Stabilisation of Clay with Fly-Ash Geopolymer Incorporating GGBFS

Hayder H. Abdullah, Mohamed A. Shahin, and Prabir Sarker
Department of Civil Engineering, Curtin University
WA 6845, Perth, Australia
H.abdullah1@postgrad.curtin.edu.au; M.shahin@curtin.edu.au; P.sarker@curtin.edu.au

Abstract – Low water/binder ratio and higher activator content can help to accelerate the setting and strength development of fly-ash geopolymers cured at ambient condition. This study aims to achieve clay stabilization with fly-ash based geopolymer incorporating ground granulated blast-furnace slag (GGBFS), to enhance soil strength performance at ambient temperature. Laboratory experiments were performed on clay samples stabilized with both slag and fly-ash geopolymer and ordinary Portland cement (OPC), including the soil plasticity, compaction and unconfined compressive strength. The investigation was expanded to include un-activated fly-ash/slag clay samples used as control mixtures. The results indicated that introducing GGBFS to class (F) fly-ash based geopolymer assists, when synthesised in certain concentrations, in achieving a setting time and compressive strength comparable to OPC stabilised clay.

Keywords: Soil Stabilisation, Ground Improvement, Fly-Ash Geopolymer, Ground Granulated Blast-Furnace Slag (GGBFS), Clay

1. Introduction

Soft soils are problematic in nature, which can be originally found onsite or borrowed, and may affect the service life of infrastructure projects. Cement modification, using ordinary Portland cement (OPC), is traditionally utilised to stabilize problematic soils through chemical reactions. As a percentage of soil, low amount of cement is being usually added to granular soils and higher amount to plastic soils. However, in the last decades, several environmental issues stemmed from the use of OPC, and carbon footprint associated with OPC construction industry formed a main environmental limitation [1]–[5]. Manufacturing of 1 tonne of OPC is usually found to release about $0.8−1$ tonne of carbon dioxide ($CO2$) to the atmosphere. Consequently, cement industry is responsible for about 7% of the total $CO2$ emission [6]. Considering the effect of such an emission problem along with other environmental effects related to the limitation in sourcing of raw materials, there has been a significant motivation towards finding alternative binders to replace cement.

Through alkaline activation, the bonding characteristics of abended pre-calcined by-products can offer a good alternative to OPC with the advantages summarized by the fact that all source materials are already calcined which eliminates the need for any energy in the manufacturing and utilisation process, and this in turn contributes to considerable reduction in $CO2$ emission [2], [3], [5]. Geopolymers, among other alkaline activation materials, are derived from low calcium aluminosilicate materials such as fly-ash, which when activated, form a gel of three-dimensional framework represented by the chemical structure N-A-S-H [4], [6], [7]. Geopolymers can possess good mechanical properties when synthesised at certain conditions. Low permeability, high compressive strength, high durability and low shrinkage can be achieved using geopolymer binders [8], [9]. However, any improvement offered by synthesised geopolymers depends mainly on several factors including the properties of source materials, chemical composition of activator, curing time and treatment temperature [1], [5], [7], [10]. Among these factors, curing temperature is the most challenging for onsite applications and strength gain in fly-ash based geopolymers [11]. Most available research and industrial applications on geopolymers are limited to steamed or dry heat-cured concrete [12], whereas for ground improvement, elevated heat is not practically possible. Therefore, soil stabilization by geopolymers has only been investigated at ambient temperature [2], [13], [14]. In fact, low temperature maintains slow rate of geopolymerisation and strength gain in stabilized soils. To increase the feasibility of geopolymers for soil stabilization at ambient temperature and make it more comparable to the cement effect in soil, lower water/binder ratio and higher activator content are required to overpass the delay in the setting and strength development [4]. To avoid this limitation, the current research is focused on using ground granulated blast-furnace slag (GGBFS) to enhance the effectiveness of geopolymer at ambient conditions, thus, bringing the strength of soil-

geopolymer to the economical boundaries. In other words, possibilities are explored using GGBFS to reduce the quantity of geopolymer required to stabilize the soils. In the alkaline activation literature, GGBFS was introduced as calcium-rich aluminosilicate slag produced from the steel industry waste, to activate the calcium silicate hydrate cementing gel C-A-S-H. However, no study in soil stabilization has been reported in detail using hybrid alkaline materials where the combination of GGBFS gel with N-A-S-H geopolymer gel were introduced in one reaction. Therefore, the current study provides a platform of understanding and evaluation, based on experimental verification data, of geopolymer performance for clay stabilization. This paper will thus form the basis for further investigation on this promising soil stabilisation technique in the near future.

