Arabian Journal for Science and Engineering (2018) 43:5193–5202
https://doi.org/10.1007/s13369-017-3033-x

RESEARCH ARTICLE - CIVIL ENGINEERING

A Laboratory Investigation of Soil Stabilization Using Enzyme and Alkali-Activated Ground Granulated Blast-Furnace Slag

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Received: 31 May 2017 / Accepted: 21 December 2017 / Published online: 9 January 2018

Abstract
Development and use of non-traditional stabilizers such as enzyme and alkali-activated ground granulated blast-furnace slag (GGBS) for soil stabilization helps to reduce the cost and the detrimental effects on the environment. The objective of this study is to investigate the effectiveness of alkali-activated GGBS and enzyme as compared to ordinary Portland cement (OPC) on the soil collected from Tilda region of Chhattisgarh, India. Geopolymers are alkali alumino-silicates produced when combining a solid alumina-silicate with an aqueous alkali hydroxide or silicate solution. Various dosages of the selected stabilizers have been used and evaluated for the effects on optimum moisture content (OMC), maximum dry density, plasticity index, unconfined compressive strength (UCS) and shear strength parameters. Effect of curing period has also been studied. Microstructural changes of the stabilized soils show aggregation of particles. Significant improvement in properties of soil is observed with the addition of stabilizers leading to an increase in OMC, UCS and shear strength parameters. It is observed that the cohesion of soil sample increases significantly with the addition of stabilizers whereas there is a marginal change in angle of internal friction. Thus, the findings recommend the use of non-conventional stabilizer such as alkali-activated GGBS and enzyme as suitable and environmental friendly as compared to OPC for soil stabilization.

Keywords Soil stabilization · Alkali-activated GGBS · Enzyme · Shear strength parameters · Microstructural images

1 Introduction

Development and use of environment friendly materials which can offer improved performance compared to traditional materials in terms of cost and sustainability is a great challenge in the construction field. Desired soil properties such as shear strength, stiffness, stability, durability, soil plasticity and swelling/shrinkage potential can be achieved by preloading or stage construction, over excavation and replacement, geosynthetic reinforcement, soil improvement techniques etc. [1–5]. Constitutive model is developed capturing the effect of cementation degradation to predict the behaviour of cement-treated soil [6] and fibre-reinforced cement-treated soil [7].

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The clay surface generally has a negative charge, cations or positively charged ions get attracted to the surfaces of clay particles to maintain the electrical neutrality. The ability of a clay particle to adsorb ions on its surface or edges is called its cation exchange capacity and these cations are called exchangeable cations. When the cation charge in the clay structure is weak, the remaining negative charge attracts polarized water molecules by filling the spaces of the clay structure with ionized water which leads to increase in plasticity characteristics [8,9].

As explained by the researchers [10–12], the mechanism of traditional soil stabilizers consists of cation exchange, flocculation & agglomeration, cementatious hydration and pozzolanic reactions. The introduction of a binder to the soil releases calcium ions and replace the metal ions present within the clay lattice. The calcium silicates/aluminates of the binders react with water to form hydration products including calcium silicate hydrates and calcium aluminate hydrates as shown in Eqs. (1) and 2 [10–12].

$$C_3S + 6H \rightarrow C - S - H + 3Ca\,(OH)_2 \tag{1}$$

$$C_2S + 4H \rightarrow C - S - H + Ca\,(OH)_2 \tag{2}$$

where C_3S = tricalcium silicate, C_2S = dicalcium silicate, C = Ca, S = SiO_2 and H = H_2O.

Literature reveals that the manufacturing process of Portland cement results in huge amount of sulphur dioxide aerosol and CO_2 emissions, dust generation, high consumption of energy (around 5% of worldwide industrial energy) and resources (1 t of OPC production require 1.5 t of limestone and sand) which leads to climate change and global warming [4,10,13–16]. Hence, there is a need of research to identify more environmentally sustainable and cost-effective materials which can deliver either comparable or surpass the performance of traditional materials within similar curing period. The alkali activation of industrial by-product generates about 80–90% less carbon dioxide than OPC [15,16]. Soil stabilization using alkali activation to GGBS is more eco-friendly as well as improve the mechanical properties of stabilized soils. Thus, it can be considered a sustainable alternative to Portland cement [13].

Mechanism of alkali activation by geopolymerization is explained by the researchers [17–22]. Geopolymers are synthetic alkali alumino-silicates produced when combining a solid alumina-silicate (pozzolanic industrial by-product) with a highly concentrated aqueous alkali hydroxide or silicate solution [10,17,18]. Structural strength is obtained by the polycondensation of silica and alumina in the presence of alkali solution which leads to the formation of alkali alumino-silicate gel ($M_n[-(\mathrm{Si}-\mathrm{O}_2)_z-\mathrm{Al}-\mathrm{O}]_n \cdot w\mathrm{H_2O}$; where M is the alkaline element, z is 1, 2 or 3 and n is the degree of polycondensation) which is different from calcium silicate hydrate produced from the pozzolanic reactions [17,18]. High hydroxyl concentration dissolves the impermeable alumino-silicate coatings on the surface of slag grains leading to further hydration. These hydration products aid the improvement in properties [13,19–22]. It is observed that the hydration rate of alkali-activated GGBS depends on the pH [20].

