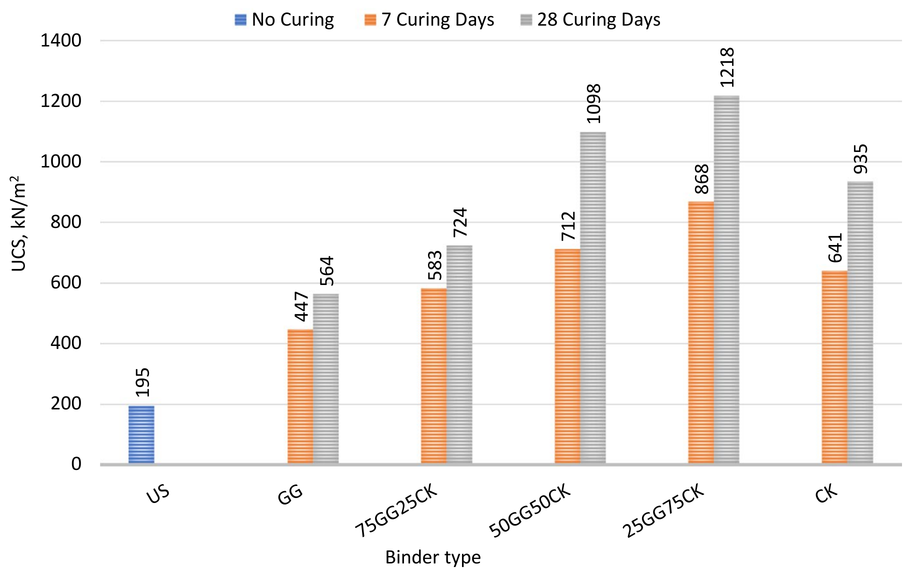


Fig. 6 Impact of binders on the UCS values of the tested soil

of curing, this binder produced 4.5 and 6.3 times higher UCS than the untreated soil, respectively. The maximal strength gain was similarly found by Konsta-Gdoutos and Shah (2003) when producing mortar from 25% GGBS to 75% CKD. Furthermore, a significant increase in the UCS of soft soil stabilized with GGBS-lime activated binder was documented by Pai and Patel (2018). The strength development was attributed to the formation of the C-S-H product and continuous hydration.

The unary CKD developed strength more slowly than the 25GG75CK binder, particularly after 28 days, which could be attributed to the presence of more $Ca(OH)_2$ than was necessary for the pozzolanic reaction. The matrix is weakened by the remaining unreacted $Ca(OH)_2$ as explained by Al-hassani et al. (2015).

Finally, as 25GG75CK binder provided the greatest impact in terms of all performed tests, it represents the optimum binder and was analyzed in the SEM test.

4.5 Scanning Electron Microscopy (SEM)

4.5.1 SEM–EDX

Figure 7 shows the EDX analysis results of various spectrums of the optimum binder paste. It can be seen the presence of C, O and Ca, Si, and Al and traces of K, S, Mg, and Fe. The calcium content of the C-S-H gel is indicative of the stability and density of the cementitious product, according to Sadique and Al-Nageim (2012). The findings show that the Ca concentration was high, leading to a stable C-S-H gel. There was enough dissolution of the raw materials to generate the high Ca content of the gelling products. In a different area of the spectrum, the binder contained less calcium and more silica and alumina, suggesting a higher activation of GGBS and, thus, a development in strength. This provides further evidence of the continuing C-S-H gel formation. Aluminum is present in the EDS data, indicating the possibility of the creation of needle-like ettringate.