2. Materials and Methodology

2.1. Materials

In this study, kaolin clay soil was chosen due to its well defined characteristics, accessibility and availability as a local subgrade material in several areas. Table 1 presents the chemical composition of the clay used, i.e. Prestige NY clay commercially available in the form of white coloured kaolin produced in Western Australia. The percentage of fines in this clay is 99% passing 53μ and its specific gravity is 2.62. The plastic limit (PL) and liquid limit (LL) of this clay are determined using the Australian Standards (AS 1289.3.1.1-2009 and 1289.3.2.1-2009) [15],[16] and found to be 27.1% and 53.6%, respectively. According to the Unified Soil Classification System (USCS), this clay is classified as CH (clay of high plasticity). The compaction properties (i.e. maximum dry density, MDD, and corresponding optimum moisture content, OMC) using standard Proctor test carried out in accordance with the Australian Standard (AS 1289.5.2.1-2003) [17] are found to be 14.95 kN/m3 and 25.2%, respectively. The fly-ash used to synthesize the geopolymer is a coal fly-ash obtained from a pulverised coal combustion known as low calcium Gladstone fly-ash (GFA), which was supplied from Gladstone power station by Cement Australian Limited. This fly-ash conformed to the Australian Standard (AS 3582.1-1998) [18] and its physical and chemical characteristics are given in Table 1. The slag used as a partial replacement of fly-ash is ground granulated blast furnace slag (GBBFS), which was supplied by Independent Cement & Lime Ltd. The composition of this GBBFS is given in Table 1, which complies with the Australian Standard (AS 3582.2-2001) [19]. The alkaline activators used are Grade D sodium silicate and 14M concentrated sodium hydroxide. Grade D sodium silicate (Na_2SiO_3) was supplied by PQ Australia and contains weight dosages of $Na_2O = 14.7\%$ and $SiO_2/Na_2O = 2$. The 14M concentrated sodium hydroxide solution (NaOH) was prepared in a fume cabinet by dissolving sodium hydroxide pellets in deionised water for at least 1 day prior to mixing.

Table 1: Chemical compositions of materials.

Material	Chemical Composition (%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI
Kaolin Clay	46.10	36.50	0.90	0.90	0.50	0.20	0.10	NA	14.3
Fly-ash	51.11	25.56	12.48	4.3	1.45	0.7	0.77	0.24	0.57
GGBFS	29.96	12.25	0.52	45.45	5.99	0.38	0.31	3.62	2.39
OPC	19.90	4.62	3.97	64.27	1.73	0.57	0.15	2.56	NA

2.2. Sample Preparation

The geopolymer binder used in this research is a mixture of fly-ash (FA) and sodium based activator. Stabilization was achieved by introducing dry components of geopolymer to dry clay as a total dry material (DM), and free water to activator solution to complete the total moisture of optimum compaction. All mixture components were mixed together in steps. The GGBFS is denoted herein as (S), was hybrid as a partial replacement of class F fly-ash (FA) to form the geopolymer dry source material, which is denoted herein as SM, i.e. SM = S + FA. The ratio S/SM was in ranges of 0%, 10% and 20%, and the amount of SM by weight of DM (i.e. SM/DM) was in ranges of 10%, 20% and 30%. To this end, a fixed weight ratio of 70:30 of sodium silicate to 14M sodium hydroxide solution was used as an alkaline activator denoted herein as (A) with ratios of A/SM equal to 0.4 and 0.8. It should be noted that the weight ratio of 70:30 of sodium silicate to 14M sodium hydroxide solution was selected because it was recommended in the geopolymer literature to maximize the strength gain [20]. As mentioned earlier, to form the ultimate moisture for the optimum compaction, the activator was diluted with free water before use. A code is used to identify the different mixtures, as follows: M(R1-R2-R3). The letter M is an abbreviation of the word "Mixture" followed by the three ratios R1, R2 and R3, included inside a bracket and separated by hyphens. The