UCS of lime-activated GGBS-stabilized clay after 90 days is reported 1.7 times more than that of the OPC-stabilized clay [23]. But researchers reported that lime does not give consistent improvement due to environmental impacts, poor early strength development, long setting time and insufficiently high pH values [10,15,19]. Metakaolin requires large volumes of water which increases the soil porosity and decreases its stiffness [10].

Formation of more hydrotalcite along with hydrated calcium silicate makes reactive magnesia (MgO) a more effective alkali activator of GGBS than hydrated lime [24]. Reactive MgO (10%)-activated GGBS yields 30% higher strength than that of $Ca(OH)_2$-activated GGBS after 28 days curing time [24]. Jin et al. [13] also reported that reactive MgO (2.5–20%) is an effective activator than hydrated lime in activating the GGBS based on UCS. Du et al. [25] reported that lightweight geopolymer-stabilized soil gives better engineering performances than lightweight cement-stabilized soil in terms of water absorption, permeability and strength characteristics. Du et al. [26] found that GGBS–MgO-stabilized kaolin clay displays higher dry density up to 7% than the cement-stabilized kaolin clay. MgO-activated GGBS accelerates the strength development rate of stabilized clay but excessive MgO with high reactivity has a negative effect on its strength performance [27].

Cristelo et al. [28] studied the effects of class F fly ash activated by NaOH (10, 12.5 and 15 molal) on soil stabilization which resulted in strength increase up to a maximum of 43.4 MPa with decreasing activator/ash ratio. UCS of the cement and alkali-activated samples were similar at 28 days curing. Sargent et al. [29] found that the effect of alkali activator (NaOH flakes and Na_2SiO_3 solution) with GGBS yielded greater strength and durability of silty sand than when used with pulverized fly ash or red gypsum. Yi et al. [15] found that GGBS activated by NaOH, Na_2CO_3 and Na_2SO_4 can accelerate the strength improvement in soft clay, but UCS was found decreasing after 90 days. Therefore, Na_2SO_4-Carbide slag-activated GGBS is concluded as the optimum binder for the marine soft clay, which yields UCS twice higher than that of cement-stabilized clay.

Bio-enzymatic stabilization of soil is proposed to be a low-cost alternative to traditional construction materials [30]. It contains protein molecules which react with soil molecules to form a cementing bond and thereby it reduces the soil's affinity for water [8]. Working mechanisms of liquid stabilizers reduce the double-layer thickness by the encapsulation of clay minerals, exchange of interlayer cations, breakdown of clay mineral with expulsion of water from the double layer or interlayer expansion with subsequent moisture entrapment, osmotic pressure gradient and surfactant mechanism [8,30,31].

The performance of liquid soil stabilizers was studied by various researchers [8,32–36]. The plasticity index, maximum dry unit weight and permeability of clayey sand decreased with increased dosage of the bio-enzyme which in turn led to an increase in California Bearing Ratio value, UCS and shear strength [33]. Ganapathy et al. [33] reported that 400 ml/m^3 of enzyme decreases plasticity index of the clayey sand by 11.2 % and increases UCS at 7 days by 30 %. The enzymatic lime develops higher strength improvement than enzyme and lime alone [36]. Gilazghi et al. [37] found that with increase in the dosage of polymer upto 13% linearly increased the strength of the stabilized sulphate-rich high plasticity clay.

Few studies showed that enzyme-treated soil do not yield significant improvement in compaction, Atterberg limits and strength tests [14,32]. Moloisane and Visser [38] investigated enzyme at a rate of 0.005 l/m^2 to the quartz gravel material for eight months. This resulted in a significant decrease in density, but showed a slight increase after 31 months of construction. Kestler [39] recommended the use of enzyme for soil having 12–24% of clay and plasticity index 8–35%.

This implies that limited studies are available on performance, test methods and reinforcement mechanisms of non-traditional additives [32,39]. Performance evaluation and effectiveness should be evaluated before its application [8,32,39]. Guidelines need to be developed based on the specific site conditions. Therefore, more research is required to understand the effects of the enzymes and alkali-activated GGBS for research, industry and commercial applications.

The development and use of non-traditional stabilizers can reduce the use of OPC in soil stabilization thereby reducing the cost and environment detrimental effects. In the study area, GGBS are available locally and its utilization will reduce environmental problems like waste disposal. Alkali activation of GGBS needs to be investigated for utilizing it to the maximum extent as an alternative to OPC. The characteristics of alkali-activated GGBS vary depending on the GGBS composition, activator type and their content which may affect the activation process.

Hence, this study presents the behaviour of soil stabilized with alkali-activated GGBS and enzyme. Various laboratory tests have been conducted on the unstabilized and stabilized soil samples for the selected dosages of stabilizers, and the results are compared with that of OPC-stabilized soil. Based on the experimental results, the optimum dosage of the stabilizers for the selected soil is obtained. However, the understanding and evolution of mechanism of the stabilized soil requires more detailed research to elucidate the activity of alkali-activated GGBS and enzyme play in the mixture.