The strength development with the use of unary GGBS or CKD can be related to the existence of cementitious compounds in the materials that contribute to forming hydration products. Nevertheless, because of its low pH of 8.5, GGBS has a glassy structure with little hydration. Naidu (2012) found that the C-S-H gel developed slightly at pH values below 9.5. The CKD initially dissolved in water with the help of an activator, producing SO_4, K^{+1}, Ca^{+2}, and OH^- ions. The Ca^{+2} ions are involved in the ion exchange reaction with the particles of clay, in which the particles of the clay dispersed and flocculated to form strong agglomerations that reduce the layer of water between the particles of clay and thereby reduce the soil plasticity. CKD and GGBS hydration reaction involved the free lime reaction, and alkali and sulfate activations. The alkali activation was produced from arcanite (K_2SO_4) which provides the CKD with high alkalinity and was responsible for providing the suitable conditions for the activation of the GGBS, the breakage of its impermeable layers, and the initiation of the reactions (Konsta-Gdoutos and Shah 2003). The OH^- ion of the CKD reaction attacks the impermeable layer of the GGBS due to the increased pH level, leading to the breaking of the bond between the lime, alumina, and silica. These dissolved ions experienced polymerization with the GGBS active surfaces, producing alkali-aluminosilicate gel. Meanwhile, the dissolved substances undergo condensation and solidification to form C-A-H and C-S-H gels (Chaunsali and Peethamparan 2011). Sulfate activation, on the other hand, occurred at the early stages of hydration due to alkali sulfate (k_2SO_4), from which the SO^{-2} ions reacted with the aluminosilicate of the GGBS, producing aluminsulfate which in turn reacted with the Ca^{+2} ions from the CKD to produce ettringite. According to El-Didamony et al. (1997), the formula of the ettringite is $(Ca_6Al_2(SO_4)_3(OH)_{12.26}(H_2O)$, which contributed to the strength development.