first, second and third ratios represent, respectively, SM/DM, S/SM and A/SM. Hence, for example, M(10-0.2-0.4) implies a mixture that contains 10% SM/DM, S/SM = 0.1 and A/SM = 0.4. Table 2 summarises details of the mixtures used. Directly after mixing, the effect of stabilizing the additives on the compaction parameters was determined through a series of standard Proctor compaction tests according to the Australian Standard (AS 1289.5.1.1-2003) [17]. Having obtained the compaction parameters, the mixtures were gradually added into polyvinyl chloride (PVC) tubes of 42 mm diameter and 84 mm height to attain an aspect ratio of height-to-diameter of 2:1. All samples were compacted at a certain controlled weight to achieve the desired density. The ends of the PVC tubes were then sealed with plastic lids to avoid moisture loss. This was followed by a standard curing time of 24 hours at room temperature (20-25 ºC) and was then demoulded and covered again with plastic bags before curing was continued until the samples were tested at the same room temperature. Other samples were also prepared and stabilised with 3%, 6% and 9% OPC and denoted as OPC3, OPC6 and OPC 9, respectively, as shown in Table 2. These samples were tested for comparison with the geopolymer stabilised soils.

Table 2: Details of the mixtures used and their corresponding designations.

Mixture No.	SM/DM (%)	S/SM	A/SM	OPC (%)
M(0-0-0)	0	0	0	-
M(10-0-0)	10	0	0	-
M(20-0-0)	20	0	0	-
M(30-0-0)	30	0	0	-
M(10-0-0.4)	10	0	0.4	-
M(10-0.1-0.4)	10	0.1	0.4	-
M(10-0.2-0.4)	10	0.2	0.4	-
M(20-0-0.4)	20	0	0.4	-
M(20-0.1-0.4)	20	0.1	0.4	-
M(20-0.2-0.4)	20	0.2	0.4	-
M(30-0-0.4)	30	0	0.4	-
M(30-0.1-0.4)	30	0.1	0.4	-
M(30-0.2-0.4)	30	0.2	0.4	-
M(10-0.2-0.8)	10	0.2	0.8	-
M(20-0.2-0.8)	20	0.2	0.8	-
M(30-0.2-0.8)	30	0.2	0.8	-
OPC3	-	-	-	3
OPC6	-	-	-	6
OPC9	-	-	-	9

2.3. Tests Conducted

The compaction tests were performed according to the Australian Standard (AS 1289.5.1.1-2003) [17]. Atterberg limits were measured for all stabilised clay mixtures at the initial mixing stage in accordance with the Australian Standard (AS 1289.3.1.1-2009 and 1289.3.2.1-2009) [15],[16]. To investigate the samples strength development, several unconfined compression strength (UCS) tests were performed at curing time of 7, 28 and 90 days. The average of two test results was reported for each sample mixture. All UCS tests were performed according to the Australian Standard (AS 5101.4-2008) [21] using a strain rate of 1% per min. All samples were remoulded with the same aspect height-to-diameter ratio of 2:1. For stabilised samples with either with geopolymer or OPC, care was taken to complete the sampling and tests for compaction and atterberg limits within 30min after mixing so as to avoid the interaction of the binder hardening. In order to verify homogeneity and uniformity, the dry densities and corresponding water contents were determined for all tested samples.

3. Results and Discussion

3.1. Physical Properties of Stabilised Clay

Fig. 1 shows the compaction characteristics of stabilised clay in terms of the maximum dry density (MDD) and corresponding optimum water content (OMC). It should be noted that the results of MDD and OMC for geopolymer stabilised clay are denoted respectively as MDD_{KG} and OMC_{KG}, and were normalised to the kaolin clay maximum dry density (i.e. $MDD_K = 14.95kN/m^3$) and its corresponding optimum moisture content (i.e. $OMC_K = 25.2\%$). Generally