Table 1 Properties of the soil and enzyme

Soil properties	
Liquid limit (LL%)	42.25
Plastic limit (PL%)	18.6
Plasticity index (PI%)	23.65
OMC (%)	13.5
MDD (kN/m^3)	17.2
Enzyme properties	
Boiling point	212 °F
Solubility in water	Infinite
Appearance	Lt. gold liquid
Specific gravity	1.05
pH	3

Table 2 Chemical composition of GGBS and OPC (weight %)

Element	OPC	GGBS
CaO	56.24	36.02
MgO	4.74	7.9
SiO_2	20.65	34.43
Al_2O_3	5.31	9.36
Fe_2O_3	3.7	0.94
Loss on ignition	1.78	0.1

2 Experimental Procedure

2.1 Materials and Test Methods

The soil sample was collected from Tilda, Chhattisgarh, India. The geotechnical characterization of the soil and enzyme properties is provided in Table 1. The chemical composition of GGBS and OPC obtained from Cement Plant at Bhilai is given in Table 2. Ground granulated blast-furnace slag (GGBS) activated by 1 molar (M) sodium hydroxide solution (NaOH), enzyme and OPC was used for the present study. Sodium hydroxide has greater capacity to liberate silicate and aluminate monomers [18].

Collected soil sample was dried and crushed with wooden mallet and sieved through 4.75 mm IS (Indian Standard) sieve. Dosages of GGBS were selected as 6, 9, 12, 15 and 20% of dry weight of soil, and dosages of OPC were selected as 3, 6, 9, 12 and 15% of dry weight of soil. Enzyme was added as 70, 100, 133, 400, 645 and 800 ml/m^3 of soil. The specimen for tests was prepared according to IS: 4332 (Part 1)-1967 (ASTM D 1632-96) [40,41] by mixing weighted dry soil with various dosages of stabilizers thoroughly until a uniform colour was observed. Various tests were performed in laboratory such as Atterberg limits [42,43], compaction characteristics [44,45], UCS [46,47] and triaxial tests [48,49]. Microstructural characterization was carried out using the scanning electron microscopy (SEM) method.

Soil specimens for UCS and triaxial tests were prepared in a standard compaction mould of 100 mm diameter and 127.3 mm height at designed water content by using modified Proctor compaction effort as per IS: 2720 (Part 8)-1985 (ASTM D1557-12) [44,45]. It is compacted into the mould in five layers, each with 25 blows and cylindrical samples of 38 mm (diameter) × 76 mm (height) was then extruded with assistance of a manual extruder. All the completely sealed specimens were stored in a humidity control chamber under controlled conditions at 95–100% relative humidity and at room temperature of 25 °C before tests were performed.

The unconsolidated-undrained triaxial tests were carried out to determine the shear strength parameters of the specimens as per the procedures recommended by IS: 2720 (Part 11)-1993 (ASTM D 2850-95) [48,49]. Specimens were tested under three different confining pressures of 50, 100 and 150 kPa.

3 Results

3.1 Atterberg Limits

Atterberg limits have been used in the literature as one of the important indicator to predict the clay behaviour. Tests were performed on the unstabilized and stabilized soils after 28 days. Figures 1, 2 and 3 present the results of liquid limit, plastic limit and plasticity index on soil samples stabilized with alkali-activated GGBS, enzyme and OPC, respectively. The plasticity index of the stabilized soil is decreased by 44, 13 and 45% by addition of GGBS (20%), enzyme (645 ml/m^3 of soil) and OPC (15%), respectively.