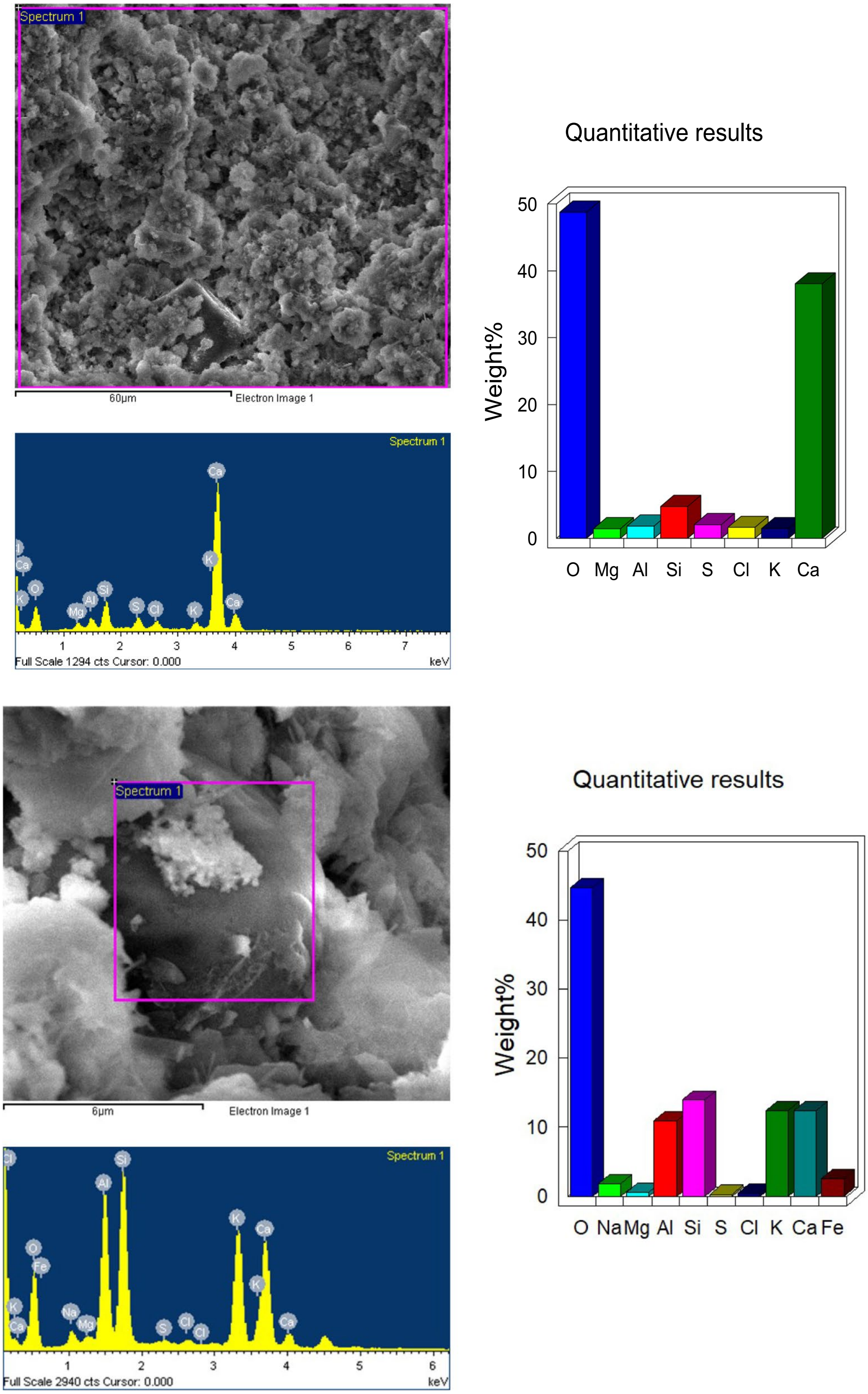
4.5.2 SEM Monograph

SEM imaging testing has been used increasingly frequently in cement and soil stabilization studies; particularly where microstructural investigation is required. An understanding of the evolution of the treated material's geotechnical properties is made easier by these high-resolution micrograph pictures, which also help detect how the microstructure evolves during the curing process (Jha and Sivapullaiah 2016). The SEM image of untreated soil is displayed in Fig. 8. The image indicated a discontinuous structure with visible voids as a result of the lack of hydration products. Dark grey-coloured silty particles were dominant with edge to face or edge to edge contacts. Between the silt particles, clay particles have appeared with army arrangements. The image also revealed the presence of small white particles of clay particles reported by Sargent (2015b) as Illite clay platelets. These were either lying between the silt particles or coating their surfaces. The surfaces of the silts and clays were relatively well-defined and clean without physical bonding which assisted in the proper identification of the microstructural changes upon stabilization.

The SEM images of stabilized soil with a unary GGBS binder at 7 and 28 days of cure are displayed in Fig. 9. At early curing, the structure showed signs of compactness and flocculation along with a considerable number of $Ca(OH)_2$ crystals, or CH, and some C-S-H gel formation. This resulted from the GGBS lime reaction with water since the GGBS characteristics caused the silica and alumina in the soil to dissolve primarily. Thus, the CH was responsible for the improvement of strength at the early stages. At late curing (28 days), a reaction of the silica and alumina with the CH occurred leading to the formation of the C-S-H. This was expected to further enhance the bearing capacity of the stabilized soil. The surfaces were more compacted though large porous were presented and the amount of the hydration products was not adequate to cover the whole soil. It was demonstrated that the C-S-H and CH phases provide crucial cementitious binding and cohesive properties (Dulaimi et al. 2020, 2016).

The SEM images of the stabilized soil with the unary CKD binder at 7 and 28 curing days are displayed in Fig. 10. Early curing resulted in the development of C-S-H gel and small amounts of ettringite that coated the clays and silts in the stabilized soil' micrograph, which revealed a more compacted structure than the untreated soil. However, the image revealed the presence of voids though with a relatively lower amount than the untreated soil. At late curing, significant formation of C-S-H gel interlocked by ettringite was shown. These provide a very dense structure of the soil and are expected to increase their strength at later ages.

The SEM images of the treated soil with the activated optimal binary 25GG75CK binder at 7 and 28 days of curing are displayed in Fig. 11. At early curing, the image indicated highly compacted densely packed with very small pores structure. The C-S-H gel was shown in considerable amounts with some needle-like ettringite. At later ages, the micrograph showed the soil with relatively no voids and was very rich with C-S-H gel with high growth of needle-like ettringite. This indicated the significant development of strength at curing ages. Furthermore, the surface of the soil was entirely covered by the hydration products, which also thickened the stabilized soil's microstructure. Similar findings from earlier research on the stability of clayey soils with additions based on calcium were found in (Sharma et al.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◂**Fig. 7** EDX results of optimum binary 25GG75CK binder paste at 7 days of curing

2018; Latifi et al. 2018). Furthermore, The capacity of clay to regulate pore space and form inter-cluster bonds were two advantages of continuous hydration product growth. This enhanced the strength of the clay by reducing the volume of pores smaller than 0.1 (Horpibulsuk et al. 2010).

