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Comparison of Mechanical Properties of Clayey Soil Stabilized With GGBS and Flyash Using Geopolymerisation Process

Shashi Kant Sharma[1], Neeraj Kumar[2]
[1,2]Dr B R Ambedkar National Institute of Technology Jalandhar
G.T.Road Amritsar Byepass, Jalandhar, India
Sharmask@nitj.ac.in; Neerajk.gg.20@nitj.ac.in

Abstract–There has always been a need to stabilize the soil to make it stable, induce strength, and be durable. Physical and chemical methods are followed for this purpose, followed by mechanical means to stabilize the soil. Much research in this regard has been done in the past, but the results were never too satisfactory as it was not possible to entirely alter/convert the soil crystal structure, or in other words, to recrystallize the silicates aluminates and lime present in the soil. Geopolymerisation, a comparatively new technology, comes as an aid towards this problem. Recent research on this process has proven beneficial for stabilization, but most studies have stated their results are based on a change in one or two parameters at a time. The present study has examined at least two parameters in detail that significantly influence the geopolymerisation of soil. These are alkali concentration and binder composition. For a given sodium silicate to sodium hydroxide ratio, i.e., 2.5, compacted soil samples have been prepared at 10% alkali solution by weight of dry soil mass and tested after 7 & 28 days. Water has been used beyond the alkali solution to achieve a maximum dry density of soil mass. It has been found that GGBS is much beneficial in the presence of flyash as their combined synergic effect improves both the gradation and polymerization potential in the soil mixture. About 40% soil substitution is appreciated as more substitution will encourage more alkali requirements which will not be cost-effective.

Keywords**:** Stabilization, geopolymerization, alkali solution, sodium hydroxide, sodium silicate, GGBS**.**

1. Introduction

Soil is made up of rock or mineral particles and water and air. Based on these elements, the soil qualities may differ from one location to another. Furthermore, various soil types respond differently in construction operations [1], [2]. Soil layers with inadequate bearing capacity are frequently discovered in construction engineering, which substantially impacts the design, execution, operating, and maintenance stages of construction [3], [4]. In actuality, there are many different types of soil, each with its unique set of characteristics, depending on the locality. This research is focused on the clayey soil that road pavements are built on [3], [5]. Because of its poor strength and stiffness, clay soil can cause damage to building foundations and road pavement fissures. As a result, it presents a problem for civil engineering professionals and businesses [5], [6]. Furthermore, clayey soil is regarded as a possible hazard that might cause serious harm to the engineering structure [6], [7]. Furthermore, due to the soil's harsh and unexpected qualities, structures erected on clayey soils are prone to considerable damage [4]–[8]. When the moisture content of the soil is reduced, the soil shrinks, and when the moisture content is increased, the soil expands [8], [9]. When clay soil is wet, it has high plasticity, little support, and a high shrinkage [9], [10]. This situation prompted civil engineers to look for ways to reinforce the soil by using soil stabilization techniques [3]–[13]. Soil stabilization seeks to improve the soil's mechanical characteristics while also reducing plasticity and shrinkage in wet soils [4], [8]–[10]. Soil stabilization procedures are required to ensure the outstanding stability of soil to properly sustain superstructure loads[6], [9], [10]. Geotechnical engineering projects have employed the soil enhancement approach of adding ground granulated blast slag (GGBS) or fly ash [11], [14]. Building foundations, roadways, dams, canals, and other embankment works are examples of these kinds of projects. [7,11,12]. According to a previous study, adding GGBS or fly ash to soils can increase their strength. [11], [14]–[16].