speaking, SM and A/SM were expected to control the compaction parameters and are thus demonstrated in Fig. 1. It can be seen from Fig. 1(a) that the ratio (MDD_{KG}/MDD_K) increases with the increase in SM/DM ratio, for all ratios of A/SM. It can also be seen that activating the source material using A/SM > 0 confirms the significant role of the activator on the MDD stabilised mixtures, especially at high SM/DM percentages. For example, an increase in the activator amount up to 80% of SM (i.e. A/SM = 0.8) increases the ratio of MDD_{KG}/MDD_K by about 17% for SM/DM ratio = 30%. On the other hand, it can be seen from Fig. 1(b) that the ratio (OMC_{KG}/OMC_K) decreases with the increase in the SM/DM percentages, for all ratios of A/SM. Again, it can be concluded that activating the source material using A/SM > 0 confirms the significant role of the activator on the OMC stabilised mixtures, especially at high SM/DM percentages. For example, an increase in the activator amount up to 80% of SM (i.e. A/SM = 0.8) decreases the ratio (OMC_{KG}/OMC_K) by 33% at SM/DM = 30%. This means that the alkaline chemicals presented in the activator seem to play a positive role in the compaction results in the form of partially reducing some of the moisture needed to reach the optimum compaction. It is interesting to mention that the role of the activator was detected earlier in this research through an attempt to compact the geopolymer samples in a state corresponding to MDD and OMC of the un-activated group at A/SM = 0. This attempt indicated a significant volume of air pockets and poor compaction at higher ratio of SM/DM and activator contents. It should be noted that the results presented in Fig. 1 are for S/SM = 0.2, and similar results were obtained for S/SM = 0 and 0.1, but are not presented herein.
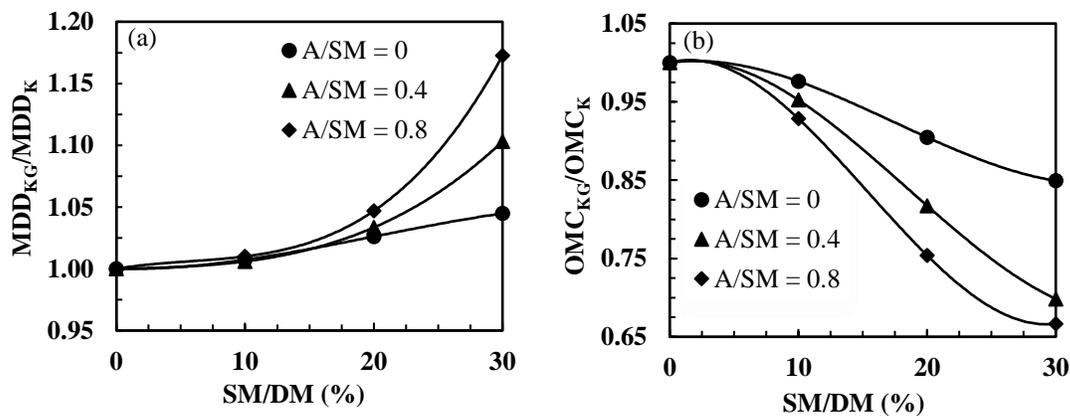

Fig. 1: Compaction characteristics of stabilised clay for S/SM = 0.2: (a) maximum dry density; and (b) optimum moisture content.

Liquid limit (LL) and plastic limit (PL) are significant indices quantifying the response of clay to water. Fig. 2 shows the effect of SM/DM and A/SM on LL and PL of two stabilised mixtures, i.e. activated with A/SM = 0.4 and un-activated with A/SM = 0, both mixtures have the same S/SM ratio of 0.2. It can be seen that the addition of SM tends to reduce both the LL and PL of stabilised mixtures, regardless of whether the mixture was activated or not. This reduction in LL and PL can be attributed to the role of the non-plastic fly-ash and slag particles introduced in the SM content as a partial replacement of the kaolin clay particles. It can also be attributed to the role of chemicals involved in the activator before the geopolymer gel formation, which tends to assist the sliding between the dry particles. As an attempt to track the effect of stabilisation on soil plasticity, the plasticity index (PI) values for stabilised activated and un-activated mixtures were calculated at different SM/DM concentrations. It was found that the PI values were reduced and changed the initial high plasticity state of the clay used towards the low plasticity state, for SM/DM ratio > 10%.
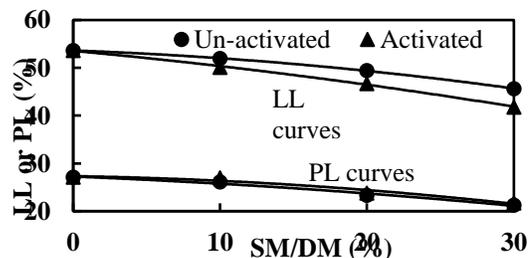

Fig. 2: Plasticity characteristics of stabilised clay, S/SM=0.2 and A/SM=0.4 for activated samples.