5 Conclusions

To stabilize weak subgrades, the goal of this research is to create a novel binary activated binder from GGBS and CKD. The following conclusions were made in light of the outcomes:

1. The Atterberg limits and compaction characteristics of treated soil were modified by an activated binder composed of GGBS and CKD. The impact increased as the amount of CKD in the binder increased. The binders significantly raised the soil LL, PL, and OMC and significantly decreased its PI and MDD. The binary binder of 25% GGBS and 75% CKD provided the optimum impact, reducing PI by about 10%. Unary CKD binder shows the same trend while unary GGBS binder provided the opposite with a slight reduction in the PI of the soil.
2. The research showed that GGBS activation significantly improves both socked and un-socked CBR values and that the benefit grows as the CKD content increases. Specifically, the results show that the use of a 75% CKD and 25% GGBS binder provided a remarkably 6 times higher CBR value (soaked and un-soaked) than untreated soil after only 7 days of curing or soaking. These results offer a sustainable and affordable substitute for conventional binder materials, which has important implications for the building sector. This binder provided strength significantly higher than unary GGBS or CKD binders.
3. The UCS was developed substantially by the use of activated binders and curing age. The impact increased as the amount of CKD in the binder increased. After 7 and 28 days of curing, the binder composed of 25% GGBS and 75% CKD produced 4.5 and 6.3 times the UCS of the untreated soil, respectively. This strength development was significantly higher than unary GGBS or CKD binders.
4. EDX analysis results of 25% GGBS and 75% CKD paste revealed the presence of significant amounts of calcium and oxygen and variable amounts of several materials that contribute to the hydration products.
5. SEM micrographs clearly illustrate the transformation of the soil structure to highly compacted surfaces with little voids and the significant formation of C-S-H gel, indicating the successful activation of the by-product materials in the binder mixture. Additionally, the presence of ettringite further supports the effectiveness of the 25% GGBS and 75% CKD binder treatment in enhancing the mechanical properties of the soil. To summarize, given the aforementioned results and conclusions, the activated binder from 25% GGBS and 75% CKD was selected as the optimum giving superior performance.

6 Limitations

Two main constraints limited the scope of the study, i.e. time and the availability of materials. These prevent carrying out the CBR test at 28 curing days and conducting other tests or the initial GGBS optimization stage.

6.1 Recommendations for Future Work

The following are suggested for further investigations:

1. Carrying out the initial GGBS optimization stage, and the CBR test at 28 curing days.
2. Carrying out other tests including durability test, swelling index, resilient modulus, and XRD for a thorough investigation.
3. Other types of soils could be investigated such as peat or expansive soil.