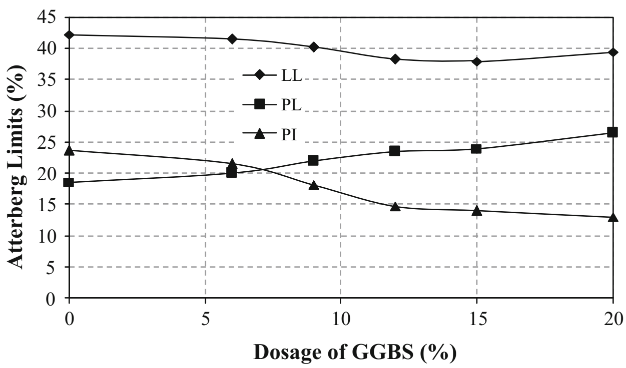


Fig. 1 Atterberg limits and PI with dosage of GGBS

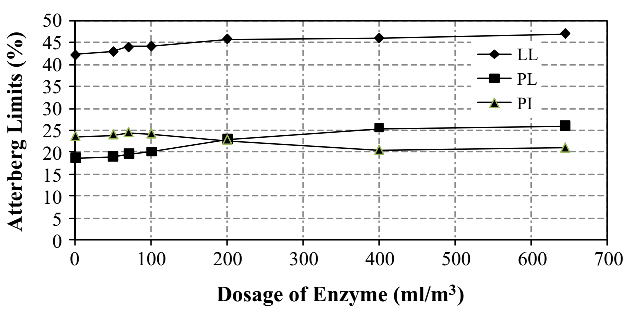


Fig. 2 Atterberg limits and PI with dosage of enzyme

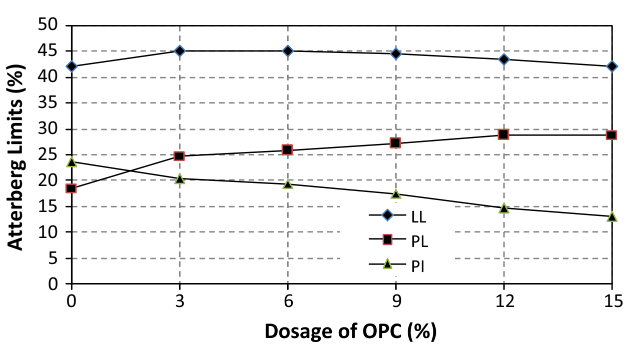


Fig. 3 Atterberg limits and PI with dosage of OPC

The liquid limit of the soil increases slightly for 3% addition of OPC and further it decreases, whereas the plastic limit of the OPC-treated soil increases with increasing dosage. The similar pattern was obtained by Asgari et al. [1].

The liquid limit decreases and plastic limit increases with increasing dosage of alkali-activated GGBS. However, the plasticity index decreases with increase in dosage of the stabilizer which leads to improvement in the behaviour of soil.

Ion concentration reduces repulsive forces between the clay particles, and this results in flocculation and decrease in water retention capacity [50]. The OPC and alkali-activated GGBS produces the hydration products which lead to a reduction in plasticity index.

The liquid and plastic limits of the enzyme-treated soil increases with increasing dosages. The decrease in PI is comparable and similar to the previous studies [33]. The reason behind the reduction in PI in enzyme-stabilized soil may be due to the enzyme making bond with organic molecules that are attracted to the clay mineral surface. It reduces the affinity of clay for moisture by neutralizing its negative charge [30,31]. The introduction of bio-enzyme weakens the bonding between adsorbed water molecules and clay particles which leads to a reduction in plasticity index of the soil [8,33].

3.2 Compaction Characteristics

Figures 4, 5 and 6 show the results of MDD and OMC on soil samples stabilized with alkali-activated GGBS, enzyme and OPC, respectively. The addition of the stabilizers to the soil decreases MDD and increases OMC for the same compactive effort. Similar trend is reported by Ganapathy et al. [33]. The decrease in the dry density could be due to the flocculation and agglomeration in the treated soil. The clay particles become bigger with more void formation caused by the rapid cation exchange [5,51]. Since, finer particles are added, it is difficult to attain good compaction due to the poor proportion of coarser material [5]. As the fine particles increase in the mixture, it absorbs more moisture.

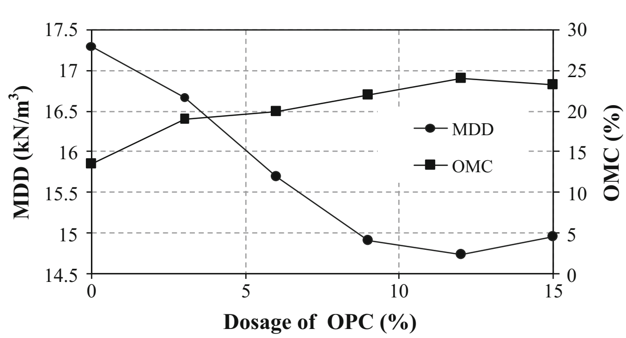


Fig. 4 MDD and OMC with dosage of OPC

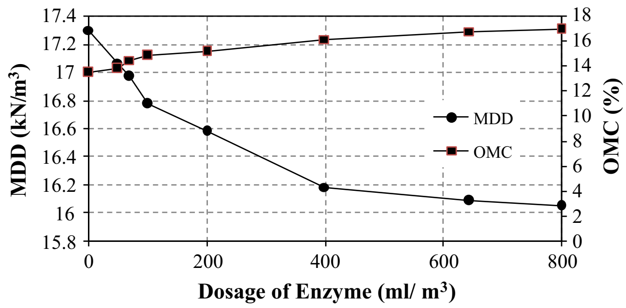


Fig. 5 MDD and OMC with dosage of enzyme

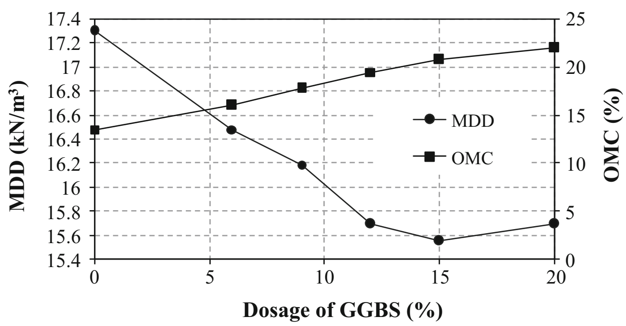


Fig. 6 MDD and OMC with dosage of GGBS

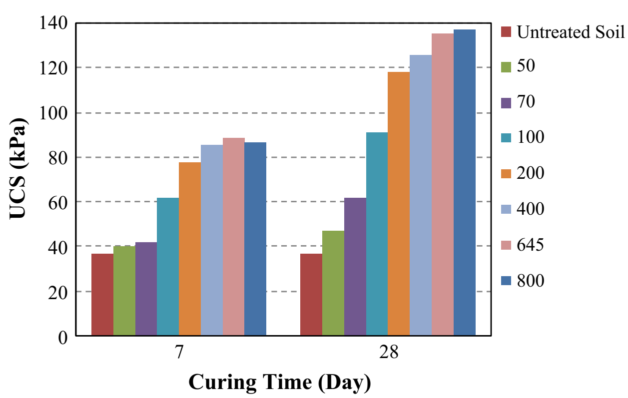


Fig. 7 UCS with dosage of enzyme (ml/m^3) at the end of 7 and 28 days curing period