3.2. Mechanical Properties of Stabilised Clay

3.2.1. Effect of GGBFS

To investigate and evaluate the effect of GGBFS on strength development of stabilized soil, variable slag percentages were used through different S/SM (slag-to-source material) ratios = 0%, 10% and 20%, against a fixed A/SM (activator-to-source material) ratio of 0.4. As can be seen from Fig. 3, the treated soil achieved a significant additional strength gain with the increase in slag percentage (through S/SM ratio), at both 7 and 28 curing days. For example, replacing 20% fly-ash by slag increased the strength at S/SM = 20% from 800 kPa to 1400 kPa. To quantify such an increase, the UCS index was presented in a normalized form, as shown in Fig. 4, by dividing the UCS values of different slag percentages to those of the non-slag geopolymer (i.e. S/SM=0). For all samples incorporating slag, the strength index was > 1. Also, increasing S/SM ratio to 20% achieved a strength gain of up to 70% at 7 days curing and 60% at 28 days. In other words, introducing higher percentage of slag provides a positive effect on the strength gain of fly-ash geopolymer, regardless of the curing time.
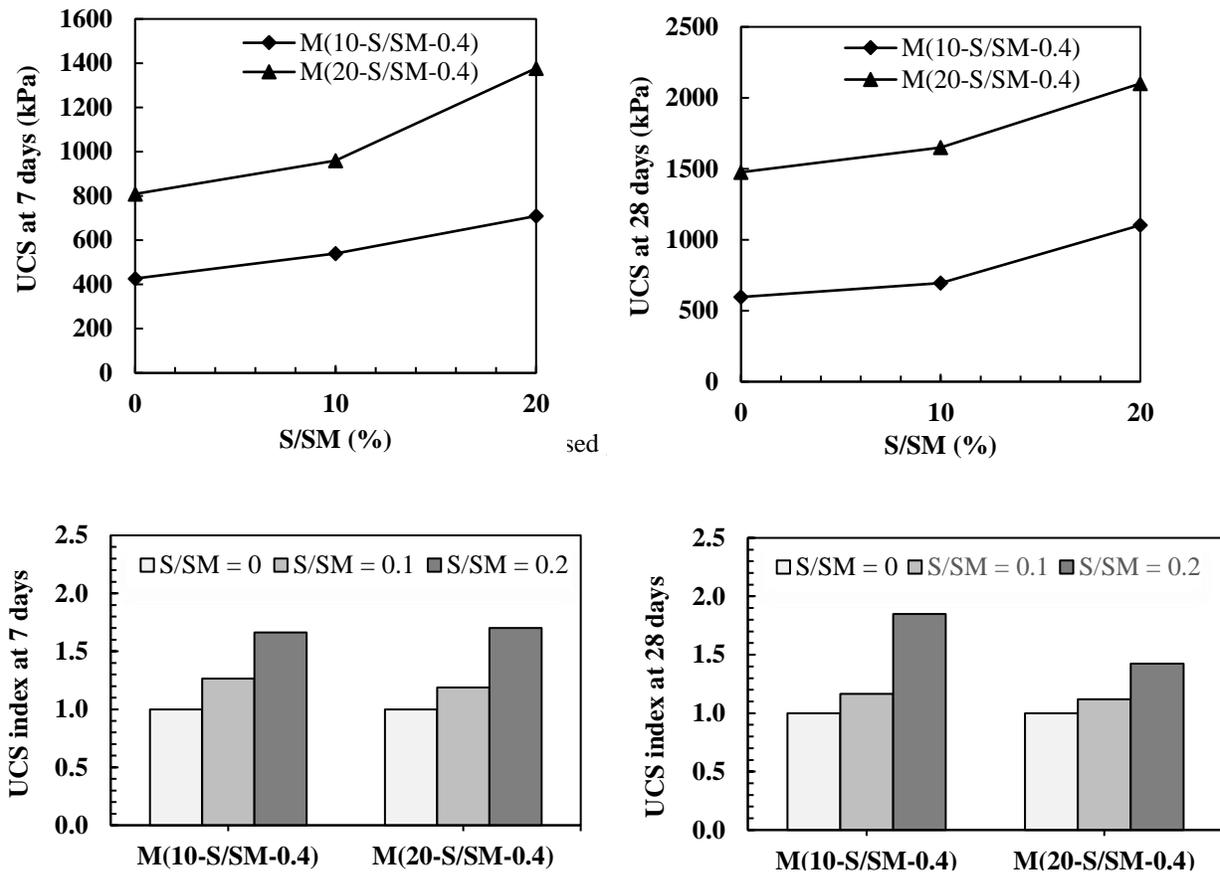