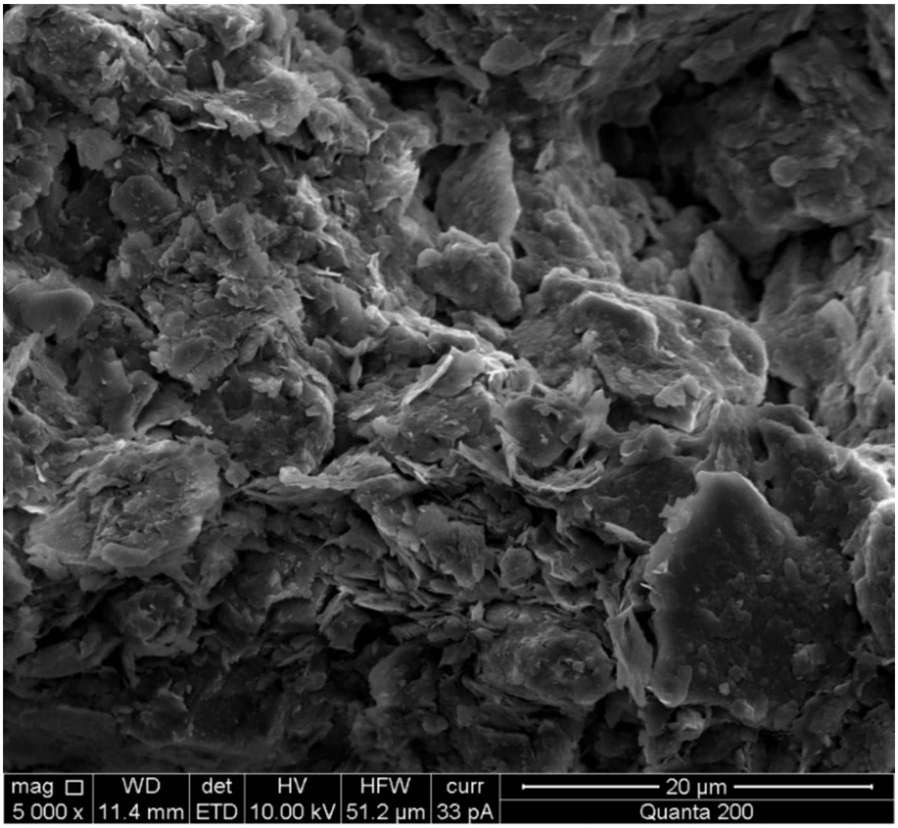

Fig. 8 SEM image of untreated soil

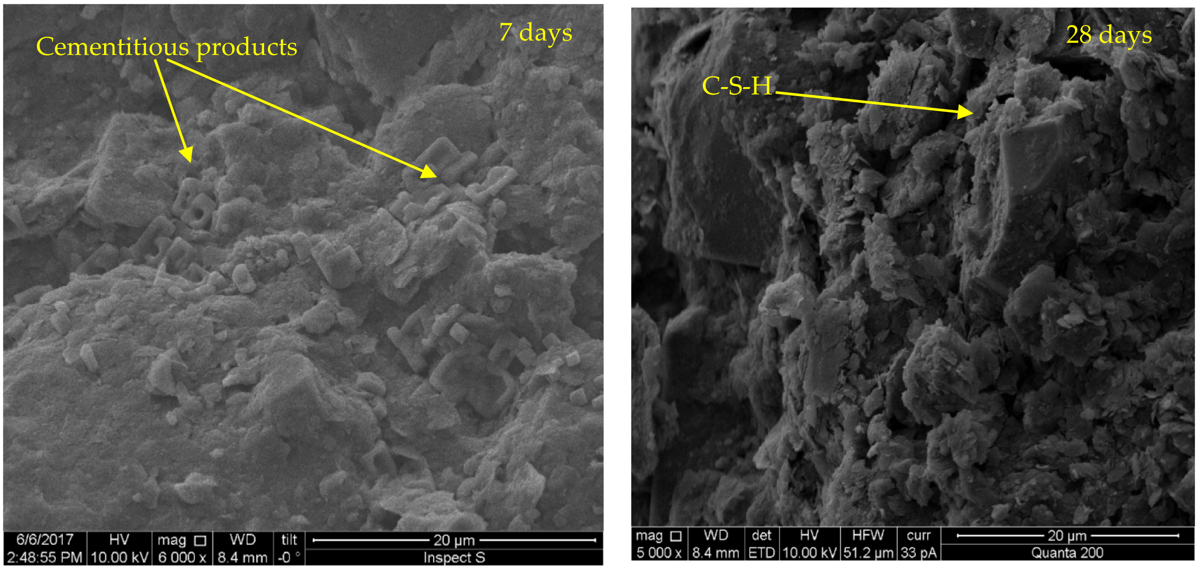

Fig. 9 SEM image of treated soil with unary GGBS binder at **1** 7 days, and **2** 28 days of curing

