

# Geopolymer stabilization of soft clays – an emerging technique

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**Abstract.** Large tracts of soft clay deposits are present in many world nations especially along their shore lines and estuaries. These deposits are characterised by their high compressibility with low shear strength making them unsuitable to serve as foundation bed. However, in view of enormous economic activity along the coasts, large scale infrastructure development becomes inevitable. In view of this, the soft clay deposits are to be improved by suitable methods of stabilization. In this direction, stone columns, preloading with or without vertical drains, deep lime or cement mixing and electro-osmosis have been popularly used across the world. In the recent years, efforts are being made to use geopolymer technology as an alternative to lime/cement mixing as an attempt to reduce the carbon footprint. Besides carbon footprint reduction, several researchers (Duxson P. et al, 2007; Majidi, 2009; Kamal Neupane et al, 2018) reported the technical advantages of high early strength, extraordinary durability, resistance to chemical attack and ability to immobilize toxic atoms for geopolymer compared to conventional lime/cement. Keeping in view these recent trends in geopolymer technology, an attempt is made to study the influence of ground granulated blast furnace slag (GGBS) binder with different molarity of activator, the sodium hydroxide (NaOH). The soft clay is simulated by preparing the clay paste at 0.75, 1.0 and 1.25 times the liquid limit water content. At these initial clay consistencies, the influence of GGBS and NaOH are studied. From this study, it is revealed that the unconfined compressive strength of stabilised clay increases with increase in activator to binder (A/B) ratio and curing period for any binder content. Increased molarity of activator has little influence on the strength gain. The strength gain is observed to be higher at higher initial consistency of clay.

**Keywords:** Soft clay; Geopolymer stabilization; Activator to binder ratio; Molarity of activator; Unconfined compressive strength;

## 1 Introduction

Large tracts of soft soils are present along the coast lines of many world nations. These deposits are characterized by high natural water content coupled with low shear strength making them unsuitable to support any civil engineering structures (Jie Han, 2014). However, essentially the major infrastructure such as transportation routes, ports and harbour structures are to be built over such deposits in view of high economic activity in the coastal regions (Porbaha, 1998). In order to build the structures

in these deposits, several ground improvement techniques such as preloading with vertical drains, stone columns, electro-osmosis and in the recent times the deep soil mixing were promulgated all over the world.

These techniques are suitable for a specific ground condition depending upon the available time and resources. All these improvement techniques except deep soil mixing require considerable time before the desired degree of improvement is attained. In view of short duration improvement of soft soils by deep soil mixing, this technique gained global prominence for its wide use. For deep soil mixing, lime and cement have been the most commonly used binders so far (Broms, 1991; Chai J. and Carter J. P., 2011; Horpibulsuk et al, 2011; Kai Yao et al, 2016). In view of environmental concerns with these binders, a great deal of research has been taken up by several investigators to develop alternative binders such as geopolymers (Sargent P. et al, 2012; Mo Zhang et al, 2013; Binod Singhi et al, 2016).

Geopolymers are cementitious binders produced by combining industrial by-products and waste products having high amorphous alumina and silica contents, such as flyash, ground granulated blast furnace slag, metakaolin, etc., with a liquid alkaline activator (like sodium/potassium hydroxide and sodium/potassium silicate), rich in soluble metals, like sodium and potassium (Mo Zhang et al, 2013; Palomo et al, 2014). The geopolymerization is a fast chemical reaction which involves four main stages (i) dissolution of solid reactants in an alkaline solution releasing silica and alumina atoms, (ii) diffusion of the dissolved species through the solution, (iii) polycondensation of the alumina and silica complexes with the added alkaline activator and the formation of gel, (iv) hardening of the gel that results in the final polymeric product (Sargent P. et al, 2012; Mo Zhang et al, 2013; Binod Singhi et al, 2016). The geopolymeric product thus formed would be a calcium sodium aluminosilicate hydrate, C-N-A-S-H (Majidi, 2009; Sargent P. et al, 2012; Palomo et al, 2014). Further, it is reported that geopolymers are more durable than cement (Palomo et al, 2014; Duxson P. et al, 2007; Majidi, 2009; Kamal Neupane et al, 2018). In view of these developments, an attempt is made to stabilize the soft soils using geopolymer.

## **2 Materials and Methodology**

### **2.1 Materials**

*Soft clay.* The locally available black cotton soil mixed with potable tap water at water content close to and slightly more than liquid limit is used.

*Sodium hydroxide (NaOH).* Sodium hydroxide, also known as Caustic Soda, is purchased from Fisher Scientific in pellets form with density 2.1 g/cm<sup>3</sup>, mass of 39.9971 g/mol and solubility in water as 111 g/100ml (20°C).

*Ground granulated blast furnace slag (GGBS).* The GGBS powder, is obtained from Vizag Steel Plant, Visakhapatnam, Andhra Pradesh, India.