3.3 Unconfined Compressive Strength

The effect of alkali-activated GGBS, enzyme and OPC on unconfined compressive strength of the soil for selected dosages is shown in Figs. 7, 8 and 9, respectively. From the figure, it can be seen that significant improvement has not been found after addition of GGBS (20%), enzyme (645 ml/m^3 of soil) and OPC (12%). Hence, the same proportions have been considered as optimum dosages for the respective stabilizers. UCS of untreated soil, 37 kPa is increased to 803, 135 and 697 kPa by addition of GGBS (20%), enzyme (645 ml/m^3 of soil) and OPC (12%), respectively, after 28 days.

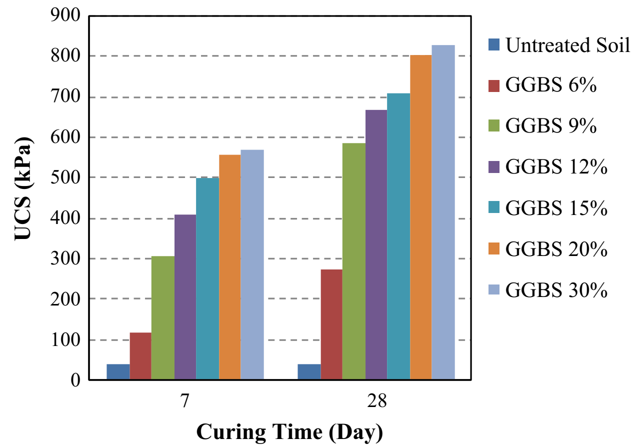


Fig. 8 UCS with dosage of GGBS at the end of 7 and 28 days curing period

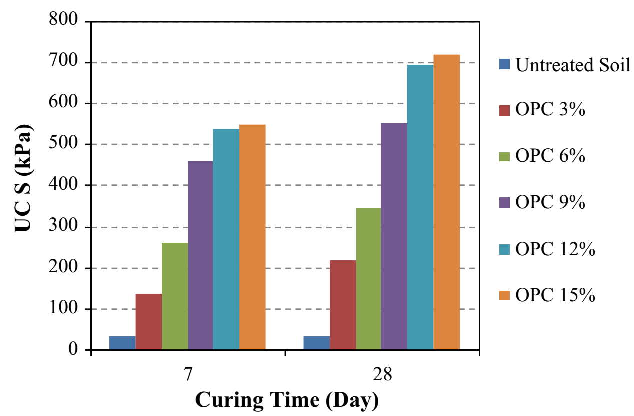


Fig. 9 UCS with dosage of OPC at the end of 7 and 28 days curing period

3.4 Shear Strength Parameters

Variation in shear strength parameters, i.e. cohesion and internal friction angle of unstabilized and stabilized soil with alkali-activated GGBS, enzyme and OPC after 28 days of curing is present in Figs. 10, 11 and 12. Stress–strain curves of the untreated and treated soil for a confining pressure of 100 kPa are shown in Fig. 13. Stress path ($p = \frac{\sigma_1+\sigma_3}{2}$ and $q = \frac{\sigma_1-\sigma_3}{2}$; σ_1= major principal stress and σ_3= minor principal stress) of the untreated and treated soil is shown in Figs. 14, 15, 16 and 17. The cohesion and internal friction angle of untreated sample is obtained as 50.9 kPa and 16^0, respectively. It is observed that the cohesion of specimen increases significantly with addition of stabilizers. But slight increase in angle of internal friction with the addition of stabilizers has been found. Cohesion of soil is increased by 199, 171 and 251% by addition of GGBS (20%), enzyme (645 ml/m^3 of soil) and OPC (12%), respectively. The organic

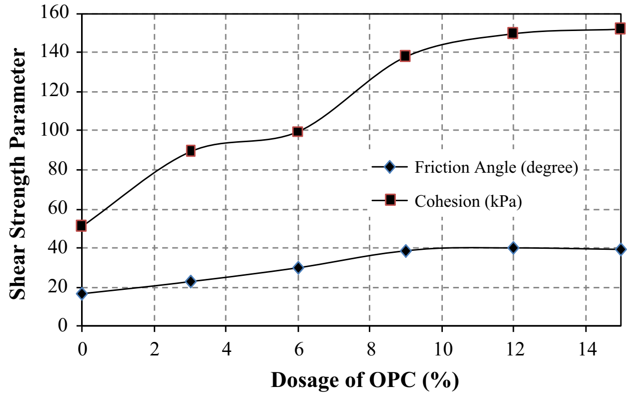


Fig. 10 Shear strength parameters with dosage of OPC at the end of 28 days curing period