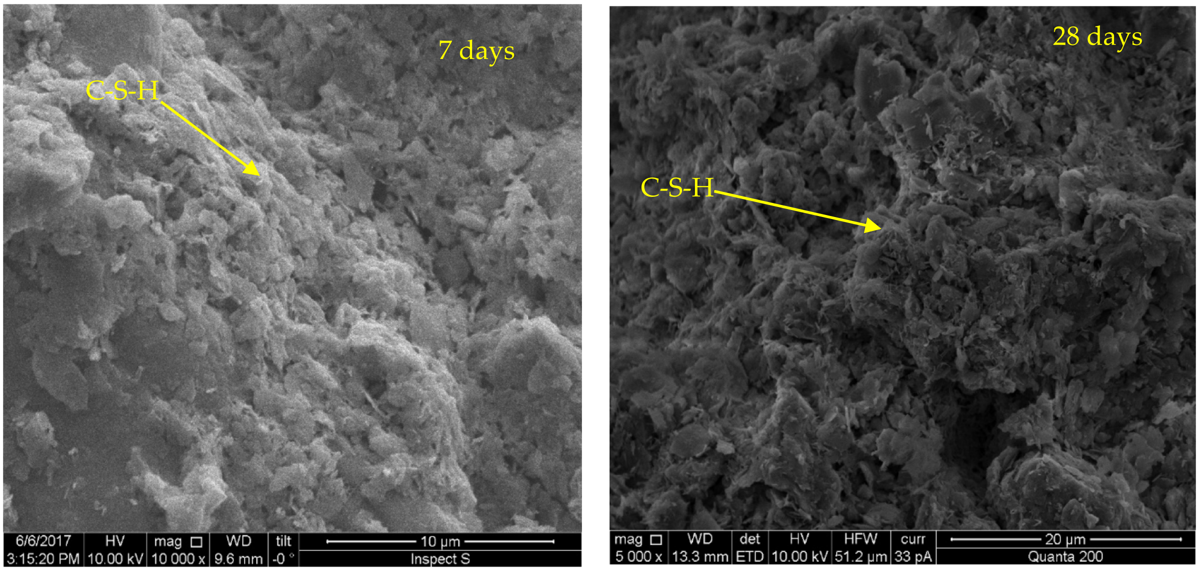

Fig. 10 SEM image of treated soil with unary CKD binder at **1** 7 days, and **2** 28 days of curing

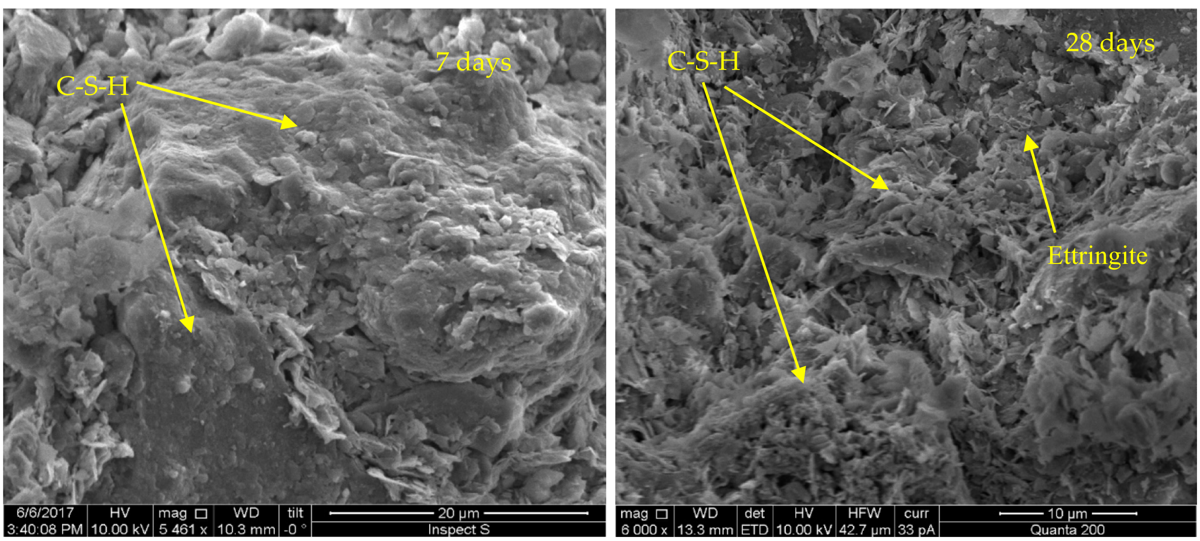

Fig. 11 SEM image of treated soil with activated optimum binary 25GG75CK binder at **1** 7 days, and **2** 28 days of curing

4. Another approach can include the addition of CKD to the GGBS by the dry soil weight rather than replacement.
5. Since the study shows the potential of using the GGBS and CKD binder, it is vital to evaluate and quantify the environmental benefits with the application and feasibility costs.

Acknowledgements The financial support of Kerbala and Babylon Universities in Iraq is gratefully acknowledged.

Author Contributions Conceptualization, Z.J. and A.D.; methodology, Z.J., A.D., H.J.; software, Z.J. and A.D.; validation, Z.J., A.D., M.Z.O.M.; formal analysis, H.J., Z.J. and A.D.; investigation, Z.J, R.Al-K.; resources, Z.J., L.F.A.B., and A.D.; data curation, Z.J., R.Al-K., A.D., and H.J.; writing—original draft preparation, Z.J., H.J., M.Z.O.M., L.F.A.B., and A.D.; writing—review and editing, Z.J., H.J., M.Z.O.M., R.Al-K., L.F.A.B., and A.D visualization, A.D.; supervision, A.D., H.J.; project administration, A.D., and H.J.; All authors have read and agreed to the published version of the manuscript.

Funding The authors have not disclosed any funding.

Data Availability Enquiries about data availability should be directed to the authors.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethics Approval The manuscript has been prepared by the contribution of all authors, it is the original authors' work, it has not been published before. The paper is not currently being considered for publication elsewhere.

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