Table-1: Soil properties

Parameters	Value/Designation
Grain size distribution	
Gravel (%)	2
Sand (%)	21
Silt (%)	34
Clay (%)	43
Atterberg Limits	
Liquid Limit (%)	68
Plastic Limit (%)	22
Plasticity Index, PI (%)	46
Optimum Moisture Content, OMC (%)	24
Maximum Dry Density, MDD (gm/cc)	1.54
Specific Gravity, G <sub>s</sub>	2.65
IS Soil Classification	CH
pH	7.4

Table-2: Chemical composition of GGBS

Oxide	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	SO <sub>3</sub>	Na <sub>2</sub> O
Composition (%)	30.1	13.4	5.7	45.8	6.1	0	0.2

## 2.2 Methodology

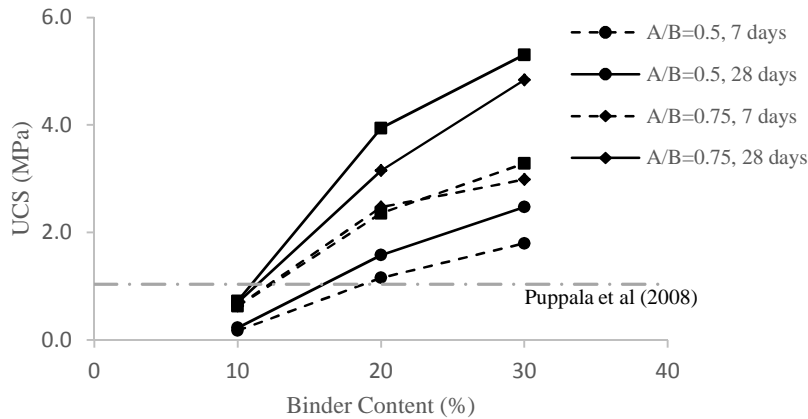
The soil slurry at the desired consistency is prepared by adding the corresponding water content. The binder (B) and activator (A) are also mixed together in the required A/B ratio. The activated binder slurry is mixed with the soil slurry and the test specimens are prepared by filling the mixture in the moulds. These specimens are cured for the required curing period by keeping the moulds in polyethylene bags and covering them with wet gunny bags for 3 days. Then the specimens are removed from the moulds and kept in the same polyethylene bags to continue the curing. At the respective curing periods of 7 and 28 days, the specimens are tested for their unconfined compressive strength as per ASTM D1633. The durability tests for wetting and drying are also carried out on the specimens after 28 days curing period as per the procedure given by ASTM D559/559M.

### 3 Results and Discussion

The results obtained from experimental investigation are presented in the following tables and figures.

#### 3.1 Unconfined compressive strength

It can be observed from Fig.1 and Table-3 that for the water content equal to 0.75 times the liquid limit ( $0.75w_L$ ), the unconfined compressive strength is increasing with the binder content for any A/B ratio at activator concentration of 8 molarity. There is a steep increase in strength upto 20% binder content and thereafter, the rate of increase in strength gain is reduced. The reduction in rate of strength gain beyond 20% binder content could be attributed to the presence of unreacted binder particles producing geopolymeric gels which form flocculated crystals that grow larger with time causing internal forces that lead to non-uniformity and minor bond breakages. Further, for the activator concentration beyond 10M, the strength reduction is noticed and it could be due to faster rate of reactions that result in non-uniformity in the strength gain. However, the target strength of 1.034 MPa (Puppala et al, 2008) for deep mixing could be obtained for binder content of 20% for A/B ratio greater than or equal to 0.75. Further, beyond the A/B ratio of 0.75, the strength gain is nominal which could be attributed to the undesirable morphological changes at higher activator content. For the water content equal to liquid limit ( $w_L$ ) and 1.25 times liquid limit ( $1.25w_L$ ) also the patterns of strength gain are similar to that at  $0.75w_L$  except the variation in magnitude of the UCS values (Table 3). It can be seen from the table that the UCS values are decreasing with increasing initial water content for any binder content and A/B ratio which could be attributed to the reduced activator concentration and presence of water voids in the cemented material.



**Fig. 1.** Variation of UCS with binder content, A/B ratio and curing time at  $0.75w_L$  and 8M

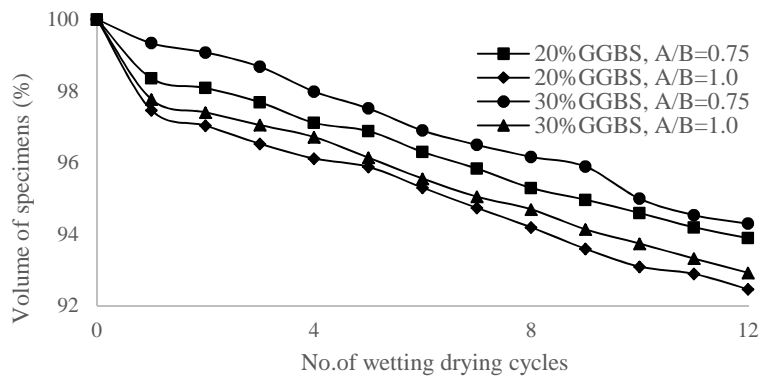
Table-3: Variation of unconfined compressive strength with initial water content, molarity of NaOH, A/B ratio and binder content