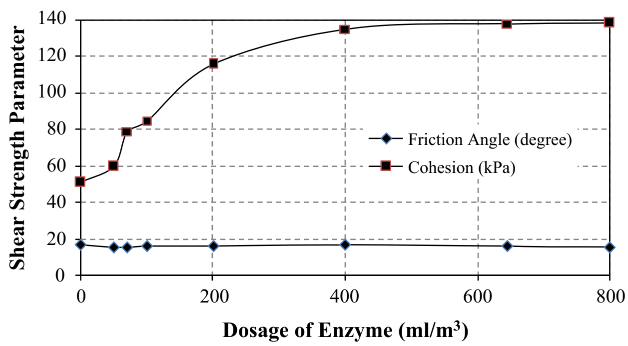


Fig. 11 Shear strength parameters with dosage of enzyme at the end of 28 days curing period

molecules envelope the clay surface leading to the formation of more stable structure on soil surface and it improves the cohesion, internal friction angle and shear strength of the soils [30,35]. The shear strength improvement is contributed from the formation of hydration bonds and cation exchange process which leads to decrease in soil porosity [30,34,35].

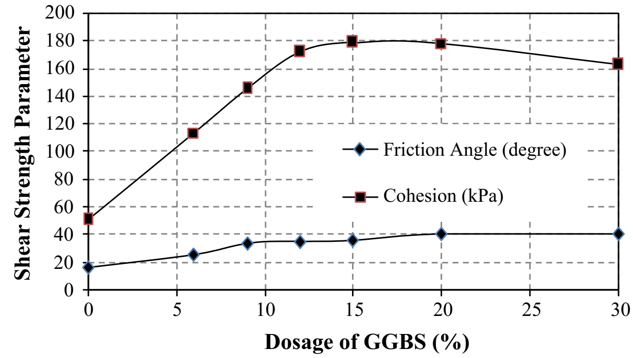


Fig. 12 Shear strength parameters with dosage of GGBS at the end of 28 days curing period

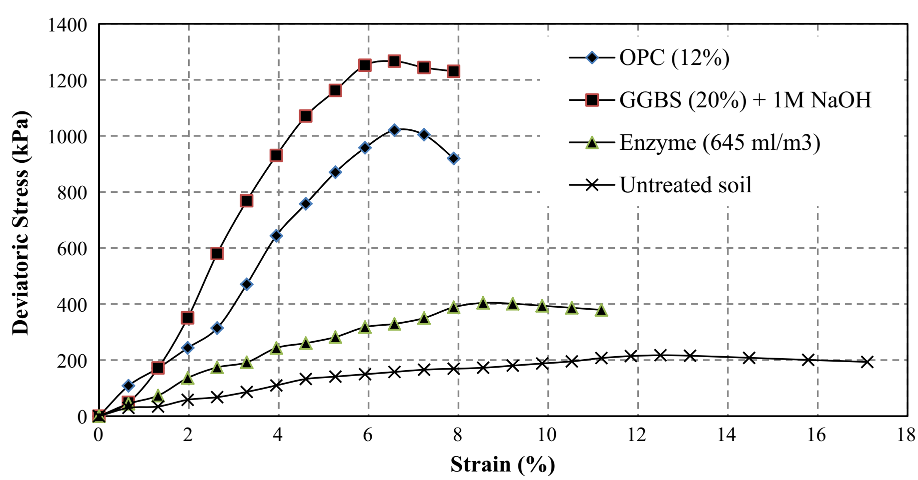
3.5 Microstructural Studies

The soil microstructure images before and after treatment by the SEM are shown in Figs. 18, 19, 20 and 21. The untreated soil can be seen in separate porous lumps as shown in Fig. 18. It is found that with the addition of enzyme the bonding and interlocking of particles increases. Microstructural image of alkali-activated and OPC-treated soils show the aggregated particles or hydration products developed from the flocculation and agglomeration process.

4 Discussion

Optimum dosage can be selected as 20% for GGBS with 1M NaOH solution, 12 % OPC and 645 ml/m^3 of enzyme from the above-mentioned tests. Significant improvement in the properties of stabilized soil has not been observed by further addition of stabilizer. The results show that UCS and shear parameters of the alkali-activated GGBS-stabilized soil with dosage of GGBS 20% surpass that of OPC-stabilized soil with dosage of 12%. Results show alkali-activated GGBS

Fig. 13 Stress–strain curve of untreated and treated soil with OPC (12%), GGBS (20% with 1M NaOH and enzyme (645 ml/m^3)