Sharman et al. [17], for soil stabilization applications, looked at the efficacy of fly ash and GGBS. At 7, 14, and 28 days of curing, the effects of adding GGBS and fly ash were examined. The plasticity index and liquid limit of clayey soil decreased, and the maximal soil strength of 0.45 MPa was achieved after a curing period of 28 days. The findings revealed that mixing GGBS with fly ash to make a binder gives a novel way to boost pozzolan activity, which can improve the unconfined compression and lower the swelling tendency of clayey soil. [14]–[17]. However, the qualities found do not match the ASTM D 4609 soil stabilizing criterion befitting road construction, particularly the pre-determined subgrade layers [19–21]. At the end of the 7-day curing period, the soil should possess an unconfined compressive strength greater than 0.8 MPa [21]. Furthermore, controlling the swelling potential of the soil was not considered in the experimental study conducted by Sharman et al. [18], which holds a massive significance for balancing the plastic and liquid limits in clayey soil. This is necessary to prevent the collapse of buildings or road constructions. Anil Kumar et al. [17] found that the optimum strength attained for a soil stabilization mixing procedure using water without an alkali activator was only 0.45 MPa after a curing period of 28 days, which remains deficient in matching the ASTM D 4609 minimum compressive strength requirement for subgrade layers [19–21]. Therefore, more research is needed into the possibility of using GGBS and fly ash as soil stabilizers to improve soil compression strength, regulate the swelling tendency of clayey soil, and shorten the curing period to obtain the maximum power of the soil [18], [19]. The Civil engineering industry has long been interested in finding a new and sustainable substance to replace Portland cement as a soil stabilizer that is both ecologically benign and low in carbon dioxide emissions. As a green material, Geopolymers have recently proven to be an ideal alternative to Portland cement for strengthening unstable soils. [18]–[20]. Engineering features of geopolymers include increased strength and higher soil adherence [18]–[22]. In addition, geopolymer is the polymerization of inorganic natural materials [22]–[24]. Ingredients with high Alumina (Al) and silica (Si) components are the founding materials needed to yield a geopolymerised substance consisting of three-dimensional chains of Aluminium-oxygen-silicon atoms, the recrystallization being done by alkalies. For geopolymer processes in soil stabilization, flyash could be obtained as a waste product from coal combustion thermal power plants, and GGBS could be obtained from the combustion of iron, exhibiting a large quantity of Si and Al [18]–[26]. A mixture of Sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) serves as the most favorable one among all alkaline solutions to dissolute the components of Si and Al and cause chemical reactions inducing recrystallization of the Si and Al [18]–[27]. Previous research on geopolymerisation of soil, GGBS, and flyash mixtures as a part of soil stabilization does not explore the various parameters like alkali to binder ratio and concentration of alkali solution corresponding to the chemical constitution of binder material. Various studies focus only on the geopolymerisation done via adopting a single concentration value of alkali solution [14]–[21]. Hence, this study aims to demonstrate the geopolymer's capacity to be employed as a stabilized material for soil subgrade in road construction. As an investigation, an unconfined compression test, California Bearing Ratio (CBR), was performed on soil-GGBS-Fly ash mixtures.

2. Materials and Experimental Method

In the present study, the clayey soil has been procured commercially from an available location in Jalandhar, Punjab, India. From the basic soil testing in the laboratory, it was found that the soil exhibited a liquid limit (LL), plastic limit (PL), and plasticity index (PI) of 45.20%, 28.32%, and 16.88%, respectively, following 2720: Part 5: 1985. Thus, our test soil falls under clayey soil with low plasticity (CL). The Atterberg limit was determined according to IS 2720: Part 5: 1985. The soil's optimum water content and maximum dry density were 22.13 and 1.66 g/cc, respectively, found via a modified Proctor compaction test following IS: 2720 (Part 8)-l983**.** The fly ash (FA) and GGBS were obtained from the GVK power plant in Jalandhar, Punjab, India, and Astra Chemical from Chennai, Tamil Nadu, India. An X-ray fluorescence (XRF) test has been performed to determine the chemical compositions of FA, GGBS, and soil, presented in Table 1. The results show that GGBS is comparatively richer in lime but exhibits a reduced amount of Silica than FA, which is rich in silica and Alumina. It has been mentioned in a study that for the stabilization of clayey soil, it is essential to provide an adequate amount of lime [28], as lime increases the cationic charge on soil particles resulting in their coagulation, thereby increasing the cohesion and friction coefficient of soil. Even if the geopolymerization process increases the cohesion, the responsibility of increasing the friction coefficient between unpolymerised soil particles could be discharged by lime. Also, lime may cause the formation of CSH to some extent and could deliver the required activation energy for sustaining the geopolymerisation reaction. Therefore, a balance in the concentration of both matters, i.e., flyash and GGBS, regarding the soil type (chemical composition and grain size).