Initial water content	Molarity	A/B ratio	UCS (MPa)			
			Binder content (%)			
			10	20	30	
0.75w <sub>L</sub>	8	0.5	0.227	1.578	2.474	
		0.75	0.698	3.153	4.836	
		1	0.724	3.941	5.304	
	10	10	0.5	0.252	1.928	2.730
			0.75	0.742	3.366	4.891
			1	0.795	4.059	5.416
		12	0.5	0.266	1.919	2.712
			0.75	0.729	3.246	4.359
			1	0.774	3.367	4.834
w <sub>L</sub>	8	0.5	0.121	1.022	1.521	
		0.75	0.396	2.421	3.627	
		1	0.446	3.002	4.081	
	10	10	0.5	0.148	1.168	1.671
			0.75	0.420	2.499	3.576
			1	0.489	3.109	4.188
		12	0.5	0.144	1.474	1.834
			0.75	0.413	2.203	3.289
			1	0.478	2.533	3.659
1.25w <sub>L</sub>	8	0.5	0.101	0.723	1.174	
		0.75	0.229	1.714	2.659	
		1	0.299	2.009	3.203	
	10	10	0.5	0.128	0.846	1.348
			0.75	0.298	1.900	2.587
			1	0.356	2.123	3.241
		12	0.5	0.112	0.820	1.310
			0.75	0.242	1.685	2.618
			1	0.329	1.900	3.122

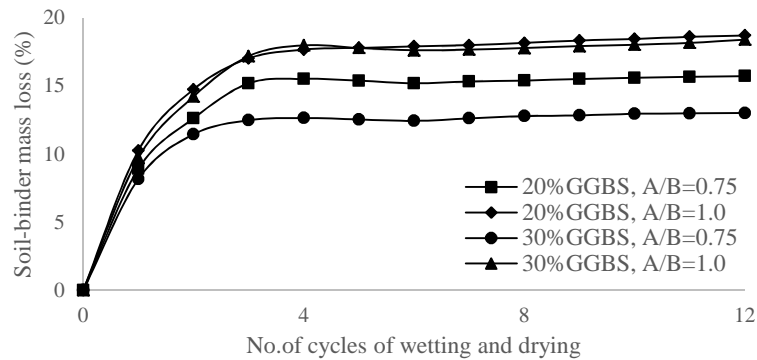
It can be observed from Fig.1 and Table-3 that for the water content equal to 0.75 times the liquid limit (0.75w<sub>L</sub>), the unconfined compressive strength is increasing with the binder content for any A/B ratio at activator concentration of 8 molarity. There is a steep increase in strength upto 20% binder content and thereafter, the rate of increase in strength gain is reduced. The reduction in rate of strength gain beyond 20% binder content could be attributed to the presence of unreacted binder particles producing geopolymeric gels which form flocculated crystals that grow larger with time causing internal forces that lead to non-uniformity and minor bond breakages. Fur-

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### 3.2 Durability



**Fig. 2.** Volume of specimens (%) for 12 cycles of wetting and drying of geopolymer specimens at  $w_L$  and 8M for binder content 20% and 30% and A/B ratio of 0.75 and 1.0.



**Fig. 3.** Soil-binder mass loss (%) for 12 cycles of wetting and drying of geopolymer specimens at  $w_L$  and 8M for binder content 20% and 30% and A/B ratio of 0.75 and 1.0.

From Fig. 2 it can be observed that there is a reduction in volume of the specimens for each cycle of wetting and drying. It can be observed from Fig. 3 that there is increase in percentage of soil-binder loss for each cycle of wetting and drying. The increase of mass loss upto the third cycle maybe due to the leaching of dissolved Si, Al and Ca. However, after three cycles, the geopolymeric network was strongly formed such that mass loss was not much affected by wetting and drying cycles. It can also be observed that the soil-binder specimens show better durability characteristics like lower volume change and lower mass loss at A/B ratio of 0.75 for 20% and 30% binder contents after 12 cycles of wetting and drying.

## 4 Conclusions

The following conclusions are drawn based on the experimental study carried out in this investigation.

- UCS values increased with the binder content for any molarity of activator. For a given molarity there is a steep increase in strength upto 20% binder content and thereafter the rate of strength gain is slightly reduced.
- For a given binder content and molarity, the UCS values increased with increase in activator to binder ratio from 0.5 to 1.0. However, for A/B ratio greater than 0.75, the rate of strength gain is reduced.
- For the initial consistencies investigated, strength is observed to be increasing with increase in concentration of NaOH from 8M to 10M and beyond this the strength reduction is observed. For any combination of binder and activator contents, the strength depends on its initial consistency.
- The target strength of 1.034 MPa could be obtained for all initial consistencies of clay using 20% binder and A/B ratio greater than or equal to 0.75. For cement stabilization, cement content required to attain this target strength is found to be 30%.
- The durability of geopolymer stabilized samples are found to be superior to cement stabilized samples.
- This study revealed that the UCS and durability criteria for soft clay stabilization could be achieved using geopolymer stabilization and hence it can be a promising alternative to traditional stabilizers like cement.

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