Fig. 4: UCS of slag to non-slag fly-ash based geopolymer for different mixtures and curing days.

3.2.2. Effect of Activator

Fig. 5 shows the effect of activator in terms of the increase in UCS values of different mixtures for 28 days curing time and with different A/SM ratios. As can be seen, at A/SM = 0 (i.e. zero activation) no strength improvement was noticed for the different mixtures considered and this is due to the weak pozzolanic reaction. For A/SM > 0 (i.e. 0.4 and 0.8), an increase in strength was detected for all mixtures. However, the two mixtures, i.e. M(10-0.2-0.4) and M(20-0.2-0.4) were found to give a strength range between 1000−2000 kPa, which fulfils most ground improvement applications. Consequently, these two mixtures are recommended for comparison with OPC treated soils, and presented in the next section.
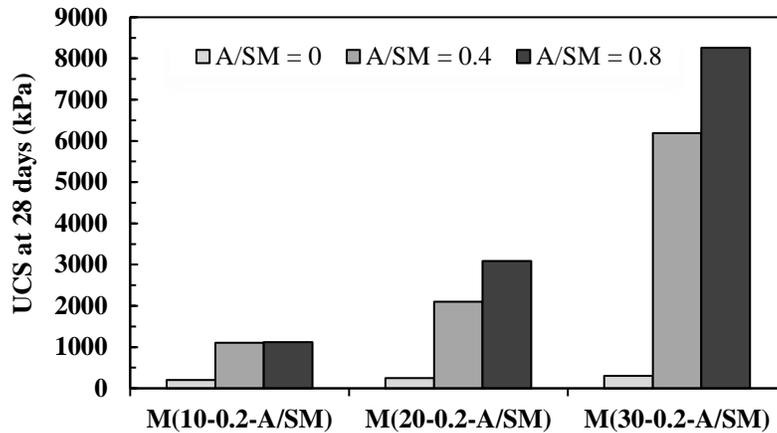
Fig. 5: Effect of activator on UCS strength for different mixtures and A/SM ratios.