The present study employs a blend of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) as an alkaline activator. The function of NaOH is explicitly to contribute to the reaction of the elements Al and Si contained in GGBS and fly ash, thereby creating a rigid polymer bond structure. Relative to this, Na_2SiO_3 acts as a catalytic agent which recrystallizes the Al and Si atoms during the chemical reactions, causing the reaction to accelerate. The concentrations of NaOH used were 8M, 10M, and 12M, which have been used to create a blending solution by mixing with Na_2SiO_3 solutions in a ratio of 2.5 by weight, respectively. The alkali activator produced by mixing NaOH and Na_2SiO_3 solutions can be used after 18-24 h due to the polymerization process, which releases an intense amount of heat compared to a hydration reaction of cement. Raw materials GGBS and fly ash were mixed with the soil after drying. As tabulated in Table 2, soil mixture specimens have been produced by mixing soil with various ratios of GGBS or fly ash by mass of mix and successively mixing with alkali activator Na_2SiO_3/NaOH. Then UCS test was performed after 7days and 28 days of ambient curing. In addition, soaked CBR samples were tested after 11 days of curing (7days ambient curing than 4days normal water curing). Mix samples with an individual 40% GGBS and 40% Flyash were also tried. A 40% GGBS by weight of clayey soil makes it too stiff to compact, and somehow even if they were made, they developed much cracking after 24 hours of curing. A 40% flyash in soil mass makes it too soft to compact and causes the soil mass to jump off the specimen on being compacted. Hence, these two mixes were not subjected to further testing in this study.

Table 1: Percentage of chemical oxides in soil, fly ash and GGBS

Element	Clay soil (%)	GGBS (%)	Flyash (%)
SiO_2	69.5	39	46
Al_2O_3	20	10.2	19.5
Fe_2O_3	5.3	6	3
CaO	0.7	42.7	16
MgO	-	1.1	4
Others	4	1	11.5

Table 2: Mix designations

Mix designation	Mix Proportion	NaOH (M)	Na2SiO3/NaOH
VS	100% Soil	-	-
GS	100% Soil		
GSF1	90% Soil+ 10%FA		
GSG1	90% Soil+ 10%GGBS		
GSF2	80% Soil+ 20%FA	8M	2.5
GSG2	80% Soil+ 20%GGBS		
GSG2F2	60% Soil+ 20%FA+20%GGBS		
GS*	100% Soil		
GSF1*	90% Soil+ 10%FA		
GSG1*	90% Soil+ 10%GGBS		
GSF2*	80% Soil+ 20%FA	10M	2.5
GSG2*	80% Soil+ 20%GGBS		
GSG2F2*	60% Soil+ 20%FA+20%GGBS		
GS#	100% Soil		
GSF1#	90% Soil+ 10%FA		
GSG#	90% Soil+ 10%GGBS		
GSF2#	80% Soil+ 20%FA	12M	2.5
GSG2#	80% Soil+ 20%GGBS		
GSG2F2#	60% Soil+ 20%FA+20%GGBS		

3. Results and discussions

3.1. OMC&MDD

The compaction test is carried out as per IS code 2720-7(1980) part 7. It helps determine the optimum moisture content required for soil to attain maximum compaction, i.e., maximum dry density for construction. Table 3 illustrates the variation of optimum moisture content (OMC) and maximum dry density (MDD) attained from a simple Procter test for clay with a wavering percentage of flyash and/or GGBS and different molarities (8M,10&12M).