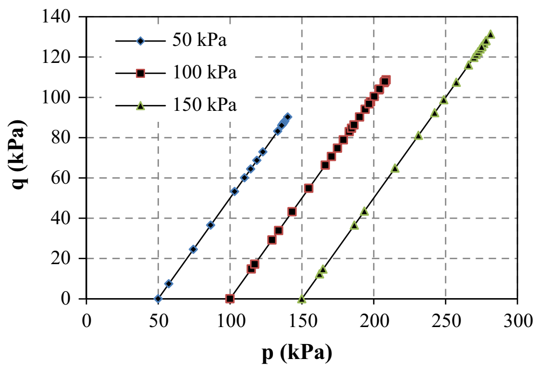


Fig. 14 Stress path of untreated soil

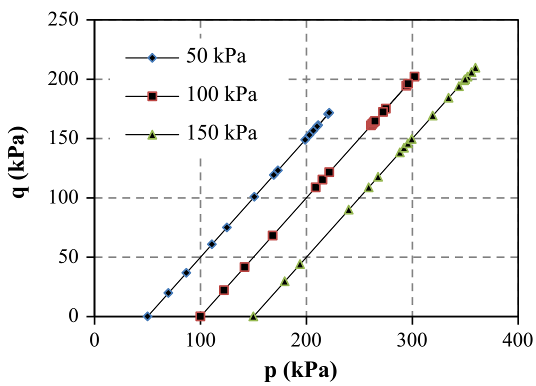


Fig. 15 Stress path of enzyme (645 ml/m^3)-treated soil

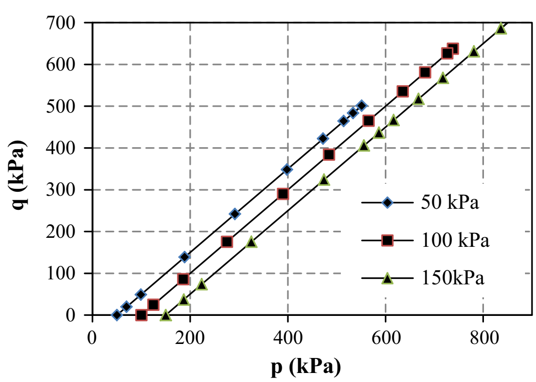


Fig. 16 Stress path of GGBS (20%)-treated soil with 1M NaOH

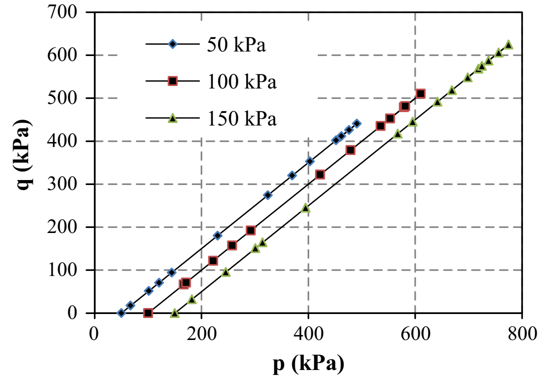


Fig. 17 Stress path of OPC (12%)-treated soil

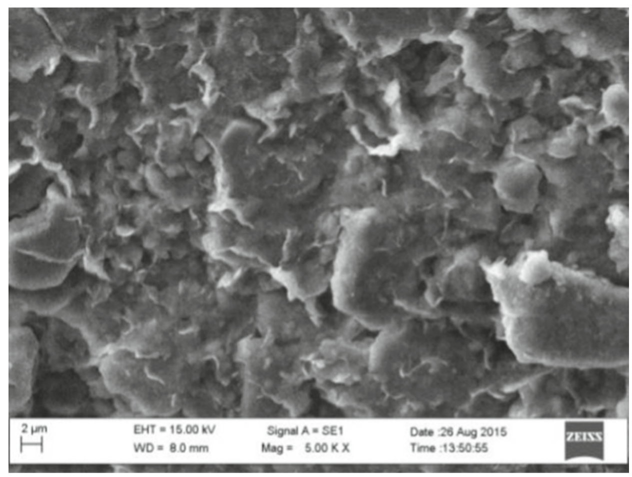


Fig. 18 Untreated soil

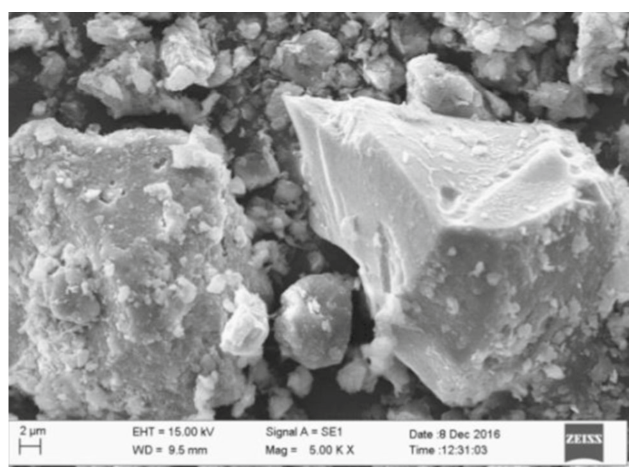


Fig. 19 GGBS (20%)-treated soil with 1M NaOH

is more effective compared to enzyme for the selected soil. UCS of alkali-activated GGBS-stabilized soil is 1.15 times that of OPC-stabilized soil whereas it is 5.5 times that of enzyme-stabilized soil.