3.2.3. Comparison between Geopolymer and Cement Stabilised Clay

Figure (6) presents comparison of soil improvement with time in terms of UCS values for different mixtures of geopolymer and OPC treated soils. It can be seen that at curing time of 7 days, the strength of M(10-0.2-0.4) is equivalent to that of OPC3, whereas the strength of M(20-0.2-0.4) is comparable to OPC9. At 28 and 90days, the strength for M(10-0.2-0.4) is almost equivalent to that of OPC6, confirming a higher rate of strength development in geopolymer mixtures compared to OPC mixtures for 7 days. On the other hand, it can be seen that M(20-0.2-0.4) shows superior development in the strength gain compared to all OPC mixtures. This geopolymer mixture was found to achieve a strength improvement of 20% more than OPC 9, at 28 days, and more than 60% at 90 days. It should be noted that the higher strength gain for geopolymer mixtures with time is due to the higher rate of geopolymerisation reaction, which happens more faster at earlier curing time of 7 days compared to later curing time of 28 and 90 days.
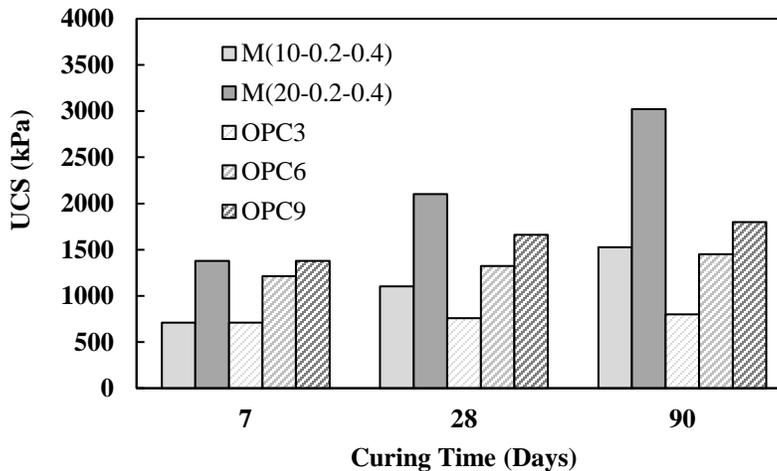

Fig. 6: Effect of curing time on UCS stabilised geopolymer-clay samples, S/SM=0.2 and S/M=0.4: (a) Against OPC-clay samples.

4. Conclusions

In this paper, the effects of ground granulated blast-furnace slag (GGBFS) added to geopolymer binder (i.e. fly-ash + activator) used for clay stabilisation was investigated and quantitatively evaluated at ambient temperature in terms of the compaction characteristics and unconfined compressive strength at curing times of 7, 28 and 90 days. A set of geopolymer-clay specimens containing the following mixtures: source material (i.e. fly-ash + slag) to clay = 10% and 20%; slag-to-source material = 0%, 10% and 20%; and activator-to-source material = 0.4 and 0.8, were investigated and compared. In addition, these geopolymer-clay mixtures were also compared with un-activated clay mixtures containing only fly-ash and GGBFS without activator.

The results indicated that higher percentage of source material and corresponding activator quantity offers an early enhancement to the stabilised clay through an increase in the maximum dry density and decrease in the corresponding moisture content required for compaction. It was found that the addition of GGBFS as a partial replacement of fly-ash in the geopolymer-clay mixtures results in an increase in soil strength, for all curing times. However, at low concentration of slag-to-source material = 10%, little promise in strength improvement was offered compared to slag-to-source material = 20%, for the two ratios used of source material-to-clay of 10% and 20%. A mixture contains source material-to-clay = 20%; slag-to-source material = 20%; and activator-to-source material = 0.4 resulted in soil strength improvement of 70% and 40% at 7 and 28 days, respectively, compared to soil stabilized without GGBFS. This mixture was also found to give soil strength equivalent to that obtained from soil stabilised with 9% OPC, at a curing time = 7 days. Interestingly, at a curing time $\geq$ 28 days, the mixture provided superior strength improvement over soil stabilised with 9% OPC. The results obtained in this study clearly promote the use of geopolymer as an effective alternative binder to traditional OPC in soil stabilisation.