Table 3: OMC and MDD results

Clay type	Molarity of alkaline activator	Geopolymer (%) by weight	FA (%) by soil weight	GGBS (%) by soil weight	MDD (gm/cc)	OMC (%)
Kaolinite Clay	8 M	10	0	0	1.704	20.9
		10	0	10	1.598	19.6
		10	10	0	1.581	23.7
		10	20	0	1.652	20.6
		10	0	20	1.741	19.8
		10	20	20	1.730	18.5
	10M	10	0	0	1.612	21.7
		10	10	0	1.567	24.2
		10	0	10	1.605	20.0
		10	20	0	1.568	22.0
		10	0	20	1.649	20.5
		10	20	20	1.665	19.6
	12 M	10	0	0	1.659	23.9
		10	0	10	1.632	19.9
		10	10	0	1.649	22.7
		10	20	0	1.666	21.3
		10	0	20	1.691	19.7
		10	20	20	1.758	18.8

3.2. Unconfined compression test.

The unconfined compression test evaluated the cohesion potential of the polymerization process in stabilizing different soil mixtures. Figure 1 showcases the unconfined compression results for various molarities and mineral admixtures (FA and/or GGGBS) after 7 days and 28 days of ambient curing. The unconfined compressive strength variation trend amongst tested mixes after 7 days is as follows:

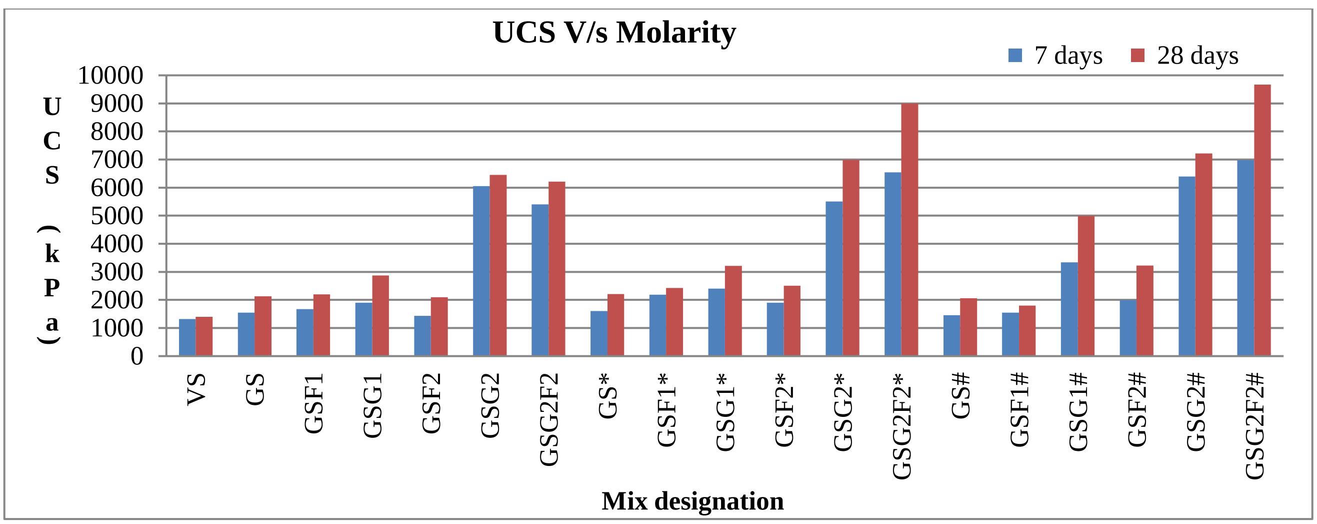
$$GSG2F2\# > GSG2F2 *> GSG2\# > GSG2 > GSG2 *> GSG2F2 > GSG1\# > GSG1 *> GSF1 *> GSF2\# > GSG1 > GSF2 *> GSF1 > GS *> GSF1\# > GS > GS\# > GSF2 > VS \quad (1)$$

All the stabilized mixes achieved higher unconfined compressive strength than virgin soil. Mix GSG2F2# (20% fly ash and 20% GGBS with 12M) achieved 81% higher compressive strength than virgin soil. From equation 1, mixes containing 20% GGBS have higher compressive strength than 10% of GGBS mix samples, followed by 20% FA mixes.