The combined effect of cation exchange and flocculation reduces the diffused double layer which results in decreased plasticity [10]. Van der Waals forces or the attractive forces change the face to face orientation of the clay particles to edge to face orientation making the structure flocculated. Because of the alkali activation in GGBS, the impermeable silicate/aluminate oxide layer on the surface of slag grains breaks which is required for further hydration [10,13,15–20].

The encapsulation of clay minerals with large organic cations makes it less moisture susceptible. It will blanket

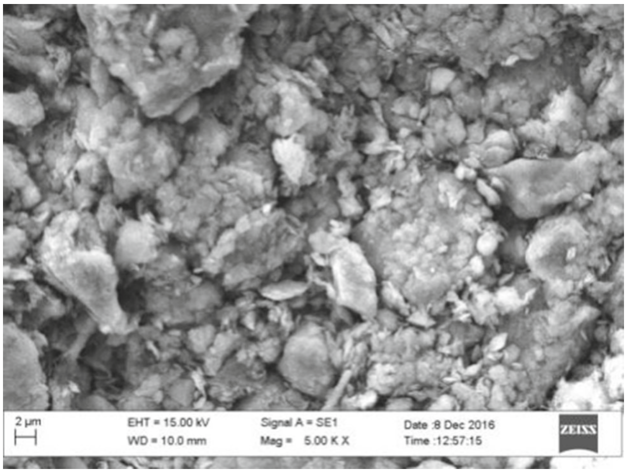


Fig. 20 OPC (12%)-treated soil

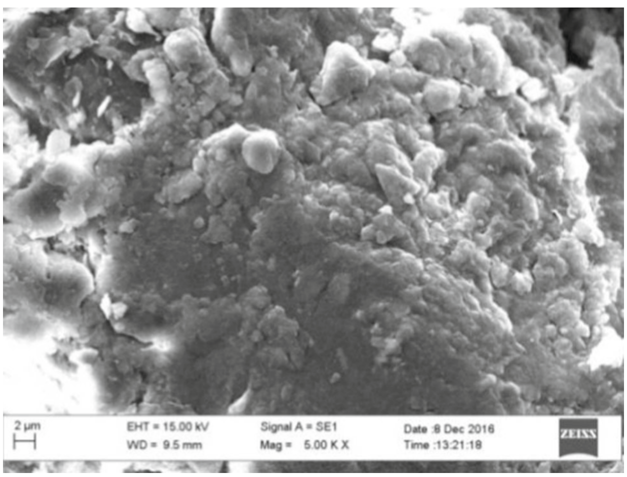


Fig. 21 Enzyme (645 ml/m^3)-treated soil

the clay particle neutralizing its negative charges and thus preventing further entry of water [30,31].

Liquid soil stabilizers work on the concept of soil electrolyte systems, osmotic gradient pressure and colloid activity [8,30,31,52]. The enzymatic emulsion surrounded over clay particle may act as a semi-permeable membrane which creates an osmotic pressure gradient. It allows movement of moisture from areas of low cation concentration to areas of high cation concentration to maintain the equilibrium of the cation concentration. This loss of moisture results in strengthening of molecular structure of clay [8,9,31]. The combined effect of encapsulation of clay minerals and osmotic pressure gradient reduces the adsorbed layer thickness which leads to improved plasticity characteristics.

The enzymatic soil stabilizer acts as a biosurfactant which also prevents entry of water [52]. Surfactants are organic compounds that reduce surface tension. It is a surface-active agent and is made of hydrophilic head and hydrophobic tail. Hydrophillic head will surround the negatively charged clay particle, and the hydrophobic end prevents further entry of water. Moreover, the effect of dielectric constant on thickness of the double layer may also be considered. Since, alcohol is present in enzyme stabilizer, thickness of the double layer reduces [9,52].

5 Conclusions

The geotechnical characteristics of soil stabilized with alkali-activated GGBS, enzyme and OPC have been studied through Atterberg limits, compaction, unconfined compression test and shear strength test and the following conclusions may be drawn from the test results.

- The increase in dosage of stabilizer decreases the MDD and increases OMC, UCS and shear strength parameters.
- It is observed that the cohesion of the treated soil increased significantly.
- Optimum dosage can be selected as 20% for GGBS with 1M NaOH solution, 12% of OPC and 645 ml/m^3 of enzyme.
- UCS and shear strength parameters of the alkali-activated GGBS (20%)-stabilized soil surpasses that of OPC-stabilized soil (12%). Curing time upto 28 days has a significant effect on increasing UCS.
- UCS of alkali-activated GGBS-stabilized soil is 1.15 times that of OPC-stabilized soil whereas it is 5.5 times that of enzyme-stabilized soil.
- Alkali-activated GGBS is more effective in developing strength compared to enzyme for the selected soil.

Non-traditional stabilizer such as alkali-activated GGBS and enzyme can be suitably used as compared to OPC as environmental friendly stabilizers. But the suitability of the invalidated stabilizers and its performance on the particular soil should be checked before using it on a larger scale. Therefore, the findings of this research work are beneficial to the researchers, industry and commercial applications.

Acknowledgements The authors appreciate the valuable help and support provided by NIT Raipur in successful completion of the work and also grateful to Avijeet agencies for providing enzyme required for laboratory experiments.

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