References
[1]   M. Zhang, H. Guo, T. El-Korchi, G. Zhang, and M. Tao, "Experimental feasibility study of geopolymer as the next-generation soil stabilizer," *Constr. Build. Mater.*, vol. 47, pp. 1468-1478, 2013.
[2]   N. Cristelo, S. Glendinning, A. Pintio, and L. Fernandes, "Effects of alkaline-activated fly ash and Portland cement on soft soil stabilisation," *Acta Geotech.*, vol. 8, no. 4, pp. 395-405, 2013.
[3]   S. Z. S. Zaliha, H. Kamarudin, A. M. Mustafa, A. Bakri, M. Binhussain, and M. S. S. Salwa, "Review on Soil Stabilization Techniques," *Aust. J. Basic Appl. Sci.*, vol. 7, pp. 258-265, 2013.
[4]   S. a. Bernal and J. L. Provis, "Durability of alkali-activated materials: Progress and perspectives," *J. Am. Ceram. Soc.*, vol. 97, no. 4, pp. 997-1008, 2014.
[5]   P. Sukmak, S. Horpibulsuk, and S.-L. Shen, "Strength development in clay–fly ash geopolymer," *Constr. Build. Mater.*, vol. 40, pp. 566-574, 2013.
[6]   I. Garcia-Lodeiro, A. Palomo, and A. . Ernandez-Jimenez, "An overview of the chemistry of alkali-activated cement-based binders," in *Handbook of Alkali-Activated Cements, Mortars and Concretes*, F. Pacheco-Torgal, J. Labrincha, C. Leonelli, and P. Sargent, Eds. Instituto Eduardo Torroja (IETcc-CSIC), Madrid, Spain: Elsevier Science, p. 47, 2014.
[7]   P. Nath and P. K. Sarker, "Effect of GGBFS on setting , workability and early strength properties of fly ash geopolymer concrete cured in ambient condition," *Constr. Build. Mater.*, vol. 66, pp. 163-171, 2014.
[8]   H. Xu and J. S. J. Van Deventer, "The geopolymerisation of alumino-silicate minerals," *Int. J. Miner. Process.*, vol. 59, no. 3, pp. 247-266, 2000.
[9]   S. O. Abarikwu, A. Gianoncelli, A. Zacco, R. W. J. Struis, L. Borgese, L. Depero, and E. Bontempi, "Fly Ash Pollutants, Treatment and Recycling," in *Pollutant Diseases, Remediation and Recycling SE - 3*, vol. 4, E. Lichtfouse, J. Schwarzbauer, and D. Robert, Eds. Springer International Publishing, pp. 103-213, 2013.
[10]   P. Sukmak, S. Horpibulsuk, S.-L. Shen, P. Chindaprasirt, and C. Suksiripattanapong, "Factors influencing strength development in clay–fly ash geopolymer," *Constr. Build. Mater.*, vol. 47, pp. 1125-1136, 2013.
[11]   A. Palomo, M. W. Grutzeck, and M. T. Blanco, "Alkali-activated fly ashes: A cement for the future," *Cem. Concr. Res.*, vol. 29, no. 8, pp. 1323-1329, 1999.
[12]   P. S. Deb, P. Nath, and P. K. Sarker, "The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature," *Mater. Des.*, vol. 62, pp. 32-39, 2014.
[13]   M. Zhang, M. Zhao, G. Zhang, P. Nowak, A. Coen, and M. Tao, "Calcium-free geopolymer as a stabilizer for sulfate-rich soils," *Appl. Clay Sci.*, vol. 108, pp. 199-207, 2015.
[14]   P. Sargent, P. N. Hughes, M. Rouainia, and M. L. White, "The use of alkali activated waste binders in enhancing the mechanical properties and durability of soft alluvial soils," *Eng. Geol.*, vol. 152, no. 1, pp. 96-108, 2013.
[15]   AS 1289.3.1.1, "Methods of testing soils for engineering purposes - part 3.9.1: soil classification tests - determination of the liquid limit of a soil," *Standards Australia*, pp. 1-9, 2009.
[16]   AS 1289.3.2.1, "Methods of testing soils for engineering purposes - Method 3.2.1: Soil classification tests—Determination of the plastic limit of a soil — Standard method," *Standards Australia*, pp. 1-5, 2009.
[17]   AS 1289.5.2.1, "Method 5.1.1: Soil compaction and density tests - determination of the dry density/moisture content relation of a soil using standard compactive effort," *Standards Australia*, pp. 1-13, 2003.

[18]   AS 3582.1, "Supplementary cementitious materials for use with portland and blended cement-Part 1: Fly ash," *Standards Australia*, 1998.

[19]   AS 3582.2, "Supplementary cementitious materials for use with portland and blended cement Part 2: Slag—Ground granulated iron blast-furnace," *Standards Australia*, pp. 1-17, 2001.

[20]   D. Hardjito, "Studies on Fly Ash-Based Geopolymer Concrete," Ph.D. dissertation, Dept. of Civil Eng., Curtin University of Technology , Bentley, W.A., 2005.

[21]   AS 5101.4, "Methods for preparation and testing of stabilized materials Method 4 : Unconfined compressive strength of compacted materials," *Standards Australia*, pp. 1-13, 2008.