In the case of 28 days, UCS variation follows this pattern.

$$GSG2F2\# > GSG2F2 *> GSG2\# > GSG2 *> GSG2 > GSG2F2 > GSG1\# > GSF2\# > GSG1 *> GSG1 > GSF2 * > GSF1 *> GS *> GSF1 > GSF2 > GS\# > GSF1\# > VS \quad (2)$$

28 days' strength of all mixes follows a similar trend to 7 days' strength. Mix GSG2F2# achieved a higher 85.491% value from the virgin soil. Mixes with 20% GGBS and 20% fly ash achieved higher compressive strength than other samples, and GGBS admixed samples achieved higher strength. Contrary, 20% fly ash & 10% fly ash based samples have lesser compressive strength than GGBS containing mixes. It has been observed that a mixture of fly ash and GGBS for clay stabilization indicated that a good gradation of the mix led to a higher UCS value. Since FA is relatively rich in silica and Alumina but deficient in calcium oxide and GGBS is rich in calcium oxide, the coexistence of these two materials could be more effective due to the synergic formation of N-A-S-H and C-(A)-S-H gels. It has been previously reported that FA requires a temperature of 40 ^{0}C -100 ^{0}C to become activated [29], [30], whereas GGBS has a desirable reactivity at ambient temperature. Hence, utilizing a mixture of these two materials enables them to be used in more comprehensive ranges of temperatures indicating that putting FA with GGBS in equal amounts by weight up to 20% in all samples cured in ambient conditions led to strength enhancement. Since FA is a material with a crystalline phase, it requires higher temperatures of about 40 ^{0}C -100 ^{0}C to attain an activation [29], [30];. At the same time, GGBS is a material exhibiting an amorphous phase, and its activation at ambient temperatures is more easily achievable, which causes the production of more C-S-H gel [31]. Therefore, partial replacement with FA and GGBS brought higher UCS values at ambient temperature. Further, previous studies confirm that if a higher calcium content is present in a given mix, the pozzolanic reactions will occur faster [32]. Additionally, the amount of calcium can affect both the kinetics of the pozzolanic reactions and the number of hydrated phases. Therefore, enhancing the amount of calcium can lead to the formation of more calcium silicate or calcium aluminate hydrated phases during polymerization [32].



Figure;1 UCS vaues of diffren mixes

3.2 Soaked CBR

The soaked CBR test was performed on clay- flyash and/or GGBS with different molarities after 11 days of curing (7days ambient curing than 4days normal water curing). All the samples were soaked in water for 4 days with a surcharge of 5.0 kg and tested using a CBR testing device with a proving ring with 10 KN, 25 KN, and 500KN. The results of the soaked CBR test have been shown in figure2. It has been observed that almost all mixes achieved more than 2% CBR except virgin soil. Mix GSG2F2# (20% GGBS and 20 % FA with 12M NaOH) achieved 323.42% Soaked CBR than GSG2# (20% GGBS with 10M), which achieved 319.8%.

$$GSG2F2\# > GSG2\# > GSG2F2* > GSG2* > GSG2F2 > GSG2 > GSG1\# > GSG1* > GSG1 > GSF1 > GSF2\# > GSF2* > GSF1* > GSF2 > GSF1\# > GS > GS* > GS\# > VS \quad (3)$$

Mix GSG2F2# achieved a 99.84% higher CBR value from the virgin soil. From equation (3), mixes containing 20% GGBS have a higher CBR value than 10 % GGBS mix and flyash mix. It has been observed that 12M NaOH with 20%

GGBS and 20% flyash containing sample achieved a higher percentage of soaked CBR than 12M NaOH, with 20% GGBS following them.

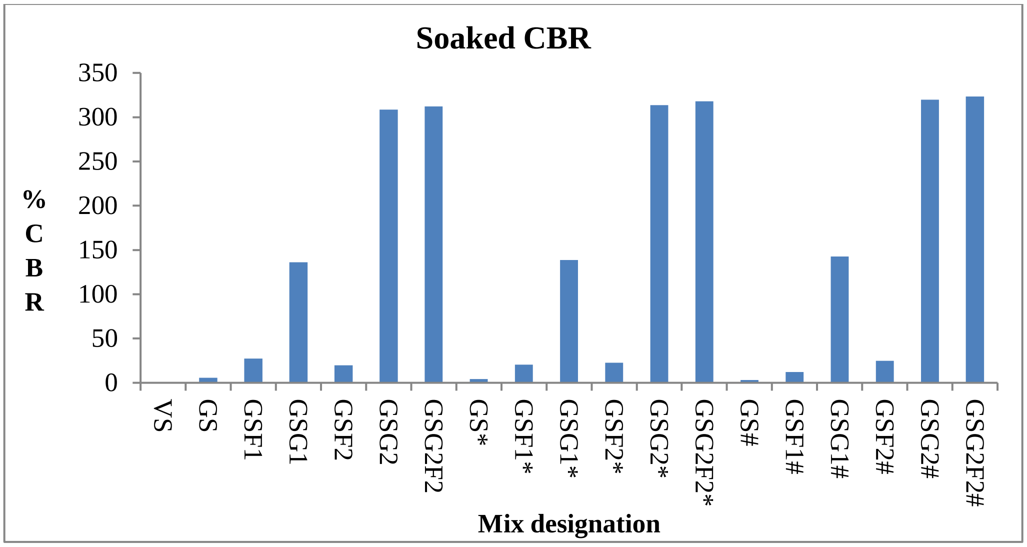


Figure:2 Soaked CBR percentages of different mixes

4. Conclusion

Based on the obtained results and discussion following conclusions can be drawn.

1. The UCS value of the geopolymer clay was found to vary with molarities and percentage of mineral admixtures, and the maximum UCS value was obtained with 20% GGBS-20% FA and 12 molarity of sodium hydroxide with sodium hydroxide to sodium silicate ratio of 2.5.
2. Using a proper mixture of FA with GGBS provides a requisite amount of calcium, silicon, and aluminium, causing the crystallization of N-A-S-H and C-(A)-S-H gels. The coexistence of these gels filled the holes in the 3D material network, resulting in a denser and more robust matrix and, terminally, higher strength values. Also, the physical grain size structure became well graded.
3. Using a combination of flyash and GGBS maintains typical reactivity at ambient temperatures. A higher amount of GGBS (40%) in the absence of flyash makes the reaction too fast in the presence of alkali activators, causing a considerable number of cracks in the cured soil specimen and even difficulty in compacting the specimen, being so stiff. Hence flyash is also essentially needed to maintain the consistency of the mix and control the polymerization reaction. A large amount of Flyash @40% by mass of soil mix causes it to become too light enough to be compacted.
4. The soaked CBR value of the geopolymer clay varies with molarities and percentage of mineral admixtures. The maximum CBR value was obtained with 20% GGBS-20% FA and 12 molarity sodium hydroxide, with a sodium hydroxide to sodium silicate ratio of 2.5. It is obtained at a value of 323.42%.
5. UCS-CBR results show similarity for mixes exhibiting GGBS, proving that the binding efficacy remains effective even under moisture conditions due to a better packing of the mix and better coagulation by lime, which increases cohesion and friction between soil particles.

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